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Eric Lichtfouse *Editor*

Organic Fertilisation, Soil Quality and Human Health

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Organic Fertilisation, Soil Quality and Human Health

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Convergence or Divide in the Movement for Sustainable and Just Agriculture

Miguel A. Altieri

Abstract 'Greening' the green revolution will not be sufficient to reduce hunger and poverty and conserve biodiversity. The increasing cost of oil and fertilizers, and the deterioration of the climate and global ecology are key factors that undermine the capacity of humankind to feed itself. This phenomena became evident when the 'perfect storm' occurred in 2008 with the alarming rise in the cost of food that sent an additional 75 million people to the world's line of hungry people. Disregarding the above issues the ruling international agricultural class continues asserting that food production will have to be increased by 70% by the year 2050. The threat to global food insecurity is the direct result of the industrial model of agriculture characterized by large-scale monocultures tailored for the export markets. We need an alternative agricultural development paradigm, one that encourages more ecologically, biodiverse, sustainable and socially just forms of agriculture.

Strategies are needed which lead to the revitalization of small and medium sized farms, and point the way towards the reshaping of the entire agricultural policy and food system in ways that are economically viable to farmers and consumers. Proposed 'sustainable intensification' is ideologically buttressed by intellectual projects to reframe and redefine agroecology by stripping it of its political and social content and promote the wrong notion that agroecological methods can co-exist alongside the aggressive expansion of transgenic crops and agrofuels. Many environmental and advocacy groups privilege those with access to capital and perpetuate an 'agriculture of the poor for the rich'. The technological determinism that the organic agriculture movement emphasizes via development and dissemination of low-input or appropriate technologies is not only naïve but dangerous, as it assumes these technologies in themselves have the capability of initiating beneficial social changes.

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A more radical transformation of agriculture is needed, one guided by the notion that ecological change in agriculture cannot be promoted without comparable changes in the social, political, cultural and economic arenas that determine agriculture. In the end the new crisis is just a new face of the old rural crisis derived from the almost total control of the food system by transnational capital aided by neoliberal programs implemented by many governments. It is imperative to realize that out-of-control trade liberalization is the key mechanism driving farmers off their land and the principal obstacle to local economic development and food sovereignty. It is also crucial to understand that a key enemy of farmers is low prices. Moving towards a more socially just, economically viable, and environmentally sound agriculture will be the result of the coordinated action of social movements in the rural sector in alliance with civil society organizations that are committed to supporting the goals of farmer's movements.

1 Introduction

High levels of hunger, inequity in the distribution of income, land, water, seeds and other resources, in addition to ecological degradation, are persistent and increasing problems at the global level. There is no doubt that the increasing cost of oil and fertilizers, and the deterioration of the climate such as frequent and severe droughts, hurricanes and floods; and the global ecology are key factors that undermine the capacity of humankind to feed itself. It is also clear that as huge tracts of land are taken out of food production to produce biofuels and more people in China and India shift to a meat-based diet from a vegetarian diet, the access to food by the poor proves increasingly more difficult. This phenomena became evident when the 'perfect storm' occurred in 2007–2008 with the alarming rise in the cost of food that sent an additional 75 million people to the world's line of hungry people, especially in Sub-Saharan Africa and Asia. Oddly, there had been no drought – the usual cause of hunger – in those regions during that period and there was plenty of food in the markets. 'For no obvious reason the price of staple foods such as maize and rice nearly doubled in a few months. There were food riots in more than 20 countries and governments had to ban food exports and subsidize staples heavily' (Holt-Gimenez and Patel 2009; Rosset 2011; Photo 1).

The same year – 2008 – that hunger expanded, cereal yields reached unprecedented levels, and the merchants of grain, e.g., Cargill and ADM, and corporate agricultural input and seed providers like Monsanto reaped enormous profits. A huge part of the problem is linked to the deregulation of international commodity markets, the privatization and elimination of grain markets in some countries, and recently the entry of speculative capital into the commodities market. The same banks, hedge funds and financiers whose speculation on the global money markets caused the sub-prime mortgage crisis are thought to be causing food prices to inflate. Between January 2006 and February 2008, financial investments pushed the prices of many food crops to higher values than those crops would have normally reached

Photo 1 Sharing the world food. Kouign amann, a special pastry from Brittany, France (Copyright: Brigitte Cauvin, Inra, 2011)

(Kaufman 2010). Contracts to buy and sell foods such as cocoa, fruit juices, sugar, staples, meat and coffee have been turned into 'derivatives' that can be bought and sold among traders who have nothing to do with agriculture.

Food prices continue to rise beyond 2008 levels. They are now rising by up to 10% a year, and some predict that it is possible that they can increase by at least 40% in the next decade (Rosset 2009). Each time food prices increase, a significant number of family and peasant farmers are expelled from the market due to the low price that they receive for their products, and in part due to the high cost of inputs, principally fertilizers. Meanwhile the cost of food for consumers increases independently from what the price of wheat, corn or rice may be in the global commodity markets. In this way the deregulated market, privatization and free market treaties negatively affect both small farmers and consumers (Rosset 2011). The situation is aggravated by the systematic elimination of national production capacity by the promotion of agroexports and biofuels, partly stimulated by government subsidies. Another complicating factor is the land grabbing led by governments such as the Gulf States and China and wealthy investors who buy or lease land on an immense scale for intensive agriculture for offshore food and biofuel production. Moreover productivity implications from extreme climatic events can be very profound for large scale farmers relying on genetically homogeneous monocultures inherently vulnerable to climate variability.

Disregarding the above issues, the "ruling international agricultural class", i.e. World Bank, CGIAR, FAO and agricultural corporations, with the notable exception of the reports issued by IAASTD (2009) and the UN Rapporteur for the Right to Food (de Schutter 2010), continue asserting that food production will have to be increased by 70% by the year 2050, and that production increases will only be possible by harnessing the power of biotechnology and that liberalized, global trade in grains is essential to food security.

2 A New Paradigm

Most people involved in the sustainable agriculture movement agrees that the threat to global food insecurity is the direct result of the industrial model of agriculture characterized by large-scale monocultures tailored for the export markets, increasingly dominated by transgenic crops, and agrofuels, which degrade ecosystems further undermining nature's capacity to supply food, fiber and energy for people. The tragedy of industrial agriculture is that a growing human population depends on the ecological services provided by nature, e.g., climate balance, pollination, biological control, soil fertility, which external input dependent monocultures increasingly push beyond the tipping point (Perfecto et al. 2009).

There is no doubt that we need an alternative agricultural development paradigm, one that encourages more ecologically, biodiverse, sustainable and socially just forms of agriculture. Strategies are needed which lead to the revitalization of small and medium sized farms, and point the way towards the reshaping of the entire agricultural policy and food system in ways that are economically viable to farmers and consumers. Throughout the world there are hundreds of movements that are pursuing a change toward ecologically sensitive and socially just farming systems from a variety of perspectives. Some emphasize the production of food that is safe for the consumer, in a way that is environmentally friendly and prioritizes animal welfare and the conservation of wild biodiversity. Others promote alternative marketing strategies , responsible land stewardship and others the empowerment of peasant communities. Although one may argue that most of these groups advocating a shift towards sustainable agriculture share the same goals, there are huge and at times insurmountable differences not only in objectives but in ideological perceptions on the root causes of the unsustainability and inequities of the agrarian structure and more importantly on the strategies on how to change such structure.

3 A Diversity of Contrasting Approaches

Given the popularity of agroecology several academic and environmental groups promote some technical aspects of agroecology. For example, some organic farmers and university researchers advance the notion that a marriage between agroecology, organic farming and biotechnology is necessary to close the yield gap while reducing agriculture's environmental footprint (Roland and Adamchak 2009; Foley 2011).

They propose adjusting the ecological inefficiencies of industrial agriculture through "sustainable intensification," e.g., by increasing efficiency of water and fertilizer use, and confronting climate change by deploying "climate-smart" genetic varieties. These superficial technical adjustments are ideologically buttressed by intellectual projects to reframe and redefine agroecology by stripping it of its political and social content (Tomich et al. 2011) and promote the wrong notion that agroecological methods can co-exist – alongside the aggressive expansion of transgenic crops and agrofuels.

Many environmental and advocacy groups expect that their goals will be met solely by promoting a set of ecologically benign technological innovations, i.e. organic farming, or by exploiting market niches available in the globalized economy. Thus, perhaps inadvertently, by working within the windows of the dominant macroeconomic system, these groups privilege those with access to capital and perpetuate an "agriculture of the poor for the rich". The "cibo pulito, justo e buono" that Slow Food promotes and the Fair Trade coffee, bananas, and other products are mainly enjoyed by the opulent in the North. Even the food movement in the USA and Europe that support sustainable agriculture via eating fresh food produced on local family farms, has left out from their radar the people of color and from low-income neighborhoods who live in food deserts and that therefore have been systematically deprived of access to such healthy and so-called sustainable food.

The "technological determinism" that the organic agriculture movement emphasizes via development and dissemination of low-input or appropriate technologies is not only naïve but dangerous, as it assumes these technologies in themselves have the capability of initiating beneficial social changes. The organic farming school that emphasizes input substitution, i.e. a toxic chemical substituted by a biological insecticide, creating farmer dependence on external inputs, but leaving the monoculture structure untouched, epitomizes those groups that have a relatively benign view of capitalist agriculture. They ignore the fact that organic products are increasingly traded as international commodities for the consumption of the rich, and that their production and distribution is slowly being taken over by the same multinational corporations that dominate conventional agriculture (Rosset and Altieri 1997). Ignoring the complex issues surrounding commercial and agroexport oriented organic agriculture is undermining the original agrarian vision of organic farming which envisioned a renaissance of a diversified and small scale agriculture in order to strengthen local production – consumption circles. This narrow acceptance of the present structure of agriculture as a given condition restricts the real possibility of implementing alternatives that challenge such a structure. Merely introducing alternative agricultural technologies will do little to change the underlying forces that led to monoculture production, farm size expansion, and mechanization in the first place.

Given their interest in conserving biodiversity in the rural landscapes, many sustainable agriculture enthusiasts embrace the Ecoagriculture movement which argues that wildlife preservation can be accomplished mainly through agricultural intensification, especially in the biodiversity hotspots of the developing world where most of the poor concentrate and have little choice but to exploit wild habitats for survival. Ecoagriculture promoters claim that the best way to reduce the impact of agricultural modernization on ecosystem integrity is to intensify production with emerging technologies, i.e. transgenic crops and plantation agriculture, in order to increase yields per hectare, and in this way spare natural forests and other wildlife habitats from further agricultural expansion. For the ecoagriculturists it makes no difference if the best results to preserve birds or other animals, are derived from large latifundia surrounded by hedgerows or a group of small farms surrounded by a matrix natural vegetation. The end goal is wildlife preservation, as long as it is achieved at a "reasonable" environmental and social cost. True, exclusive attention to increasing yields for meeting food needs can exert a very high toll on the environment, but a sole focus on preserving nature condemns millions to hunger and poverty (Altieri 2004).

In their attempt to obtain better prices for small farmers and thus reduce poverty, Fairtrade leads a worldwide movement for ethical consumption with commodities that include coffee, cocoa, tea, bananas, and sugar. Fairtrade experienced rapid market expansion when large corporations and brands including Costco, Sam's Club, Seattle's Best, Dunkin Donuts, Starbucks, and McDonalds began offering Fairtrade Certified coffee. These companies were certified with the Fairtrade seal regardless of their dismal labor or environmental records. In 2005 the Fairtrade market ballooned to $500 million, the fastest growing segment of the specialty coffee market. To reach such amounts, the Fair Trade focuses on exports and contributes little to local food security, at times creating social stratification in rural communities as relatively few families benefit from the good prices. Fair Trade companies have not joined other social movements demanding structural change – like getting agriculture out of the WTO, abolishing NAFTA and other regional free trade agreements, not support rural social movements and government policies for local, and sustainable food production.

4 A More Progressive and Transformational Agenda

A more radical transformation of agriculture is needed, one guided by the notion that ecological change in agriculture cannot be promoted without comparable changes in the social, political, cultural and economic arenas that determine agriculture. In the end the new crisis is just a new face of the old rural crisis derived from the almost total control of the food system by transnational capital aided by neoliberal programs implemented by many governments (Rosset 2009).

The organized peasant and indigenous based agrarian movements, i.e. the Via Campesina, consider that only by changing the export-led, free-trade based, industrial agriculture model of large farms can the downward spiral of poverty, low wages, rural-urban migration, hunger and environmental degradation be halted. These movements embrace the concept of food sovereignty which constitutes an alternative to the current mainstream thinking on food production. The concept behind food sovereignty contrasts the neo-liberal approach that believes that international trade will solve the world's food problem. Instead, it focuses on local autonomy, local markets and community action for access and control of land, water, agrobiodiversity, etc., which are of central importance for communities to be able to produce food locally. The concept of food sovereignty implies a shift in the role of subsidies which results in northern food surpluses being dumped in poorer countries, towards a system of land reform so that peasant and family farmers have access to land and support vibrant rural economies. This requires policies that prioritize national-regional-local food security above the production of exports and dependence on imports. It also requires a shift away from hi-tech, intensive monoculture agriculture dependent on high levels of pesticide use, and transgenic crops, and instead the promotion of agroecology (Altieri and Toledo 2011).

It is imperative to realize that out-of-control trade liberalization is the key mechanism driving farmers off their land and the principal obstacle to local economic development and food sovereignty. It is also crucial to understand that a key enemy of farmers is low prices. And farm gate prices continue to drop even while consumer prices rise. This is because the main force dictating low prices to farmers is the same one that dictates high prices to consumers: the monopoly control that corporations like Cargill, Archer Daniels Midland, Dreyfuss, Bunge, Nestlé, and others exert over the food system. That means that breaking up these monopolies by enforcing antitrust laws nationally and globally is a key step toward ensuring that farmers can earn a living on the land and consumers can have access to affordable, nutritious and healthy food.

There is no doubt that an alliance between farmers and consumers is of strategic importance. Consumers need to realize that their quality of life is intractably associated with the type of agriculture practiced in the urban green belts, not only because of the quality of the food produced, but also because agriculture is multifunctional producing a series of environmental services such as water quality and biodiversity conservation. But this multifunctionality can only emerge if agricultural landscapes are dotted by small, diversified farms which as studies show they can produce from 2 to 10 times more per unit area than do larger, corporate farmers. In the USA the top quarter sustainable agriculture farmers, which are mostly small-medium size, exhibit higher yields than conventional farmers, as well as a much lower negative impact on the environment. Small farms are ‘multi-functional’ – more productive, more efficient, and contribute more to economic development than do large farms. Communities surrounded by populous small farms have healthier economies than do communities surrounded by depopulated large, monoculture, mechanized farms. Small farmers also take better care of natural resources, including reducing soil erosion and conserving biodiversity. Thus it should be obvious to city dwellers that eating is both an ecological and political act; that buying food at local farmers markets will support a very different model of agriculture if buying food in a supermarket.

Moving towards a more socially just, economically viable, and environmentally sound agriculture will be the result of the coordinated action of social movements in the rural sector in alliance with civil society organizations that are committed to supporting the goals of the farmers movements. Concerted action is needed so that multinational companies and government officials feel the impact of environmental, farm labor, animal rights and consumer lobbies, pressuring them to ensure that all countries retain the right to achieve food sovereignty by developing their own domestic farm and food policies, which respond to the true needs of their farmers and all consumers, especially the poor.

Evidence emerging from dozens of studies is conclusive: new approaches and technologies spearheaded by farmers, local governments, and NGOs around the world are already making a sufficient contribution to food security at the household, national, and regional levels. A variety of agroecological and participatory approaches in many countries show very positive outcomes even under adverse conditions. Potentials include: raising cereal yields from 50% to 200%, increasing stability of production through diversification and soil/water management, improving diets and income with appropriate support and spread of these approaches, and contributing to national food security and to exports. Importantly, the agroecological process requires participation and enhancement of the farmer's ecological literacy about their farms and resources, laying the foundation for empowerment and continuous innovation by rural communities.

Whether the potential and spread of these thousands of local agroecological innovations is realized depends on investments, policies, and attitude changes on the part of researchers and policymakers. Major changes must be made in institutions, research and development, and policies to make sure that agroecological alternatives are adopted, made equitably and broadly accessible, and multiplied so that their full benefit for sustainable food security can be realized. Existing subsidies and policy incentives for conventional chemical approaches must be dismantled. Corporate control over the food system must also be challenged. Governments and international public organizations must encourage and support effective partnerships between NGOs, local universities, and farmer organizations in order to assist and empower poor farmers to achieve food security, income generation, and natural resource conservation (Van der Ploeg 2009).

Equitable market opportunities must also be developed, emphasizing local commercialization and distribution schemes, fair prices and other mechanisms that link farmers and consumers more directly and in more solidarious ways. The ultimate challenge is to increase investment and research in agroecology and scale up projects that have already proven successful to thousands of other farmers. This will generate a meaningful impact on the income, food security, and environmental well being of all the population, especially small farmers who have been adversely impacted by conventional modern agricultural policy and technology.

5 Conclusion

In summary, "Greening" the green revolution will not be sufficient to reduce hunger and poverty and conserve biodiversity. If the root causes of hunger, poverty and inequity are not confronted head-on, tensions between socially equitable development and ecologically sound conservation are bound to accentuate. Organic farming systems that do not challenge the monocultural nature of plantations and rely on external inputs as well as foreign and expensive certification seals, or fair-trade systems destined only for agro-export, offer very little to small farmers that become dependent on external inputs and foreign and volatile markets. By keeping farmers dependent on an input substitution approach, fine-tuning of input use does little to move farmers towards the productive redesign of agroecosystems which would move them away from dependence on external inputs. Niche markets for the rich in the North, in addition to exhibiting the same problems of any agro-export scheme which does not prioritize food sovereignty perpetuate dependence and hunger.

There is a general belief that the alternative agriculture movement is an homogenous block and that stands united in its challenge against industrial agriculture. Despite differences, if the majority converge with peasant movements under the banner of food sovereignty, the counter-movement opposing the corporate food regime will be strengthened. On the other hand if the majority align themselves with either neoliberal or reformist projects of the corporate food regime, the results will be disastrous for the peasantry and poor consumers. However, a critical debate and dialogue is essential to move forward with the alternative agriculture movement, especially if the goal is to promote a truly alternative agricultural path. Only a strong counter-movement can open possibilities for transformation of the current unjust food system.

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No-Till Agriculture in the USA

Jared Margulies

Abstract No-till farming is a form of conservation tillage in which crops are seeded directly into the soil through previous crop residues, most commonly managing weeds using broad-spectrum herbicides and increasingly, transgenic herbicide-resistant crop varieties. Today, nearly a quarter of US cropland is farmed using no-tillage methods, a phenomenon which has been repeatedly described as one of the greatest agricultural revolutions of modern times. No-till advocates promote this method for its ability to reduce soil erosion, sequester soil carbon, reduce agricultural runoff, and improve farmland wildlife habitat, all while maintaining or even improving crop yields. Problems of water quality and contamination, as well as newly emerging problems associated with herbicide-resistant weeds, however, exist for no-till. This article reviews current literature on specific problems related to no-till agriculture, including soil and water impacts, soil carbon sequestration and greenhouse gases, and herbicide-resistant weeds; as well as the potential future of no-till farming and alternative no-till strategies that may address these problems.

The major points are the following. (1) No-till farming practices frequently result in increased soil organic matter content, soil moisture content, and soil biodiversity compared to conventional plow-tillage systems. Bulk soil density is often higher under no-tillage systems, but there is also greater macropore structure under no-till because of the preservation of earthworm burrows compared to conventional tillage systems. No-till's net benefits for preserving soil structure and biota are well-described and demonstrated. (2) Although many no-till advocates have suggested no-till could make a significant contribution to mitigating anthropogenic climate change via soil carbon sequestration, the most current research indicates that no-till's

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potential contribution to reducing anthropogenic contributions to global climate change is limited.

(3) Rainfall intensity and timing of chemical applications significantly impact water contamination from surface and subsurface runoff under no-till management. Because of increased macropore structure, no-till systems can result in increased transport of agrochemicals, nutrients, and animal wastes in subsurface water compared to conventional tillage practices. Increased subsurface transport of chemicals may pose environmental and public health threats in no-till agriculture systems. (4) The emergence of herbicide-resistant weeds in no-till systems presents a major risk to the success of current no-till practices, which are entirely reliant on chemical weed suppression. Alongside the need for rapid development of novel herbicides and the diversification of herbicide application regimes, other no-till agricultural methods, such as organic no-till agriculture and perennial grain agriculture systems, should be further developed and prioritized for research to meet the challenges of both preserving environmental water quality as well as reducing soil erosion while protecting future food security.

Keywords No-till agriculture • Agricultural sustainability • Herbicides • Herbicide-resistant weeds • Mulch-farming • Soil erosion • Water quality • Soil carbon sequestration • Corn Belt

1 Introduction

In 1943, Ohio experimental agrarian Edward H. Faulkner wrote a book entitled, “Plowman’s Folly,” in which he argued plowing was the single greatest misstep in the advancement of agriculture. Instead, he suggested that farmers should leave crop residues at the surface of the soil, only working them into the upper layer of the soil using a disk-harrow or other surface tillage instruments (Faulkner 1943). Radical though his theory was, the book was a great success amongst the lay public and farmers alike, and went so far as to be discussed in such unlikely places as *The New Yorker* magazine (Bromfield 1988). However, Faulkner’s ideas were also met with great skepticism and ridicule amongst agricultural scientists (Triplett and Dick 2008). Nevertheless, the US Soil Conservation Service’s interest in reducing soil erosion from agricultural lands led to a concerted effort in researching new agricultural techniques to minimize soil loss, including stubble-mulch farming, a technique similar to Faulkner’s (Coughenour and Chamala 2000; Rasmussen 1983–1984). With the emergence of agro-chemicals following World War II, a new form of farming, using herbicides rather than plowing to control weeds emerged, with experiments conducted by both farmers and research centers (Coughenour and Chamala 2000). These new chemicals, coupled with the production of new machinery to cultivate and plant seeds through crop residue, set the stage for a new type of *no-tillage* farming (Montgomery 2008).

Over 60 years later, no-tillage (or “no-till”) farming now covers almost 25% of cultivated lands in the United States, with related conservation tillage practices,

Fig. 1 A modern no-till cornfield in Ohio (Courtesy of OH-DNR)

defined as agricultural land with maintenance of >30% residue cover (CTIC 1998), covering approximately 40% of U.S cropland (Montgomery 2008). However, modern no-till agriculture is not without faults or cause for concern, and stands in striking contrast to the ideas of a *plowless* agriculture first set forth in the middle of the twentieth century by experimental agriculturalists both in the United States and abroad (Fig. 1). By briefly examining the scientific as well as socio-cultural emergence and practice of no-tillage agriculture in the United States, focusing largely on no-till corn *(Zea mays L.)* research and production in the Corn Belt, this paper will attempt to answer the question of no-till agriculture's present and potential future impacts on land and water quality, as well as suggest what, if any, role no-till agriculture may play in a future permanent and sustainable U.S. agriculture.

2 What Was Old Is New Again: The Emergence of American No-Till Farming

At the time Faulkner was engaging in experimental agriculture systems, no-tillage agriculture was at once entirely radical and something quite ancient (Faulkner 1943). Examples of ancient no-tillage agriculture are found worldwide, from *zaï* holes in Africa to direct seeding with "digging sticks" which may have appeared simultaneously around the globe (Lal 2009; Ouédraogo and Bertelson 1997). However, with the advent of the moldboard plow beginning in the seventeenth century, the practices of inverting the soil to bury vegetation and pulverize soil for a

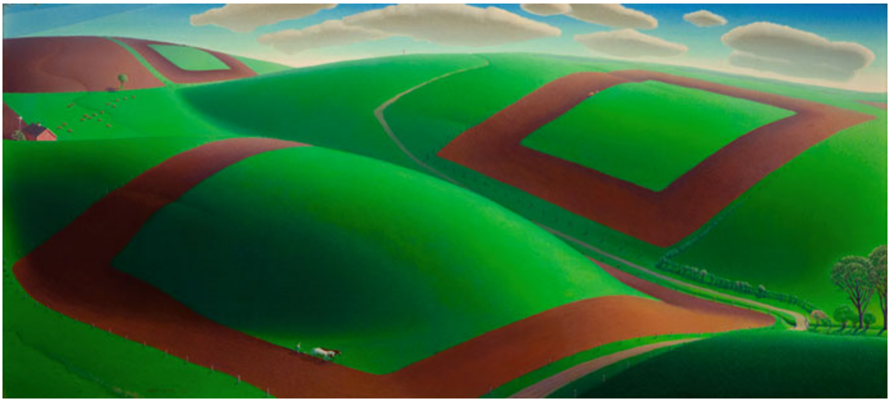

Fig. 2 Persistent iconic imagery of American agricultural landscapes shaped by the moldboard plow. Grant Wood, 'Spring Turning' (1936) (Courtesy of Reynolda House Museum of American Art, Winston-Salem, North Carolina. Art © Figge Art Museum, successors to the Estate of Nan Wood Graham/Licensed by VAGA, New York, NY)

neat and tidy planting surface became fundamental to the very idea of agriculture throughout the now-developed world (Sprague 1986).

Plowing may have become the symbol of farming life in the United States in the nineteenth century just as much for powerful aesthetic and cultural reasons as agricultural ones. As Coughenour and Chamala (2000) describe, quoting Leo Marx (1964):

> 'Beginning in Jefferson's time, the cardinal image of American aspirations…was a rural landscape, a well-ordered garden magnified to continental size (Marx 1964, 141).' The Bucolic image of rolling pastures, neatly trimmed fields with ordered rows of corn and waving fields of golden grain… still remains our dominant image of a lovely countryside…The picture gains its dynamism from the fact 'that down to the twentieth century the imagination of Americans was dominated by the idea of transforming the wild heartland' of America into this kind of well-ordered landscape (Marx 1964, 141). (Coughenour and Chamala 2000, 3–4).

It is no coincidence that during Thomas Jefferson's 8-year term as President he helped shape this neat and pastoral image of what the American agricultural landscape should look like (Fig. 2), as he also played an important role in optimizing the shape of the moldboard plow, whose widespread use enabled these tidy landscapes (Sprague 1986; Marx 1964).

The agricultural disaster known as the Dust Bowl of the 1930s in the United States was an important catalyst for revising how agriculture in the United States was practiced and understood (Fig. 3). On May 11th, 1934, the skies over Washington D.C. darkened from the massive dust storms gathering in the American Plains. Soil needed conserving, and erosion and drought protection were at the forefront of agriculturists' minds. In many ways, Faulkner's work was merely a reasonable extension of well-established agricultural ideas – that bare soil led to increased erosion events, and green manures and mulching were useful for introducing

Fig. 3 A common depiction of Dust Bowl era agriculture (Photograph by Dorothea Lange (1938). Courtesy of Library of Congress, Prints and Photographs Division, FSA-OWI Collection [LC-USF34- 018267-C])

nutrients and organic matter into the soil. Faulkner argued for a style of farming he called "trash farming," in which organic matter, rather than being buried by the plow, was kept on top of the soil or incorporated into the upper layer using a disk-harrow. In this way, he argued, farming could mimic the natural process of forest litter decay, but at much faster rates (Faulkner 1943). It was this latter belief that was perhaps most difficult for agricultural scientists and government researchers to swallow: that Americans could improve their agricultural techniques by *learning from nature*, rather than through technological advancement, was an idea very much at odds with the post-World War II ethos of American technological and scientific innovation (Cohen 1976b; Nelson and Wright 1992).

And so in the mid-twentieth century two different perspectives on no-tillage farming emerged. On the one hand, American figures like Faulkner, Louis Bromfield (who farmed just 40 miles away from Faulkner at his now-famous Malabar Farm near Mansfield, Ohio) and J.I Rodale (founder of the American organic agriculture movement who opposed the direction American agriculture was moving just as much for philosophical and health as well as soil conservation reasons (Rodale 1945; Bromfield 1947, 1988), found resonance with organic farming innovators in England who believed nature was the greatest model for agricultural innovation (Howard 1940; Balfour Lady 1950). And although they did not know it at the time, an even more radical farmer, scientist-turned farmer Masanobu Fukuoka was developing his own version of "natural farming" in Japan (Fukuoka 1978), which shunned any disturbance of the soil, relying on well-timed surface seedings for weed control.

At the same time, another group of agriculturalists in Kentucky and neighboring Corn Belt states, motivated by the mantra *soil, toil and oil*, were also experimenting with no-tillage farming techniques. Unlike the work of the former, who were convinced that the future of farming lay in mimicking natural patterns of soil formation and litter decay, using terms such as *natural*, *organic* and *holistic* to describe their farming techniques, this latter group farmed conventional land holdings, and was interested in the practical economic benefits no-tillage agriculture might provide. In 1962, Harry Young, Jr. of Christian County Kentucky became the first farmer on record in the United States to successfully grow corn without tillage by using herbicides for weed suppression (Coughenour and Chamala 2000). By applying pre-emergent herbicides prior to planting and weighing down his seeder to penetrate crop residue on the soil surface, Young planted corn directly into the previous season's cover crop, with little disturbance of the topsoil. Young's work sparked a farmer and extension office-led initiative which would creep across the United States and eventually lead to what is now called *the no-till revolution*.

Today's proponents of no-tillage agriculture are varied and many, ranging from agriculture scientists to geologists to climate-change experts. But no-till agriculture is not without faults: in its current form, it is still predominately found in developed countries, as the use of agro-chemicals and specialized machinery makes no-till adoption difficult in resource-poor nations (Lal et al. 2004). Globally, only 5% of cropland is managed under no-till practices (Lal et al. 2004). No-till's heavy reliance on herbicide applications for the management of weeds is also cause for concern: in addition to notable environmental and human health risks from specific herbicides, herbicide-resistance amongst weeds is an increasing problem (Triplett and Dick 2008). Before suggesting what the future role of no-till farming may look like, a critical review of current problems facing no-till and its impacts on land and water quality is necessary.

Conclusion: Technological advances as well as socio-cultural phenomena influenced the development of agriculture in the United States. While the first proponents of *plowless* agriculture were informed by natural ecological processes in developing new farming techniques, following the advancement of agrochemicals, new, chemical-based weed management farming systems were developed and quickly emerged as the dominate form of modern no-till farming.

3 Modern No-Till Agriculture: Land and Water Impacts

3.1 Soil Erosion by Wind and Water

It is generally accepted that modern no-tillage agriculture has significantly lower soil erosion rates than conventionally tilled soils, and that these rates are closer to "geological rates" of soil formation (Montgomery 2007). Montgomery (2007) reviewed 39 studies comparing no-till and conventional tillage practices on soil

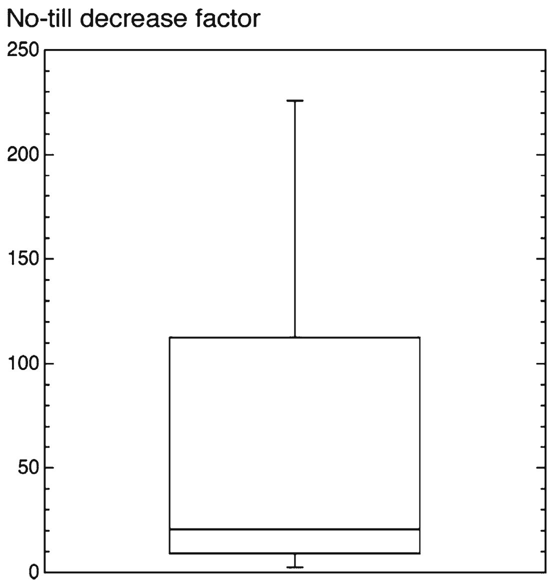

Fig. 4 Box-and-whiskers plot showing the range of reported decreases in erosion rate for studies reporting direct comparisons of conventional tillage and no-till practices for comparable settings (n = 39, median = 20, mean = 488, minimum = 2.5, maximum = 7,620). Data include studies that reported both rates individually and those that simply reported a ratio between erosion rates under conventional or no-till cultivation. From Montgomery (2007) (Copyright 2007 National Academy of Sciences, U.S.A)

erosion, which found no-till practices to reduce soil erosion rates by upwards of 98% (Fig. 4), including long-term experiments with no-till corn plantings. Soil erosion is significantly reduced under no-till by minimizing soil transport both by wind and water erosion (Hagen 1996; Triplett and Dick 2008). Standing crop residues reduce wind velocity (Hagen 1996), and raindrop impact and flow rates are minimized, decreasing sediment transport. Triplett and Dick (2008) found an elevation difference of 9.0 cm after 42 years of continuous corn cropping between conventional and no-till plots in Wooster, Ohio, with an estimated soil loss of 1,260 Mg ha^{-1} from the conventional plots relative to no-till plots. In a similar side-by-side experimental site near Coshocton, Ohio, the effectiveness of no-till in controlling soil erosion from cornfields was clearly demonstrated over just a 3-year period (Fig. 5) (Harrold and Edwards 1974).

Local factors such as soil type, cropping system, rainfall intensity and frequency, and field slope greatly affect the success of no-tillage techniques in minimizing soil loss compared to conventional or other conservation tillage systems (Montgomery 2007; Cannell and Hawes 1994; Sprague 1986; Wendt and Burwell 1985), with some studies finding limited differences in soil erosion between no-till and conventional tillage practices (Lal et al. 1989). In long-term field studies comparing no-till and conventional tillage, the greatest losses of soil are often during high intensity storms,

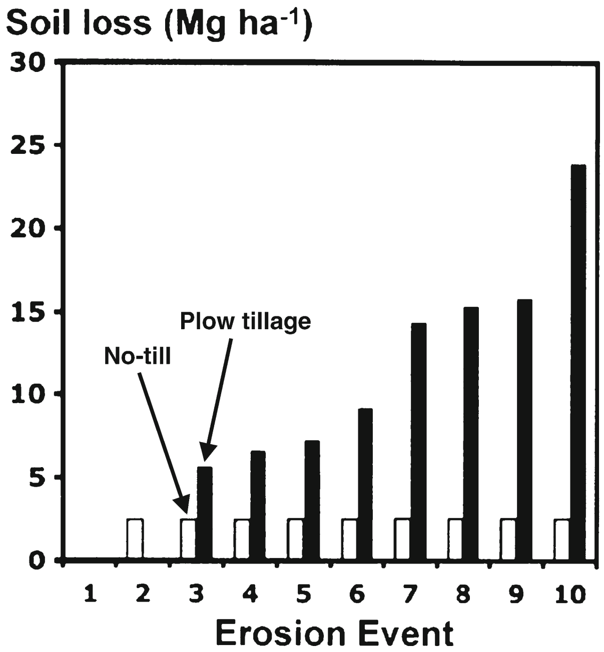

Fig. 5 Cumulative soil loss from no-till and plow tillage watersheds at Coshocton, OH, for the years of 1970–1973. The erosion events are all rainfall events that produced runoff and erosion during this time period. To visualize the no-till values, they were multiplied by ten before being plotted in the graph (From Harrold and Edwards (1974). Reprinted with permission of the authors)

where no-till has been found to be effective at minimizing soil loss (Raczkowski et al. 2009). Of no-till's many touted benefits, no-till's ability to reduce soil erosion compared to conventional tillage systems is the most conclusively demonstrated.

Partial Conclusion: No-till farming greatly reduces wind and water erosion of soil (2.5 to >1,000 times) compared to conventional tillage farming systems by leaving crop residues at the soil surface.

3.2 Soil Physical and Biological Properties

No-till farming influences more than soil erosion rates, causing changes in soil properties including soil density, organic matter content, moisture, temperature and aggregation, as well as affecting plant roots (Sprague 1986). Organic matter content in soil, vitally important for soil structure, water retention, and crop yields, is consistently higher under no-till management compared to conventional plowing (Montgomery 2008; Cannell and Hawes 1994; Mahboubi et al. 1993; Sprague 1986). In a 10-year study comparing no-till and conventional corn production in Kentucky, Blevins et al. (1983) found increased soil moisture, organic matter in the

0–5 cm soil layer, and microbial activity under no-till production, although they found increased soil pH under no-till from nitrogen fertilizer remaining at the soil surface. Soil type plays an important role, however, in determining how no-till farming influences these properties (Cannell and Hawes 1994). Concern has been generated that bulk density of soil increases under no-till farming (Cannell and Hawes 1994; Mahboubi et al. 1993; Sprague 1986), but results vary depending on soil type and differences may largely be due to sampling depth (Locke and Bryson 1997; Blevins et al. 1983; Lal et al. 1994; Griffith et al. 1977).

No-till study plots have shown consistently higher levels of biological life in the upper soil layers compared to conventional tillage sites (Kladivko 2001; Mijangos et al. 2006; Kladivko et al. 1997). Giller et al. (1997) argue that ecosystem function may "significantly be impaired by loss of soil biodiversity" (14), making no-till an attractive alternative to conventional tillage in regards to soil biodiversity. Although there is a trend towards fungal dominated communities at the crop-residue layer in no-till, microbial biomass is also generally higher in no-till fields than conventional fields, as are earthworm populations, which play an important role in maintaining soil porosity and aggregation, root growth, organic matter decomposition and nutrient cycling (Simonsen et al. 2010; Kladivko 2001). The role of earthworms and earthworm burrows in water transport in no-till systems will be further discussed in Sect. 3.4.

Conclusion: Site specific factors such as soil type play an important role regarding no-till's impact on soil physical and biological parameters. Nevertheless, no-till farming practices frequently result in increased soil organic matter content, soil moisture content, and soil biodiversity compared to conventional tillage systems. Bulk density is often higher under no-tillage systems, but there is also greater macropore structure under no-till because of the preservation of earthworm burrows compared to conventional tillage systems.

3.3 Soil Carbon Sequestration and Greenhouse Gas Emissions

No-till agriculture has been touted as an important mechanism for reducing overall anthropogenic contributions to global climate change through increased rates of soil carbon sequestration (Lal 1997, 2004; West and Post 2002; Lal et al. 2004; Montgomery 2008). However, these claims have more recently been called into question and have led to a renewed interest in researching no-till's true contribution to carbon sequestration. When considering the entire soil profile, no-till's ability to sequester soil carbon compared to conventional tillage is minimal – although no-till fields sequester greater amounts of soil carbon in the upper soil layers (<30 cm), conventionally-tilled fields have been shown to sequester more soil carbon at greater soil depths (Dolan et al. 2006; Baker et al. 2007; Blanco-Canqui and Lal 2008; Christopher et al. 2009). Definitive results from carbon sequestration studies are further compounded by problems of sample size and appropriate analysis (Kravchenko and Robertson 2011; Syswerda et al. 2011). A recent meta-analysis of 69 paired no-till and conventionally-tilled soil experiments found no net gain in soil carbon sequestration under no-till compared to conventional tillage (Luo et al. 2010). Additionally, further research is needed to understand no-till's role in cycling N_2O, a greenhouse gas 300 times more potent than CO_2 (Rodhe 1990), as well as other greenhouse gas contributions under different tillage systems. Research indicates no-till has the potential to lead to increased N_2O emissions compared to conventional tillage systems (Grandy et al. 2006; Bavin et al. 2009; Powlson et al. 2011), but more research is needed.

Conclusion: The most current research indicates no-till's potential contribution to reducing anthropogenic contributions to global climate change is more limited than previously believed, but more research is needed to further understand no-till's role in sequestering soil organic carbon and cycling greenhouse gas emissions such as N_2O.

3.4 Water Quality

A long held assumption in no-till farming is that no-till techniques reduce downstream pollution (Ritchie and Follet 1983); however, this may not always be the case (Hinkle 1983). Although sediment loads, a critical form of agricultural pollution, are lower under no-till management (Yates et al. 2006), the movement of water via runoff and subsurface infiltration on no-till fields has important implications for watershed quality vis-à-vis nutrient and chemical transport. Although both soil erosion and water runoff are often significantly reduced under no-till management (Burwell and Kramer 1983; Raczkowski et al. 2009), nutrient and chemical concentrations in runoff, and their infiltration into groundwater, can vary greatly under no-till and conventional tillage (Isensee and Sadeghi 1993; Phillips et al. 1993; Malone et al. 2003; Yates et al. 2006; Triplett and Dick 2008). In a 2-year cornfield test in Beltsville, Maryland, total runoff volume from no-till and conventional plots depended on soil moisture levels prior to rainfall events, with runoff volume higher on no-till plots compared to conventional plots, when soil moisture levels were high (Isensee and Sadeghi 1993). Pesticide concentrations in runoff were consistently higher on no-till sites in this study (Isensee and Sadeghi 1993). In a 6-year study in North Carolina, however, no-till plots had lower volumes of water runoff compared to conventional tillage because no-till plots did not experience soil surface sealing, which is common on Piedmont soils (Raczkowski et al. 2009). Similarly, a 24-year trial of corn no-till and conventional tillage in Missouri found no-till fields to have 13% less runoff than conventional fields (Burwell and Kramer 1983), and a multi-year survey of pesticide use under different tillage systems for both corn and soybeans across the U.S. suggests there is little difference in pesticide use with no-till systems (Bull et al. 1993).

Using an extensively tested and validated soil model (EPIC), Phillips et al. (1993) found nitrogen (N) and phosphorous (P) losses via water runoff to be significantly higher for no-till corn and corn/soybean rotations than respective conventional tillage plantings in Illinois. In all of their models, Phillips et al. (1993) also found nitrate

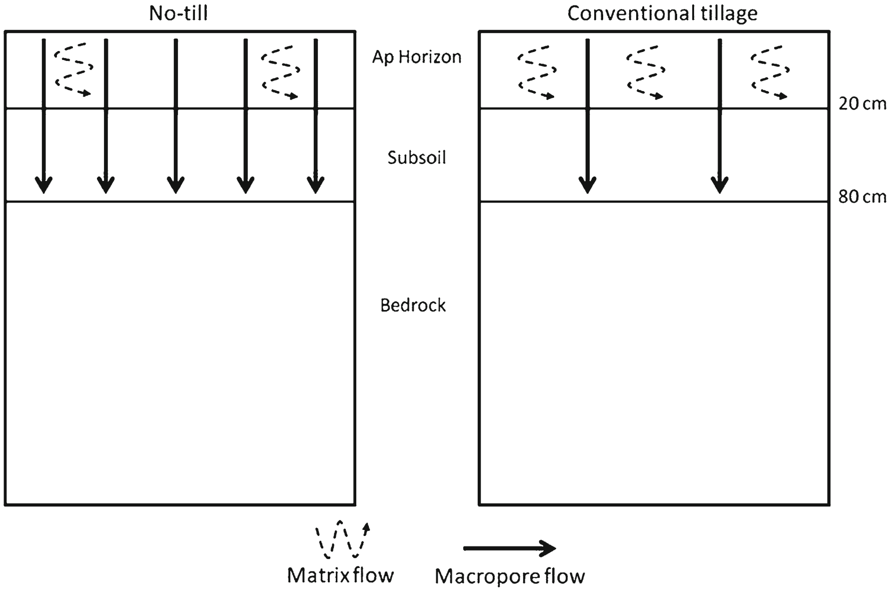

Fig. 6 Illustrative depiction of subsurface water flow under (**a**) no-till and (**b**) conventional tillage systems during the growing season. Earthworm burrow preservation under no-till creates a preferential flow of water via macropores under no-till systems compared to conventional tillage (Adapted from Shipitalo et al. 2000)

concentrations in subsurface water flow to exceed U.S drinking water standards. Yates et al. (2006) found reduced sediment loads in an Ontario watershed from no-till fields improved overall stream ecosystem health; however, they noted increased concentrations of nitrates in the watershed from no-till fields compared to conventional fields. Differences between studies regarding concentrations of pesticide and nutrient losses from conventional and no-till fields may be related to whether surface runoff or subsurface drainage are measured (Yates et al. 2006), with no-till fields experiencing higher nutrient and chemical losses via subsurface flow due to greater soil macropore structure, which has been attributed to a larger abundance of earthworm burrows (Shipitalo et al. 2000).

An important consideration for chemical transport in no-till systems is the increase in soil macropore formation and preservation, which enables increased subsurface transport at higher velocities of water, chemicals, and injected animal wastes under no-till compared to conventional tillage (Edwards and Shipitalo 1993; Shipitalo et al. 2000; Shipitalo and Gibbs 2000). Compared to conventional plowing systems, no-till farming better preserves earthworm burrows – biopores which act as preferential flow routes that are normally disturbed by conventional plowing systems (Shipitalo et al. 2000) (Fig. 6). In their study of water and chemical transport under long-term no-till and conventional tillage experimental sites, Shipitalo et al. (2000) found that storm intensity and timing of chemical applications could significantly impact the role of macropores in transporting water and agricultural chemicals from no-till fields. They concluded that high-intensity storms shortly following chemical applications could result in increased transport of chemicals via macropores and result in higher rates of chemical leaching from agricultural fields, though with good management practices the timing of chemical applications could reduce this likelihood (Shipitalo et al. 2000).

Although nutrient and pesticide movement through soil loss is minimized under no-till cultivation, the evidence regarding the movement of these chemicals through both surface runoff and subsurface drainage may be cause for concern. As Phillips et al. (1993) describe, "there is a conflict between the advantages of leaving crop residue on the surface to minimize erosion, and the disadvantage of increased susceptibility of fertilizer application to runoff losses" (455). Though the impacts of no-till practices on chemical soil surface runoff are conflicting (Fawcett et al. 1994), more definitive is the increased presence of chemicals in subsurface percolate, field drainage, and groundwater where no-till is used (Malone et al. 2003). Ultimately, as Charles E. Little asked in 1987, "is…conservation tillage actually a middle way, a partial return to the ecologically benign realms of the nonmanipulative…or does it simply substitute one kind of adverse environmental impact with another, continuing – maybe even increasing – the serious environmental 'externalities' of modern-day commercial farming?" (101). Echoing Hinkle (1983), it is possible modern no-till agriculture may be trading in one type of degradation for a less noticeable, and less understood one.

Conclusion: Rainfall intensity and timing of chemical applications significantly impact water contamination from surface and subsurface runoff under no-till management. Because of increased macropore structure, no-till systems can result in increased transport of agrochemicals, nutrients, and animal wastes in subsurface water compared to conventional tillage practices. Although no-till reduces surface sediment transport, an important form of agricultural water contamination, increased subsurface transport of chemicals may pose an environmental and public health threat in no-till systems.

4 Problems in No-Till

Despite no-tillage agriculture's successes in reducing soil erosion and managing water runoff, problems related to pesticide and nutrient transport into bodies of water exist, as noted earlier. This is of concern for both environmental as well as public health reasons (Hinkle 1983; van der Werf 1996). However, there are additional concerns with no-till practices, including increased use of emergency pesticide applications, herbicide carryover with consequent yield reductions, increasing herbicide resistance amongst weeds, and the subsequent need for the development of new herbicide-tolerant crops and novel herbicides (Hinkle 1983; Smika and Sharman 1983; Goldburg 1992; Locke and Bryson 1997; Triplett and Dick 2008). There is not space to address all of these concerns in detail here; however, the issues of herbicide resistance and pesticide use warrant further attention.

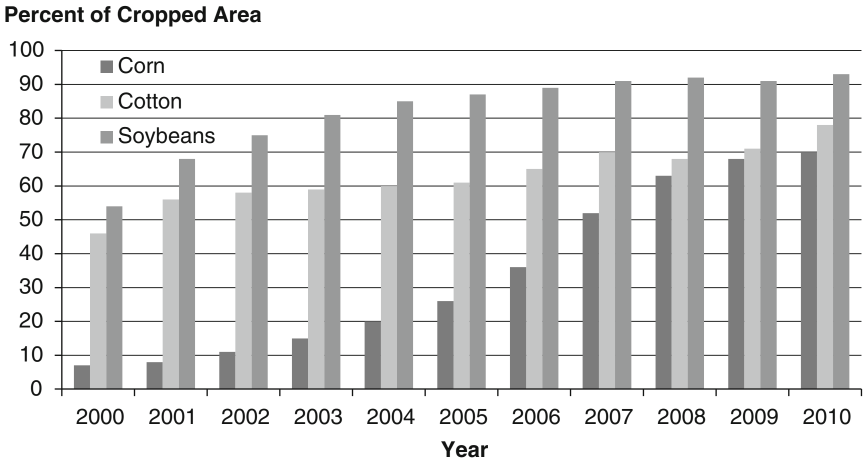

Fig. 7 Herbicide-tolerant crops as a percentage of total cropped area. Percentages are totaled from herbicide-tolerant only crops and herbicide-tolerant and insect resistant (Bt) crops (stacked varieties) (Data from USDA ERS 2011)

In 1983, Maureen Hinkle of the National Audubon Society called attention to these problems in light of the rapidly expanding practices of no-till and conservation agriculture. In her critique, Hinkle (1983) stated that no-till and other conservation agriculture practices may lead to increased pesticide use. In compiling data from 5 years of multi-state agriculture surveys, Day et al. (1999) found that farmers in the Corn Belt used more herbicides under no-till than conventional plowing, although there is conflicting evidence elsewhere (Fawcett 1987; Fawcett et al. 1994; Fuglie 1999). Nevertheless, sufficient documentation of the environmental and human health consequences of both acute and chronic pesticide and nutrient exposure exists to warrant concern over the long-term consequences of such heavy reliance on chemical applications for food production (Soule and Piper 1992; van der Werf 1996; Horrigan 2002; Conway and Pretty 2009).

Several types of widespread weeds are now resistant to popular broad-spectrum herbicides such as atrazine, 2,4-D, and glyphosate, and new resistances undoubtedly will emerge (Hinkle 1983; Feng et al. 2004; Triplett and Dick 2008). The introduction and adoption of transgenic herbicide-tolerant crop varieties, specifically glyphosate-resistant crops, has been rapid: in the past decade the area of land cultivated with glyphosate-resistant corn in the U.S. has expanded from less than 10% in 2001 to 70% in 2010, while 93% of land for soybeans is cultivated with the glyphosate-resistant variety (Fig. 7).

Increasing cases of herbicide-resistant weeds give cause for concern with no-tillage farming, which relies on the effectiveness of herbicides for weed management (Hinkle 1983; Feng et al. 2004; Powles 2008a, b; Duke and Powles 2009). As resistances to specific herbicides increase, new, potentially more toxic chemicals may replace less-effective ones, with consequent environmental and human health costs

(Gardner and Nelson 2008). Related to this problem are environmental concerns over potentially higher rates of herbicide applications with increasing use of genetically modified herbicide-tolerant crops (Goldburg 1992). Alarmingly, despite increases in herbicide-resistant weeds in the United States, concern about herbicide-resistant weeds among farmers, including no-till practitioners, is less than might be expected (Johnson et al. 2009). As Johnson et al. (2009) concluded in their study of farmer perceptions of herbicide-resistance, most farmers believed novel herbicides would be developed in time to cope with problems of herbicide resistance – however, it is unlikely new herbicides will reach market in the next 5–10 years given the time and costs associated with their development (Johnson et al. 2009). As new herbicide resistances emerge, continuing research and development into new herbicides and herbicide-tolerant crops will remain necessary to maintain crop yields, but may not happen quickly enough to combat increasing weed resistance.

Conclusion: The emergence of herbicide-resistant weeds in no-till systems presents a major risk to the success of current no-till practices. Considering the percentage of crops now grown in the United States using both no-till management and herbicide-resistant crops, herbicide-resistant weeds pose a serious threat to American food security if weed suppression using existing herbicides continues to decline in efficacy.

5 Discussion

5.1 The No-Till Revolution We've Been Waiting for?

The word *revolution* comes from the Latin *revolutio,* translated as "a rolling back, or a return" (Cohen 1976a, 258). Before taking on its modern connotations of radical social and political change amidst the eighteenth Century, revolution was understood as "a cyclical phenomenon, a continuous sequence of ebb and flow, a kind of circulation and return, or a repetition" (Cohen 1976a, 257–258). For decades, no-tillage agriculture has been repeatedly hailed as an *agricultural revolution* (Triplett and Dick 2008; Montgomery 2008; Little 1987; Sprague and Triplett 1986), and in many ways one more akin to this earlier, cyclical conceptualization. As Lal (2009) concluded, "since the onset of settled agriculture about 10 to 13 millennia ago, methods of seedbed preparation have gone full circle. Agriculture began with scattering of seeds in an untilled field, and is now trying to achieve the same through the modern techniques of NT [no-till] farming" (82). Lal's words are much the same as those of Faulkner's in the concluding sentence of "Plowman's Folly" in which he wrote of "a 'new' agriculture which is in reality very old" (Faulkner 1943, 155). But yet, the biotechnology industry no-tillage farming has come to rely on seems far removed from the early experimental work in conservation and *plowless* agriculture, and even further away from "a scattering of seeds in an untilled field" than Lal's remark suggests.

This is not intended, however, as a Luddite's chastisement of modern no-till agriculture. Modern no-till agriculture can improve farm economics, soil quality and structure, and agricultural wildlife habitats and aquatic ecosystems, whilst reducing fossil fuel consumption and soil erosion (Rodgers and Wooley 1983; Warburton and Klimstra 1984; Weersink et al. 1992; Lokemoen and Beiser 1997; Uri et al. 1999; Yates et al. 2006; Montgomery 2008; Triplett and Dick 2008). In addition, no-till has been shown to produce equivalent or marginally better crop yields than conventionally tilled sites (King 1983; Sprague 1986; Cannell and Hawes 1994), as numerous long-term tillage experimental sites have demonstrated (Lal 1989; Ismail et al. 1994; Kapusta et al. 1996). Through briefly charting the emergence of no-tillage agriculture, however, no-till appears less revolutionary than its proponents suggest. Rather than mimicking ecological patterns as its original progenitors intended, modern no-till and less extreme forms of conservation agriculture rely on continuous advancement in biotechnology industries in the replacement of mechanical and physical labor with novel chemical and plant genetics technology, a trend across much of modern agriculture with notable environmental and human health consequences (Soule and Piper 1992; Horrigan 2002; Conway and Pretty 2009; Sutton et al. 2011). Alternative forms of no-till agriculture, less reliant on agrochemical innovation and transgenic crop species, exist, however, and deserve discussion.

5.2 A Different Future for No-Till?

There are researchers who have continued to investigate the problem of the plow without turning to heavy pesticide applications and herbicide-resistant crops. At the Rodale Institute in Kutztown, Pennsylvania, researchers with funding from the National Resources Conservation Service have designed a mechanical no-till roller-crimper to kill cover crops without the use of pesticides, with initial corn yields comparable to both chemical-based no-till and conventional field trials (Wilson and Ulsh 2007). It should be noted, however, that this form of no-till still requires surface disking of the soil during some seasons, which some researchers argue reduces no-till's ability to reduce soil erosion (Triplett and Dick 2008). In Salina, Kansas, researchers at the Land Institute are hybridizing annual grain crops with perennial varieties, in the hopes of creating a prairie-like, perennial grain agriculture (Soule and Piper 1992; Cox et al. 2005, 2006; Glover 2005). The vision of the Land Institute is to develop a permanent prairie agriculture within the next 25 years that is much less reliant on fossil fuels than current monoculture farming. The aim is to sustainably produce grain crops year after year while minimizing both soil erosion and water contamination without heavy reliance on synthetic fertilizers or pesticides (Glover 2005; Cox et al. 2010). Innovative research like this holds the promise of balancing the need to conserve soil while maintaining water quality and reducing human and environmental exposure to potentially harmful substances, though major advancements in grain yields will be necessary for perennial grain agriculture to be a viable option for farmers.

It is not coincidental that many no-till experiments began in the Corn Belt when atrazine, a major broad-spectrum herbicide, entered the market beginning in the early 1960s (Triplett and Dick 2008). Today, it is still one of the most popular herbicides used on no-till corn crops in the United States (Ackerman 2007). Unfortunately, it is also the herbicide most commonly found in groundwater in the United Sates, and was banned from use in Europe in 2004 due to mounting environmental and public health concern (Ackerman 2007). No-till agriculture, as it is currently practiced, trades one type of degradation for another. A growing body of evidence indicates that water contamination from pesticides and nutrient leaching is persistent on both conventional as well as no-tillage fields, with both environmental and human health consequences (Goldburg 1992; Soule and Piper 1992; van der Werf 1996; Conway and Pretty 2009). And, as the prevalence of herbicide-resistant weeds in no-till fields increases, for modern no-till agriculture to remain effective new protocols for herbicide diversification and management, in addition to development of novel herbicides and transgenic varieties, will be necessary. Despite continuing calls for a full embrace of the *no-till revolution*, it may already be time to reevaluate the goals and ideas that sparked the emergence of an agriculture without the plow, and look backwards in order that agriculture does not become just as synonymous with extensive chemical applications and herbicide-resistant weeds as it was historically with plowing away the soil. The trajectory of no-till farming appears to have diverted from the initial course of *plowless* farming early on. While its earliest proponents suggested that farmers would be best served in mimicking natural ecosystem processes to retain soil and suppress weeds, the result today is an agriculture that traded in the plow for pesticides and soil erosion for water contamination, the full consequences of which we may not know for some time.

6 Conclusion

The first modern no-till agriculture pioneers in the United States sought to reduce soil erosion through mimicking natural ecosystem processes, replacing deep moldboard plowing with surface disking and ‘mulch-farming’ techniques. With the advent of agrochemicals following World War II, no-till entered a new era of chemical weed management and more recently incorporated herbicide-resistant transgenic crop varieties into no-till production of corn, soybeans, and cotton. Despite notable benefits for improving farmland wildlife habitats, increasing soil biota, and reducing soil erosion, no-till must now combat concerns of increasing herbicide-resistant weeds and water contamination from agrochemicals. Rather than continuing to only rely on transgenic crop varieties and agrochemicals, more sustainable forms of no-till research and practice should also be pursued and prioritized, including mechanical no-till methods and the development of perennial grain systems which both reduce soil erosion and preserve environmental water quality.

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Organic Fertilizers in Sub-Saharan Farming Systems

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Abstract Soil has played major roles throughout human history and civilizations. In sub-Saharan Africa, the soil has been subjected to key challenges such as organic matter export, loss to termites, burning, and diversion to competing uses. These issues lead to a decline in fertility that threatens the sustainability of actual agricultural systems. Therefore the use of organic fertilizers and conservation agriculture is promoted. Farmers recycle organic resources by composting and other practices. However, the adoptions of both organic fertilizers and conservation agriculture have remained low due to limited knowledge on these practices, lack of policy support, and insufficient labor. In response, emphasis on the use of organic resources and mineral fertilizers in Africa has been shifting over the years. Here we review the current role of organic resources in the farming systems of sub-Saharan Africa in order to clarify avenues for enhancing it. The major points are (1) due to their increasing recognition of the role of organic fertilizers in the farming systems, policy-makers in Africa are increasingly supporting issues of sustainable agricultural production systems. (2) There is an increasing awareness on the need for efficiency in the use of organic resources. (3) The consensus that the most sustainable gains in crop productivity are achieved from combined application of organic and mineral fertilizers is driving forward integrated soil fertility management in Africa.

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(4) Small farmers who are generally unable to apply the recommended rates of organic resources are increasingly experimenting options to upgrade their use of organic inputs.

Keywords Organic fertilizer • Soil quality • Soil health • Farming systems • Sub-Saharan Africa

Acronyms and Abbreviations

AfDB	African Development Bank
FAO	Food and Agriculture Organization of the United Nations
KARI	Kenya Agricultural Research Institute
N	Nitrogen
ORD	Organic Resource Database
P	Phosphorus
UNEP	United Nations Environmental Program

1 Introduction

Over the ages, soils have been playing pivotal roles. For instance, the development, survival, or disappearance of civilizations has been shown to be based on the performance of soils to provide food, fiber, and other essential goods for humans (Mueller et al. 2010). Among other functions, the capacity of the soil to produce plant biomass (the productivity function) remains essential. This function is closely associated with the main global concerns of the twenty-first century such as food security, the demands for energy and water, carbon balance, and climate change. Soil organic matter plays a key role in making this to happen, especially if organic inputs are properly handled to deliver their high fertilizer equivalency values. Improved soil fertility also enhances the nutritional balance of foods, including their mineral and vitamin contents (Sanginga and Woomer 2009).

In Sub-Saharan Africa, the soils face the challenges related to the export of organic materials from fields; loss to termites and burning and alternative uses; low nutrient concentrations and decline in organic matter content; drought and overgrazing; and acidity. All these lead to low and declining soil fertility and low crop yields, increasing gap between potential and actual crop yields, and decline in per capita food production.

Given their environmental friendliness, among other reasons, the use of organic fertilizers and conservation agriculture are being advocated to sustainably address these challenges. By making composts, and through the use of pruning from farm boundary trees, and practices that increase the yields of crops and residues, farmers make efforts to increase their access to and use of organic resources. This notwithstanding, the adoptions of both organic fertilizers and conservation agriculture have remained low for reasons that include: lack of adequate knowledge on these practices, lack of policy and institutional support, and insufficient labor availability. In response and to ensure relevance, emphasis on the use of organic resources and/or mineral fertilizers in Africa has been shifting over the years. The current trend is that policymakers in Africa are increasingly recognizing the importance of organic fertilizers, the consequences of poor organic resources management, the need for efficiency in the use of organic resources, and the consensus that the highest and most sustainable gains in crop productivity are achieved from combined application of organic and mineral fertilizers.

The objective of this review paper is to underscore the current role of organic resources in the farming systems of sub-Saharan Africa and to clarify avenues for enhancing this role.

2 Challenges of Soil Fertility

The soils in sub-Saharan Africa are facing great and varied challenges; these are related to the export of organic residues from fields, the low quality of the soil's organic resource quality, a decline in organic matter content, low and declining soil fertility, overgrazing, drought, soil acidity, and the competition for the use of organic resources. These constitute fundamental problems for agricultural productivity in sub-Saharan Africa. Farmers have little choice but to try to rehabilitate their affected fields. Organic resource management is sometimes employed, especially where crops also respond poorly to the application of fertilizer alone (Sanginga and Woomer 2009). Each challenge is further discussed below.

The export of organic residues from fields through crop harvests and marketing leads to a decline in the organic matter content of many soils and therefore to soil degradation. This constitutes a major problem in the banana farming systems of Kenya, Tanzania, and Uganda (Baijukya et al. 2005; Sanginga and Woomer 2009). This decline has also been noted to cause soil degradation in the European semi-arid Mediterranean regions (Diacono and Montemurro 2010). The amount of organic matter in soil depends on the input of organic material, its rate of decomposition, the rate at which existing soil organic matter is mineralized, soil texture, and climate (Johnston et al. 2009). The management of available organic resources by smallholder farmers seeking to diversify and address new market opportunities often demonstrates an intuitive understanding of nutrient recycling (Giller 2002). Most African farmers make innovative use of field and farm boundaries. They collect useful organic materials from outside their farms and then incorporate these into their major farm enterprises, particularly cereal-based cropping and livestock rearing. A close integration of crop and livestock enterprises helps to tighten nutrient cycles and increases the supply of animal proteins to household (Woomer et al. 1999; Sanginga and Woomer 2009; Plate 1).

Plate 1 Export of organic resources from fields

Although the use of organic inputs is hardly new to tropical agriculture, the seminal analysis and synthesis on the decomposition and management of organic matter was contributed not so long ago by Swift et al. (1979). This work established a conceptual framework for the understanding of the decomposition of various organic materials, the regulation of mineralization, nutrient release during decomposition, and the transformation into soil organic matter (Woomer et al. 1994). The nutrient contents of a wide range of farmer-available organic resources, including crop residues and livestock manures were characterized by the Tropical Soil Biology and Fertility Institute and other research groups (Palm et al. 2001). Some organic resources and their chemical composition are presented in Table 1 with their nutrient contents. Similarly, the nutrient content of selected livestock manures is presented in Table 2.

Green manures, livestock manures, and composts are examples of high quality organic materials; farm by-products, domestic wastes, and most crop residues are low quality organic materials, generally high in lignin and polyphenol and low in nutrients (Palm et al. 2001).

Higher quality organic amendments contain the required nutrients in the proportion in which they are required by plants (Palm et al. 2001). Caution must be exercised in applying low quality organic materials, even in conjunction with mineral fertilizers. Organic inputs that are extremely low in nutrients and high in lignin and polyphenols must not be incorporated into the soil as these will be likely to result in the immobilization of soil nutrients and applied fertilizers (Sanginga and Woomer 2009). Instead such materials are best applied as surface mulches. Special handling is required to transform low quality organic materials into high quality organic fertilizers. This could be achieved through fortification with composts. Here, nutrient-poor crop residues are improved with small amounts of fertilizers or agro-minerals. Such a mixture is protected against nutrient loss to produce a valuable organic fertilizer within only 4 months (N'dungu et al. 2003). Another approach is the use of

Table 1 Content of mineral nutrients and organic components of some common organic resources (After Sanginga and Woomer 2009)

Material	Comment	N	P	K	Ca	Mg	Lignin	Polyphenol
		kg t^{-1}						
Crop residues								
Groundnut (Arachis hypogea)	Leaf	32.0	1.8	24.0	13.0	4.0	50.8	28.7
Pigeon pea (Cajanus cajan)	Pruning	24.0	1.5	12.0	5.7		150.5	52.3
Soybean (Glycine max)	Pruning	27.0	1.9	22.0			85.3	17.7
Lablab (L. purpureus)	Leaf litter	29.0	2.3	8.8	20.0	4.1	157.7	7.8
Cassava (Manihot esculenta)	Leaf litter	30.0	1.9	7.3	11.0	5.6	375.2	
Rice (Oryza sativa)	Straw	8.5	0.6	14.0	3.8	1.6		
Bean (Phaseolus vulgaris)	Stover	9.9	1.1	19.0	9.2	2.6	108.2	3.4
Pea (Pisum sativum)	Stover	14.0	0.8	11.0	14.0	2.6	82.0	16.0
Sorghum (S. bicolor)	Stover	6.3	1.0	14.0	4.9	1.4	42.3	29.2
Cowpea (Vigna unguiculata)	Pruning	24.0	3.1	11.0	12.0	7.1	127.0	11.1
Maize (Zea mays)	Stover	8.3	0.8	13.0	3.4	1.9	88.2	7.4
Green manures								
Crotalaria spp.	Leaf	42.0	1.9	14.0	16.0	3.7	66.9	15.9
Desmodium intortum	Pruning	22.0	1.5		5.2		164.9	113.3
Lantana camara	Pruning	20.0	1.8	29.0	9.9		152.4	33.9
Leucaena spp.	Pruning	30.0	1.8	16.0	10.0	3.8	164.7	71.6
Mucuna pruriens	Pruning	29.0	2.3	15.0	9.0	5.4	78.6	88.1
Tithonia diversifolia	Leaf	38.0	3.8	46.0	20.0	4.1	116.6	34.6
Agro-industrial by-products								
Coffee (Coffea robusta)	Husk	17.0	1.3	29.0		1.8	39.6	13.8
Rice (Oryza sativa)	Husk	6.3	1.4	3.8	0.8	0.4	166.6	0.1
Sugarcane (Saccharu officinarum)	Bagasse	3.9	0.4	7.0	2.4	0.4	160.2	3.5
Water hyacinth (Eichhorna. crassipes)	Whole plant	14.1	2.2	32.3	12.7	3.9	100.0	
Agroforestry species								
Acacia spp.	Leaf	25.0	1.7	11.0	7.2	2.4	144.5	99.6
Albizia spp.	Leaf	34.0	1.8	4.1	7.3	3.0	106.0	33.4
Calliandra calothyrsus	Leaf	33.0	1.7	8.5	1.6	3.1	165.5	94.6
Grevillea robusta	Pruning	15.0	0.8	11.0	1.0	1.8	240.8	45.7
Guava (Psidium guajava)	Leaf	23.0	2.0	15.0	9.4	3.2	19.2	138.6
Sesbania (S. sesban)	Leaf	35.0	2.1	14.0	18.0	3.6	5.7	58.9

Table 2 Nutrient and lignin concentration of selected manures available to small-scale farmers in Africa (Adapted from Sanginga and Woomer 2009)

	N	P	K	Ca	Mg	Lignin
Source	kg t^{-1}					
Cattle manure	9.8	2.2	8.5	4.0	2.3	84.8
Cattle manure fresh	15.0	5.4	6.4			
Composted manure	18.2	10.0	15.1	30.6	5.7	76.4
Goat manure	15.0	4.0	5.3			
Pig manure	2.0	11.9	4.9			
Poultry manure	28.8	15.8	22.5	32.0	6.9	119.3
Rabbit manure	16.0	4.0	5.0			
Sheep manure	12.8	4.7	57.7	11.0	14.5	51.8

epigeic earthworms to process farm by-products, crop residues, and domestic wastes into a rich humus while producing a protein-rich feed for poultry and fish (Edwards 1988; Savala et al. 2003).

More information related to Tables 1 and 2 can be found in: http://www.ciat.cgiar.org/webciat/ORD. This database contains extensive information on the organic resource quality of fresh leaves, litter, stems, and roots from almost 300 species utilized within numerous tropical agro-ecosystems. These were evaluated in terms of their contents of macronutrients, lignin, and polyphenol. Data on the soil and climate from where each material was collected were included, also the decomposition and nutrient-release rates of many of the organic inputs. Infrared spectroscopy has been shown to be widely applicable for characterization of tropical organic resources (Shepherd and Walsh 2007). This technique also allows rapid, reliable, and low-cost soil analysis.

Compared with compound farms and near fields, low and declining soil fertility is usually more pronounced in distant fields compared with compound farms and near fields as these are frequently infertile, depleted, and severely depressed in soil organic matter contents (Sanginga and Woomer 2009). The soils of the Sahelian drylands of sub-Saharan Africa are quite sandy and often acidic with low levels of organic matter. They exhibit low water holding and low cation exchange capacities and hardly retain nutrients, thus constituting a fundamental problem for agricultural productivity (Bationo and Mokwunye 1987; FAO 2002; Sanginga and Woomer 2009).

Drought is more likely to occur on degraded rather than fertile lands. In the Sahelian drylands, such as northern Senegal, southern Mauritania, Mali, northern Nigeria, Niger, the northern tip of Cameroon, Chad, and Sudan, overgrazing has led to extensive land degradation and desertification (Herlocker 1999; Sanginga and Woomer 2009). Agricultural droughts often result from overgrazing and the cultivation of crops poorly suited to available moisture. The agricultural drylands, therefore, pose a double challenge to their farmers.

Since they are derived from cultivated and natural lands, organic resources should be abundant in Africa. However, they are under-utilized within the context of integrated soil fertility management and, in many circumstances; a limited supply leads to competition for their use. For instance, multipurpose legumes serve as animal feed and as cover crops. The availability of organic resources as the sources of nutrients is also limited by their uses as fuel for cooking and for fiber, and by the labor required to collect and process them. Materials that cannot serve as livestock feed tend to be quite inexpensive or even free but their bulk and the transportation cost tend to limit their usefulness as the distance from their source widens. The increasing value of groundnut and cowpea residues as marketable commodities in West Africa is generating income for farmers. Livestock manure is also marketed in northern Nigeria and Madagascar (Sanginga and Woomer 2009). The competition for organic resources is the reason why crop residues and/or manures are often not returned to soils even in many production systems where the yield levels are not adequate to support the food needs of the population (Alley and Vanlauwe 2009). This clearly shows the problem of tradeoff.

3 Evidence of Low and Declining Soil Fertility

The fertility of soils is often reflected in good crop yields, especially with good management practices. The most direct clear evidence of the low and declining soil fertility in sub-Saharan Africa is the persisting low and falling yields affecting many crops. As a result, there is a huge gap between the experimental station and potential farmers' yields and farmers' actual yields (Bationo et al. 2006). In many places, farmers' yields of cereals rarely exceed 0.5 $t\,ha^{-1}$ while a potential of 6–8 $t\,ha^{-1}$ is attained at on-station research trials and by some commercial farmers. In 2001, cereal yields averaged 1.23 $t\,ha^{-1}$ in Africa, very low if compared with yields of 3.09 $t\,ha^{-1}$ in Asia, 3.04 $t\,ha^{-1}$ in Latin America, and 5.47 $t\,ha^{-1}$ in Western Europe where farmers use modern production factors (FAO 2004). Banana yields have declined in traditional growing areas in Uganda and Kenya, largely due to declining soil fertility and uncontrolled attacks of pests and diseases (Sanginga and Woomer 2009). In the west of Lake Victoria in Bukoba district, Tanzania, Baijukya et al. (2005) noted that the farming system has fallen below the sustainability threshold because of a low and declining soil fertility status, leading to reductions in the productivity of banana. Farmers in the district reacted by rapidly shifting to annual crops and vegetables such as maize and green amaranths.

Apart from low and declining soil fertility, other biological factors such as low yielding varieties, weeds, diseases and insects, and water and nutrient deficiencies as well as socio-economic factors such as costs and benefits, access to financial services, access to agro-inputs and services, and social attitude also contribute to the huge gap between the potential and the actual crop yields achieved by farmers in sub-Saharan Africa (Woomer 2007; Sanginga and Woomer 2009).

4 Organic Fertilizers and Soil Fertility Maintenance

Organic fertilizers are generally made up of plant residues and animal manures. The use of cattle manure to fertilize crops was introduced by the colonial agricultural officers throughout Africa (Sanginga and Woomer 2009). Although generally in limited supply with competing uses, organic resources have certain key attributes and roles in African farming systems. These include land rehabilitation, reduction of soil erosion and acidification, replenishment of organic matter, enhancement of soil moisture content, improvement in soil fertility and nutrient supply to crops, promotion of nutrient cycling, increases in soil nutrients and water retention, and the maximization of returns to the use of other inputs.

Acidification occurs when land is converted from natural vegetation to crops. The use of mineral fertilizers may aggravate the decline in pH. This is particularly the case with ammonium-based fertilizers, such as ammonium sulphate, mono-ammonium phosphate, urea, and Di-ammonium Phosphate. During the nitrification process of NH4+ to NO3−, these fertilizers release H+. Long-term data collected from a series of trial sites in East and West Africa show that pH declines with no organic inputs and the use of acidifying fertilizers and could reach up to one full unit in 5–10 years (Smaling and Braun 1996; Bado et al. 1997; Vanlauwe and Giller 2006).

Like lime or dolomite, the application of organic fertilizers such as manure can prevent or rectify this situation. Fields that farmers know are poorly responsive need to be rehabilitated through the application of organic manures or through fallowing before the use of fertilizer should be recommended. In the least responsive fields, the application of a wider range of nutrients that include Ca, Mg, S, and micronutrients rather than simply using N, P, and K may prove necessary to provide a more balanced nutrient supply (Sanginga and Woomer 2009). Organic amendments also counteract aluminum toxicity (Pypers et al. 2005).

Soil erosion is a critical environmental problem throughout the world's terrestrial ecosystems. Erosion inflicts multiple and serious damage on managed ecosystems, such as crops, pastures, or forests, as well as in the wild. In particular, erosion reduces the water-holding capacity of the soil because of the rapid water runoff and also organic matter. As a result, nutrients and valuable soil biota are transported. At the same time, the species diversity of plants, animals, and microbes is significantly reduced (Duran and Rodrfguez 2008).

Organic sources of nutrients add to the soil the organic matter that is critical to maintaining productivity. Among other benefits, this helps to improve soil moisture retention and resistance to wind erosion. Good soil structure improves air exchange and plant root development. Additions of organic matter provide several mechanisms for improved agronomic efficiency. These include the better synchronization of nutrient supply with crop demand, and an improvement in soil health through increased soil biodiversity and carbon stocks (Alley and Vanlauwe 2009). In the long term, continuous organic inputs influence the levels of soil organic matter and the quality of its nutrient pools (Woomer et al. 1994; Vanlauwe et al. 1998; Cadisch

Table 3 Pearl millet yield, N uptake, N recovery, and soil properties following 4 year of application of fertilizer (urea) compared with the combination with organic materials of differing qualities (Adapted from Goyal et al. 1992)

Treatment!	Grain yield t/ha	N uptake kg/ha	N recovery %	SOM-Ct g/kg	Microbial C mg C/kg
NOPO	1.51	31	–	4.0	180
N120 P40	2.76	66	29	4.3	290
N60 P20 + N60 (FYM)	2.81	71	33	5.0	330
N60 P20 + N60 (wheat straw)	2.33	51	17	4.5	355
N60 P20 + N60 (sesbania)	3.15	76	38	4.8	315
LSD (P = 0.05)	0.27	5.7		0.6	19

t *N* = kg of N added as fertilizer or organic material, *P* = kg of P added as inorganic fertilizer

and Giller 1997). Maintaining permanent soil cover, as in conservation agriculture, protects against erosion, suppresses weeds, increases water infiltration, and promotes soil biological activity (Sanginga and Woomer 2009). Organic amendments, such as urban wastes, industrial wastes, composts, sludge, and municipal solid waste composts, are used for organic matter replenishment, reducing the application of chemical fertilizers. Long-lasting application of organic amendments increased organic carbon by up to 90% versus levels in unfertilized soil, and up to 100% versus results from chemical fertilizer treatments.

A 4-year experiment in India (Goyal et al. 1992) compared the N substitutive effects of wheat straw, FYM, and sesbania (species not given) green manure on pearl millet [Pennisetum glaucum (L.) R. Br.] yields, N uptake, and SOM. Nitrogen was applied at a rate of 120 kg N/ha, as urea alone or one half applied as urea and one half as wheat straw, FYM, or sesbania. The result is presented in Table 3. Crop yields, N uptake, and N recovery were greater with the combination of FYM or green manure and urea compared with urea alone but less when wheat straw was combined with urea, due to the net N immobilization that would be expected from a material with a C-to-N ratio of 102. The authors attributed the higher N use in the combined sesbania or FYM with urea to the immediate availability of N from urea and its delayed release from the organics, achieving greater synchrony with crop demand.

Stabilized organic amendments improve the yield quality of crops. Repeated application of composted materials enhances soil organic nitrogen (N) content by up to 90%, storing it for mineralization in future cropping seasons, often without inducing nitrate leaching to groundwater (Diacono and Montemurro 2009). Increased cultivation of symbiotic legumes and agroforestry trees are important sources of organic N (Giller et al. 1997).

Organic resources applied to soils release nutrients and enhance soil moisture conditions (Barrios et al. 1997). The application of crop residues to soils through incorporation or mulching promotes nutrient recycling. It also improves fertilizer use efficiency and contributes to soil organic matter, feeding soil biological processes (Sanginga and Woomer 2009). Feeding residues to domestic animals and then applying manures from those animals have a similar effect. Additions of organic material to the soil provide several mechanisms for improved agronomic efficiency.

Regular addition of organic residues, particularly the composted residues, increases soil fertility, mainly by increasing the stability of soil aggregates and decreasing soil bulk density. Soil structure is improved, leading to reduced erosion, enhanced water infiltration and storage, and improved root development (Hudson 1994; Diacono and Montemurro 2009; Sanginga and Woomer 2009). The best agronomic performance from compost is often obtained with the highest rates and frequency of applications. Furthermore, additional benefits were observed, such as the slow release of N fertilizer and increases in crop yields of up to 250% following long-term applications of high rates of municipal solid waste compost (Diacono and Montemurro 2009). Agronomic considerations for Integrated Plant Nutrient Management within the context of a total crop management program include the influence of organic nutrient sources on soil properties such as aggregate stability and structure. Aggregate stability improves as soil organic matter increases because organic matter binds together mineral particles, sand, silt, and clay. Soils with high aggregate stability resist the impact of rain drops and are less susceptible to erosion (Alley and Vanlauwe 2009).

The recycling of manures and crop residues provides organic matter for improving soil physical properties. It also supplies significant amounts of nutrients to crops. Stable soil organic matter is approximately 5% N (Alley and Vanlauwe 2009). The available N supply from the soil increases with an increase in the level of soil organic matter following the applications of manures, crop residues, or through the effect of cover cropping.

Many types of manure are high in P, moderate in N, and low in K. Crop residues may be high in K, low to moderate in P, and relatively low in N. As a result, where these organic resources are used, additional nutrients are generally required to achieve a balanced nutrient supply. Similarly, the decomposition or mineralization of crop residues and manures releases N from organic forms, unavailable for plant uptake, to mineral forms, ammonium and nitrate, as long as temperature and moisture conditions are suitable for microbial activity and C: N ratios are smaller than 20:1. Organic materials with C:N > 30:1 releases N more slowly because soil microorganisms use mineral N to increase their populations. Organic materials with C: N ratios between 20:1 and 30:1 may show a slight delay in mineralization because of immobilization by microorganisms. Mineralized N is first present as ammonium but is rapidly converted to nitrate. Both forms are plant available, but nitrate is subject to leaching. Residues with high C:N ratios should be applied far enough ahead of planting so that mineralization and N release are occurring at the time plants are beginning their growth (Alley and Vanlauwe 2009). According to these authors, if cool temperatures prevent mineralization before planting, manufactured N fertilizers can be applied at planting to satisfy the early-season plant growth, with the remainder of the crop's N requirement supplied by mineralization from the organic source. Phosphorus (P) availability in the soil is particularly enhanced by the application of organic residues (Nziguheba et al. 2000).

Given that they are unable to purchase sufficient fertilizers and other inputs for use at the recommended levels to optimize crop production, smallholder farmers seek to maximize returns per unit input. If combined with management practices

Plate 2 Organic fertilizers

that retain organic residues in the soil, nutrients supplied in manufactured fertilizers can reverse the downward spiral in productivity and soil quality (Alley and Vanlauwe 2009). This can also happen through other crop management practices. For instance, while cassava farmers in humid West Africa rely upon rotation with groundnut, cowpea, or pigeon pea, those in Bénin rely upon complex *mucuna* intercropping or rotations as a strategy for regenerating soil fertility in cassava croplands (Sanginga and Woomer 2009). Often, to compensate for shortfalls in their level of farm input use, they substitute labor for cash by collecting, processing and applying available organic resources (Plate 2).

5 Organic Fertilizer Use and Conservation Agriculture

The colonial agricultural officers came up with rates of cattle manure use that are beyond the reach of small-scale farmers. For example, in the 1920s, 40 $t\,ha^{-1}$ of kraal manure was recommended for maize cultivation in Zimbabwe. However, these rates were adjusted down as mineral fertilizers became available (Sanginga and Woomer 2009) and initial recommended levels were gauged using crop performance under the influence of organic fertilizers applied at specific levels.

Experience from KARI's Fertilizer Use Recommendation Project shows that too often the recommended rates of fertilizer were well beyond the investment capacity of most smallholder farmers (Sanginga and Woomer 2009). Even the levels of livestock manure of 5–10 $t\,ha^{-1}$ that served as a comparison of organic resource management were unrealistically high. More realistic levels of organic inputs were later included within an innovative extension booklet published by KARI (Kanyanjua et al. 2000).

Plate 3 Maize under conservation agriculture in Western Kenya

Conservation agriculture is an important, recent, and evolving concept of land and organic resource management. It seeks to optimize crop yields and farm profits in a manner that balances economic and environmental benefits (Dumanski et al. 2006). Within its context, the role of organic resources is of paramount importance. Crop residues are regarded as organic resources; burning them is anathema. Nearly permanent soil cover is one of its foundations. Practitioners must find a means to gain access to sufficient organic materials. Soil conservation improves soil tilt and reduces the labor required for land preparation. Surface mulching and vegetative groundcovers protect the soil and reduce the labor need for crop maintenance operations, particularly weeding (Roose and Barthes 2001; Sanginga and Woomer 2009). The guidelines for conservation agriculture suggest that 5–8 t of crop residues need to be applied as soil cover per year. When a lower quantity is applied, this disposes the soil to erosion and a greater quantity may interfere with field operations (Goddard et al. 2008). However, it is important to note that in a market garden program in Togo, small-scale farmers apply several hundred kg of fertilizers and over 10 $t\,ha^{-1}$ of manure to improve soil fertility for the increased and sustainable production of vegetables (Debra (2003) cited by Sanginga and Woomer (2009); Plate 3).

Conservation agriculture was first developed for application by large mechanized farms in North and South America. It emerged as a refinement of the no-till farming systems and is being modified to suit other agricultural systems and locations. Unlike organic agriculture, it does not prohibit the use of any inputs. However, it stresses that inputs must be applied at times and rates that cause minimal disturbances to beneficial soil organisms and processes (Goddard et al. 2008). Conservation agriculture is built around a suite of land management principles that integrate ecological management with scientific agriculture through the minimal disturbance of the soil. Over several years, a soil under conservation agriculture develops an organic surface horizon that promotes a healthy, living soil and serves to recycle organic matter in a manner similar to that of the natural ecosystem.

Some field practices, such as soil tillage, burning of crop residues, or natural fallows, run counter to the principles of conservation agriculture (Sanginga and Woomer 2009). Advocates argue that soil tillage or intensive soil tillage for that matter is destructive and unnecessary because they lead to soil degradation and the loss of crop productivity. They point out that the earliest planting was performed on an unprepared soil with a stick. This practice proved effective for many years. Soil biota and roots naturally turn the soil, with organic recycling providing a constant supply of mineral nutrients. In his book *The Plowman's Folly* Faulkner (1943) challenged the need for tillage. He stated, "*no one has ever advanced a scientific reason for plowing*". He went further to state, "*the plow has actually destroyed the productiveness of our soils*". Despite these conclusions, no-till agriculture could not be practiced without use of herbicides to control weeds.

Increases in coverage by conservation agriculture over the past 15 years are about ninefold. Farmers practicing it are expected to increase substantially in the near future, particularly in South America. Conservation agriculture is practiced on a large scale in South Africa (377,000 ha) and to a lesser extent in other African nations (e.g., on 35,000 ha in Ghana). Maize, sorghum, wheat, and cotton are the crops most often cultivated under this system (Derpsch 2008). Approximately 60,000 farmers in Zambia are employing two or more conservation farming techniques being promoted by their producers' associations (Haggblade and Tembo 2003).

Despite the skepticisms related to conservation agriculture, its adoption is known to bring direct financial rewards to farmers and the broader community, even under drylands farming systems. Its adoption is also associated with environmental benefits (FAO 2008; Bhan and Bharti 2008). In sub-Saharan Africa, conservation agriculture was profitable in Zambia and provided farmers with 1.1 t ha^{-1} of additional maize although the associated costs of production were high. In Zimbabwe, on-station trials on well-drained soils conservation agriculture showed an increase in maize yield from 3,200 to 4,000 kg ha^{-1}. Other important outcomes were reduced water runoff and less soil erosion. In drier locations, maize yields increased from 2,900 to 3,600 kg ha^{-1} (Elwell 1995). Soil carbon sequestration has been identified as an additional benefit (Lal 1997; Reicosky 2008; Novak and Fiorelli 2010). However, there is a debate on the recognition, measurement, and repayment for this important below-ground carbon sinks (Noble and Scholes 2001). At its current adoption rates, the use of the legume residues has the potential to reach several million farmers with an internal rate of returns of 50–103% (Kristjanson et al. 2002). Greater reliance upon legumes and mixed farming improves the soil. It also leads to an upgrade of the protein, vitamin, and micronutrient contents of household diets (Manson et al. 2001).

Different reasons have been adduced for the limited adoption of conservation agriculture in sub-Saharan Africa (Rumley and Ong 2007; FAO 2008; Derpsch 2008; Sanginga and Woomer 2009; Giller et al. 2009). These include (i) farmers' conservative mind set and their unwillingness to undertake a radical departure from their conventional field operations; (ii) the long transition period required before the full benefits of conservation agriculture are realized ; (iii) the notion that conservation practices are specific to certain crops, within defined cropping systems, and are not to be readily adapted by small and mixed enterprise farmers; (iv) the requirement for no-till, continuous soil cover with crop residues and mulch, and crop rotation; (v) the difficult and unclear pathway to achieving the longer-term economic and environmental benefits in small-scale farming; (vi) the difficulty in convincing poor farmers to abandon digging when a hoe is the only implement they know and own; (vii) a lack of support infrastructure and policy will for a transition to conservation agriculture in most rural settings of Africa; and (viii) the need to feed livestock with crop residues, rather than use them as soil cover, to generate the manure that small-scale farmers value highly as a soil input critical in nutrient recycling.

In view of the above, it is perhaps unfair to blame non-adopters of conservation agriculture for narrow-mindedness. A review of the policy and by-laws relating to land management and conservation in Africa indicate that many measures were potentially useful but were ineffectively implemented because responsible institutions were weak or poorly organized (Eicher 1999). Enforcement of such policies is a pre-requisite to the benefits from sound integrated soil fertility management and conservation agriculture. In many cases, community by-laws protect the rights of stubble grazing by livestock that interferes with adopters' attempts to establish continuous mulch cover. However, precedents exist for African farmers to protect their rights to mulch (Erenstein et al. 2008).

6 Constraints to Organic Resources Management

When organic resources such as crop residues are applied as mulches, they are subject to rapid losses to termites and other soil fauna. Sometimes, termites may consume dried surface mulch within weeks and then turn their attention to the crops. This often defeats the intended purposes of applying these resources. Apart from such losses, there is a high demand for crop residues for use other purposes, such as feed for livestock, fuel for cooking, and the construction of houses. The competing uses of crop residues for other needs are among the numerous factors limiting the adoption of no-till farming (Powell et al. 2004; Lal 2009a) and further complicate the chances of conservation agriculture being adopted (Sanginga and Woomer 2009). In addition, a lack of tenure security in many sub-Saharan African countries, such as Ethiopia and Tanzania, strongly discourages tree planting.

The application of residues in soil fertility maintenance is an important indicator of soil health. The burning, selling, or discarding of such residues, therefore, constitutes a wasted opportunity. This is commonly the situation in the Sahel where the practice of residue burning is an important component of land preparation. Although, residue burning effectively mobilizes nutrient bases, the practice may result in the loss per hectare of 40 kg N and 10 kg Sulfur (S) in each cropping cycle. It also reduces soil microbial activity and contributes to the massive nutrient loss in

Plate 4 Bush burning in northern Nigeria

Sahelian soils (Nye and Greenland 1964; Bationo 2008). Improved organic resource management that eliminates burning and includes mulching with straw has the potential to reverse the loss of soil organic carbon as has been demonstrated in Senegal (Feller et al. 1987). However, the availability of N is improved through the decomposition of root biomass a few weeks after burning (Araki 1993; Plate 4).

Very often the organic resources most available to farmers in sub-Saharan Africa have low nutrient concentrations. Such organic resources have a limited potential to improve crop yields, especially when applied as the only source of nutrients (Vanlauwe et al. 2006).

7 Soil Fertility Management Paradigms

Over the years, there have been several paradigms and paradigm shifts in soil fertility management in the farming systems of sub-Saharan Africa. In all, these shifts portray the changing emphasis on the use of fertilizer inputs in the farming systems. Each paradigm emphasizes either mineral fertilizers or organic inputs.

The **First** Paradigm, 1960s and 1970s, emphasized the use of mineral fertilizers, with organic resources playing a minimal role. According to this, mineral fertilizers alone would improve and sustain crop yields. Widespread adoption and impact under this paradigm were forestalled by the limited access small-scale farm families had to mineral fertilizers. This was principally because of shortfalls in infrastructure, policy, and the farming systems.

The **Second** Paradigm, 1980s, emphasized organic inputs, with mineral fertilizers playing a minimal role. Organic resources were the main sources of plant nutrients. In this paradigm, biological processes were also important. For instance, adapting germplasm to adverse soil conditions, enhancing soil biological activity, and optimizing nutrient cycling to minimize external inputs and maximize the efficiency of their use were critical. The need to combine essential and farmer-available organic inputs with fertilizers was recognized. Through positive interactions among the soil's biological, chemical, and physical properties, combining mineral and organic inputs result in greater benefits than the use of either input alone. The concept of integrated soil fertility management was derived from this paradigm (Sanchez 1994). However, the adoption of the Second Paradigm by farmers was limited by the excessive requirements of land and labor in the production and processing of organic resources. Farmers were reluctant to commit land solely to the production of organic resources at the expense of crops and income (Sanginga and Woomer 2009).

In the **Third** Paradigm, 1990s, while organic resources were the entry point, serving other functions besides nutrient release, the use of mineral fertilizers was essential to alleviate the main nutrient constraints. Adoption was hampered by difficulties in accessing organic resources such as those obtained from improved fallow systems.

The **Fourth** Paradigm, 2000s, is still ongoing. It emphasizes mineral fertilizers, noting that these are the major entry points to increase crop yields and also supply the organic inputs needed. This paradigm is labeled "Integrated Soil Fertility Management". It recognizes the importance of an enabling environment that permits farmers to invest in soil fertility management. It also recognizes the critical importance of agro-input suppliers and dealers, fair dealing in produce markets and prices, favorable policies, and properly functioning institutions, such as agricultural extension. This is because access to organic resources has social and economic dimensions. This paradigm is supported by the recommendation of the Africa Fertilizer Summit held at Abuja in 2006. Some success stories have been recorded.

8 Organic Resources Available to Farmers

Green manures are fresh plant materials applied directly to the soil to increase soil fertility and/or soil organic matter content. The release of N and other nutrients is associated with the quality of their source and the environmental conditions. Localized trial data are needed to develop specific estimates of the nutrients supplied from green manure crops. In their absence, general rules can be used to determine the appropriate nutrient release on the basis of organic resource quality (Vanlauwe et al. 2005; Alley and Vanlauwe 2009).

Farmers can obtain green manures from sources such as planted fallows. In West and Central Africa, numerous technologies in the areas of planted fallows have been tested both in on-station trials and on-farm over several years. Alley

Plate 5 Legume cover crop: *Mucuna* (*left*), Alley cropping in Uganda (*right*)

cropping and herbaceous legume cover crops are some of the most promising planted fallow technologies for resource-poor farmers (Hauser et al. 2006). It is, however, important to note that the practice of using soil improving legumes to replace traditional shifting cultivation has been a topic of debate over many years. Some people conclude that the use of green manures will never be a significant factor in the farming systems of Africa. Others are of the view that the agronomic exploitation of biological N fixation, through the use of green manures must become more important in the future. Soils in Africa have become exhausted and can benefit from N fixation. The current average application of mineral fertilizers in sub-Saharan Africa is about 8 kg N ha^{-1} (Plate 5).

Maintaining and/or increasing soil organic matter requires organic inputs from crop residues and/or manures. Crop residues vary greatly in nutrient content. Plant available nutrients released in a specific time period can be determined only by using local data. An organic resource database on the nutrient contents of almost 300 plant species and parts has been developed for tropical agro-ecosystems (Palm et al. 2001). Information on carbon quality and nutrient release rates for the various plant materials is also included. Nutrients in crop residues are released through microbial decomposition, which is directly related to their C content relative to N, P, and S. Plant residues or manures with moderately low ratios of C:N (<20:1), C:P (<200:1) or C:S (<400:1) are associated with a pattern of initial net release of nutrients from the organic material during decomposition; residues with high ratios tend to result in the immobilization of nutrients. Immobilization occurs when essential nutrients are utilized by soil microorganisms during the decomposition of residues and become unavailable for plant uptake (Alley and Vanlauwe 2009; Plate 6).

Animal manures are valuable sources of nutrients. Poor quality feed for livestock results in manure with low levels of nutrient contents. In Africa where livestock receive poor quality feed, the N content in manure is often below 2% (Harris 2002). In North America and Europe, the legally mandated nutrient management plans for intensive livestock production require that animal manures be analyzed for their nutrient content on a regular basis (Oenema 2004; NRCS-USDA 2005).

Plate 6 Crop residues harvesting, storage and marketing in northern Nigeria

Table 4 Nutrient content values (g/kg dry weight) of crop residues and poultry and livestock manures (Source: Alley and Vanlauwe 2009)

		Manure	
Nutrient	Crop residues	Poultry	Livestock
N	10–15	25–30	20–30
P	1–2	20–25	4–10
K	10–15	11–20	15–20
Ca	2–5	40–45	5–20
Mg	1–3	6–8	3–4
S	1–2	5–15	4–50

Since much of the nutrient content is in organic forms, localized nutrient "availability coefficients", especially for N, have been developed for specific manures under varying conditions of climate and soil. The coefficients enable farmers to make better estimates of appropriate application rates. An example of how to calculate application rates for use in crop production is found in the Manure Management Planner software developed at Purdue University (Joern and Hess 2005). Table 4 shows the ranges of nutrient content values of typical crop residues and various manures.

These are the residual solids from the treatment of municipal wastewater that can be recycled. They provide significant quantities of plant nutrients as well as organic matter (Alley and Vanlauwe 2009; Table 5).

Nutrients in bio-solids vary in their forms, depending on the source, treatment, storage, and handling process. Nutrient availability depends on the particular bio-solid and the local environment (Alley and Vanlauwe 2009). Generally, bio-solids are analyzed for their content of organic and inorganic N, total P, trace elements, and toxic metals. If appropriate steps such as "evaluation and monitoring of its composition for quality and computation of proper application rates" are taken, the agricultural use of bio-solids is supported by the United Nations Environmental Program (UNEP 2000). However, bio-solids must be analyzed for toxic metals, such as mercury and arsenic, before application. Many developing countries still need to build laboratories and train individuals to utilize bio-solids safely and efficiently for crop production (Alley and Vanlauwe 2009).

Table 5 Representative concentrations of macro- and micronutrients and other trace elements in bio-solids (Source: Alley and Vanlauwe 2009)

Element	Mean or median concentration
Macronutrients:	(g/kg)
N	33
P	23
K	3
Ca	39
Mg	4
S	11
Micronutrients:	(mg/kg)
B	13 (median)
Cu	741
Fe	12,000 (median)
Mn	276 (median)
Mo	9
Zn	1,202
Ni	43
Other trace elements:	(mg/kg)
Arsenic (As)	10
Cadmium (Cd)	7
Chromium (Cr)	119
Mercury (Hg)	5
Fluorine (F)	49 (median)

9 Fertilizer Equivalency Values of Organic Inputs

The fertilizer equivalency value of an organic input directly relates it to a manufactured fertilizer, the nutrients from which are readily plant-available. Best-bet recommendations advised that 2 t of manure or compost may replace the application of pre-plant Di-ammonium Phosphate and that low cost urea may replace Calcium Ammonium Nitrate if it is quickly incorporated into the soil. This level of fertilizer input is similar to the nutrient target of 50 kg ha^{-1} established by the Africa Fertilizer Summit (2006). A cow produces about 700 kg of dried manure per year (Sanginga and Woomer 2009). This is equivalent to about 50–100 kg of N fertilizer depending on how well it is protected from nutrient loss through volatilization and leaching. Results from Eastern, Southern, and West Africa indicate that the fertilizer equivalency values of organic inputs are quite high. In the savannas of northern Nigeria, combining cowpea or soybean residues with 45 kg urea N ha^{-1} provides maize yields similar to those expected from the recommended rate of 90 kg urea N ha^{-1} on even the poorest fields. Costs and benefits of the treatment of a maize rotation with an improved promiscuous soybean crop can provide a net benefit of US $1,450 over two seasons (Sanginga et al. 2001).

The capacity of crop residues to replace the application of N fertilizer is related to the N content and the percentage of carbon and lignin they contain. These must decompose before the nutrients in such crop residues can become available for plant use.

Table 6 Ranking of nutrient sources used by women and men farmers in Zimbabwe (After Mapfumo et al. 2001)

Nutrient resource	Ranking by[a]		Factors (restrictions)
	Women	Men	
Inorganic fertilizer	1	2	Results in immediate and reliable benefits (cost prohibitive)
Animal manure	2	1	Affordable and longer-lasting in soil (requires ownership of substantial numbers of livestock)
Compost	3	4	Available from processing local materials (labor intensive to produce)
Termite mounds	4	3	Readily available in fields and long-lasting (labor intensive to recover and spread)
Agricultural lime	5	6	Markedly improves groundnut yield (not widely available)
Leaf litter transfer	6	5	(Increasingly less available)

[a]1 = Most preferred, 6 = Least preferred

The knowledge of the fertilizer equivalency values of organic inputs reduces the risk of both insufficient and excessive plant nutrition. Such knowledge also maximizes the nutritional benefits for the crops from organic residues (Alley and Vanlauwe 2009). Apart from the nutrient supply, organic resource management affects the health and the physical, hydrologic, and biological dimensions of the soil.

The nutrient contents of crop residues vary, depending on the fertility of the soil on which the organic input is produced and the handling method. The nutrient content of manure is influenced by the diet of the animal producing the manure. For legumes, if only the grains are harvested and the residues are recycled, net accrual of soil N from the incorporation of such residues can be as high as 140 kg N ha^{-1} depending on the legume. This can contribute to substantial improvements in the yield of subsequent crops. This amount of N surpasses the 50 kg nutrients ha^{-1} in mineral fertilizer use across sub-Saharan Africa as recommended by the African Heads of State and Governments at the Abuja Fertilizer Summit in 2006. Therefore, depending on their composition and quantity, organic resources may replace or counteract the effects of mineral fertilizers (Giller 2001; Sanginga and Woomer 2009).

In the communal farming areas of Zimbabwe, farmers have a variety of nutrient resources available to them. Preference for these resources varies between men and women (see Table 6). Women prefer the use of inorganic fertilizers compared with animal manure, in large part because they have little control over livestock (Mapfumo et al. 2001).

10 Organic Fertilizer Needs and Availability

In most farming systems in sub-Saharan Africa, the quantity of organic inputs available for use by farmers is usually inadequate. Among other reasons, this is because many rural farm households either do not possess livestock or often mostly keep poultry and small-ruminants and in such low numbers that they do not have access to enough manure. Within most smallholder farming communities in sub-Saharan Africa, the demand for animal manure is usually greater than the supply (Sanginga and Woomer 2009). Chianu and Tsujii (2005) highlighted how the inadequate availability of manure was one of the major constraints that prevented the full integration of the various components of integrated nutrient management by farmers in northern Nigeria. In pastoral areas with substantial livestock, free grazing poses difficulties in collecting and transporting this important organic resource (Lekasi et al. 2003a, b).

However, it is often possible for farmers to improve the availability of organic resources. This can be done through agricultural practices (cereal–legume rotation) that lead to increases in the yields of cereal crops. Such practices also directly improve the availability of crop residues. Maize–soybean rotations also improve the availability of organic resources. Growing maize after soybean improves grain yield from 1.2 to 2.3-fold. This practice will be likely to be sustainable, especially given that most of the legume varieties being used have traits (e.g., high yields of both grain and fodder, pest and disease resistance, promiscuous root nodulation by rhizobia, etc.) that are appreciated by farmers because they greatly help to increase farm income by 50–70% compared with continuous maize cultivation. The promiscuously nodulating soybean varieties produce high yields and are also multi-purpose in terms of their leafy biomass production that is available for livestock and as an organic input for the soil (Sanginga et al. 2001). Such rotations also lead to significant biological N fixation, the suppression of *striga* (a pernicious plant parasite of cereals) and the replenishment of soil nutrients (Woomer et al. 2008). The promiscuous soybean and the dual-purpose cowpea lines that are now available to farmers in West Africa produce about 2.5 t ha^{-1} of grain and 2.5–4 t ha^{-1} of forage. There is every indication that further progress can be made. They fix between 44 and 103 kg N ha^{-1} and have a positive N balance of 43 kg N ha^{-1}.

The other way through which farmers can improve upon the availability of organic resources is by pruning and applying residues from the trees or shrubs used to mark farm boundaries. This is often the practice in densely populated settings in Africa. Here, farmers find it necessary to mark farm boundaries with trees, shrubs, or impenetrable hedgerows. Some farmers also embark on compost making to increase the availability of organic inputs for use in improving farm productivity (Plate 7).

11 Organic Resource System

In sub-Saharan Africa technologies have been developed for the production, storage, and utilization of organic resources. There have also been socio-economic studies on organic resources. For production, the existing technologies include (i) bulking and storing organic resources to concentrate their nutrients, (ii) fortification of composts with lime, fertilizers, and agro-minerals, and (iii) construction of cattle stalls in a manner that separates urine and manure and allows their different handling

Plate 7 A composting making scheme

and application. For manure storage, the existing efficient technologies include: (i) recessing manure into shallow pits and covering the heaps (Lekasi et al. 2001), (ii) using sloping concrete stalls, (iii) adding and collecting bedding materials from the stalls, (iv) applying ash, rock phosphate or mineral fertilizers, and (v) incorporating green manures into the heap. Urine from livestock is best applied to crops immediately after collection to avoid N loss through volatilization; manures are best heaped and composted for use during the next cycle of cropland preparation.

Increased fertilizer use is central in reversing land degradation and achieving food security in Africa. However, the prices of mineral fertilizers have continued to rise more than the prices of agricultural commodities. One way of reducing the impact of high fertilizer prices is increased integration of legumes in the farming system. This is because legumes fix atmospheric nitrogen, reducing the need for fertilizers in the subsequent cereal crop.

Several technologies have been developed on the collection, processing, and application of cattle and poultry waste. For instance, through composting, it is possible to bulk and store organic resources and to concentrate their nutrients. Composts may also be fortified with lime, fertilizers, and agro-minerals. In groundnut production, women have been noted to recognize better than men the importance of applying lime. This is because the pegging of groundnut required calcium, applied from an external source (Lekasi et al. 1998).

Increased use of fertilizer was viewed as central in programs to reverse land degradation and achieve food security in Africa (Africa Fertilizer Summit 2006). Since then, the prices of mineral fertilizers have continued to increase rapidly,

Plate 8 Cereal-legume intercrop

largely because of the increasing price of petroleum. Similarly, the prices of commodities have also increased but have not kept pace with the increase in the prices of mineral fertilizers. This has resulted in fertilizer use having a different level of profitability compared with the recommendations formulated only a few years ago (Sanginga and Woomer 2009). The increase in the prices of mineral fertilizers has again drawn attention to the great importance of legumes in the farming systems of Africa. This is because, through their ability to fix atmospheric N, legumes have the ability to reduce the mineral fertilizer needs of the subsequent cereal crops.

Farm input suppliers sometimes market organic inputs such as compost, guano, manure, and other nutrient-rich materials. Sometimes, however, they are more efficiently stockpiled, processed, and applied as organic resources available within and beyond the farm. Because of a limited potential for investment, poor households find some organic-based systems more attractive as they cannot obtain or afford inorganic fertilizers (Reardon et al. 1997; Place et al. 2003; Plate 8).

12 Constraints to Use of Organic Fertilizers

As a constraint to the use of organic fertilizers in sub-Saharan Africa, generally, farmers lack knowledge on their production, conservation, and effective use. Given the critical role that organic inputs can play in agricultural productivity, there is a strong need to address this problem through training and capacity building of the resource-poor farmers (Sanginga and Woomer 2009). Labor shortages also reduce farmers' willingness to adopt organic resources-related technologies, such as alley farming. This is because gathering and using organic resources from planted trees, shrubs, and herbaceous legumes fallows and the collection, processing, and application of livestock waste are labor-intensive exercises (Ong and Black 1995).

Some of the sources of organic inputs require farmers to set aside some farmland to plant trees, shrubs, and/or herbaceous legumes with the hope of harvesting the leaves and other materials as sources of organic inputs. Apart from labor constraints, the lack of sufficient land, because of population pressure, constitutes a huge constraint to this practice. For instance, although the use of green manure is a proven means of restoring and maintaining soil fertility, particularly in the rehabilitation of degraded soils, it is difficult for small-scale producers to adopt. Similarly, practices such as natural and improved fallows, rotational paddock grazing, and increasing herd sizes become restricted as population pressure on land intensifies (Sanginga and Woomer 2009). In the semi-arid and the Sahel regions, it is extremely difficult to muster sufficient quantities of organic resources for agricultural production purposes since these have alternative and competing uses.

Application of science and technology alone will have a limited positive impact on agricultural productivity. It will, therefore, not reverse the poverty trend in the continent. Lack of or a limited policy and institutional support is a key constraint to the widespread use of organic inputs in the farming systems of sub-Saharan Africa. Policy and institutional instruments are, therefore, needed to create incentives for the widespread production and use of organic fertilizers to reap the maximum benefit from science and technology. Such incentives are needed in the areas of land and tree tenure, gender equity, access to farm credit, and labor-saving agricultural technologies and practices. Despite their prime responsibility for food production, women generally have limited access to land. Usually they have the right only to use the land with the consent of a male relative. Women also tend to be allocated land of inferior quality. The insecurity of tenure reduces the likelihood that women will make long-term investments in land development or adopt environmentally sustainable farming practices such as the planting of trees. More details could be found in the section on Policy and institutions and the use of organic fertilizers.

Contrary to the ideas of many people, ownership of livestock, especially the large and small ruminants, by smallholder farmers in sub-Saharan Africa is not widespread. This is both in terms of ownership and Tropical Livestock Unit. Based on a study carried out in several districts in Western Kenya, the extent of ownership of different types of livestock ranged from about 18% (for improved cows) to about 40% (for calves). Mean numbers of different cattle types (local cows, improved cows, heifers, steers, and calves) owned by different numbers of owners were usually low, ranging from 1.9 (heifer/calves) to 3.2 (improved cows) (Chianu et al. 2008).

Table 7 A comparison between organic and inorganic fertilizers (Adapted from Woomer et al. 1999)

	Nutrient source	
Feature	Organic fertilizer	Mineral fertilizer
Nutrient concentration	Low, unknown and variable between batches	High and based upon labeled nutrient contents
Nutrient availability	Slow release regulated by soil biological process	Subject to loss through leaching and ammonia volatilization
Acquisition and cost	Low because it is locally produced	High because it is often purchased, sometimes from imperfect markets
Labor requirement	High	Low
Environmental impacts	Positive, favor carbon sequestration and soil biodiversity	Negative at excess rates, pollution of aquatic systems
Estimated nutrient addition	Difficult as nutrient release pattern is controlled by biological processes	Easy

13 Combination of Organic and Mineral Fertilizers

Based on their nutrient concentration, availability, acquisition, and cost and labor requirements, environmental impacts, and the estimation of nutrient additions through application, a comparison of organic and mineral fertilizers as nutrient sources is presented in Table 7.

Despite Table 7, the interaction between mineral and organic inputs has been noted to be strongly beneficial. Combining mineral fertilizer with organic inputs can substantially improve the agronomic efficiency (a ratio describing the increase in crop yield per unit of applied nutrients) of the nutrient use compared with the same amount of nutrients applied through either source alone. A combined application of 45 kg urea-N ha^{-1} and 45 kg green manure-N ha^{-1} resulted in a yield benefit of 0.5 t grain ha^{-1} compared with the application of either source alone (Vanlauwe et al. 2001a, b). Within the context of integrated soil fertility management, regardless of farm size and production objectives, it is important to combine organic and mineral sources of nutrients to obtain the full advantages of both sources (Giller 2002).

Combined application results in improved agronomic efficiency for a number of reasons. First, common mineral fertilizers lack the minor nutrients essential for crop growth. Organic resources contain these, but to meet the crop's major nutrient requirements (N, P, and K), often excessive application rates (> 10 t ha^{-1} of dry matter) are required if these organics are the only input. The use efficiency of nutrients applied through organic materials alone is often low (Vanlauwe and Sanginga 1995; Cadisch and Giller 1997). Combining both sources enables all nutrients to be supplied in suitable quantities and proportions. Secondly, a combination of inorganic and organic nutrient sources results in a general improvement in the soil fertility status (Okalebo et al. 2003). Nutrient retention, turnover, and availability

Plate 9 Effect of balanced nutrition on crop performance: Embu, Central Kenya

are improved by an increased content of soil organic matter. Combining mineral fertilizers with organic resources may result in greater nutrient use efficiency (Vanlauwe et al. 2006) but achieving this effect requires the strategic management of fertilizers in terms of form, timing, and placement, as well as a sufficient supply of organic resources.

As a result of the foregoing and other research findings across numerous countries and diverse agro-ecological zones of sub-Saharan Africa, a consensus has emerged that the highest and most sustainable gains in crop productivity per unit nutrient are achieved from mixtures of fertilizer and organic inputs (FAO 1989a, b; Pieri 1989; Giller et al. 1998; Vanlauwe et al. 2001a, b). It is probably for the same benefits that African farmers have been described as excellent spatial manipulators of soil fertility. The only unfortunate thing is that they create relatively fertile islands by applying both organic and mineral fertilizers to the more accessible and secure fields, often at the expense of more distant fields and communal lands that become degraded along the line (Plate 9).

14 Other Issues Related to Organic Resources

Although organic fertilizers are of paramount importance in the farming systems of sub-Saharan Africa, their level of adoption is below expectation. Most of what had been recorded as adoption was confounded by the promotional and incentive effects from research institutes, agricultural extension, and NGOs (Eilitta et al. 2004; Giller 2001; Kiptot et al. 2007). For instance, green manures are difficult to manage and require a lot of labor. In countries such as Zimbabwe, the use of green manures declined with the advent of mineral fertilizers and they were replaced in rotations when soybean became an important grain legume crop. Evidence for the uptake of legume green manures and improved fallows solely for the improvement of soil fertility appears to be limited (Sanginga and Woomer 2009).

Similarly, a rapid adoption of legume-based integrated soil fertility management requires the availability of farm inputs, investment by the farmers in those inputs, and ready markets for the crop surpluses resulting from improved farming (Crawford et al. 2003; Bingen et al. 2003).

Applying large amounts of organic materials without taking the nutrients from these materials into account can result in an excess of nutrients and environmental pollution. Such soil nutrient imbalance can also lead to adverse conditions. For instance, excess N and P in compost systems are often associated with low nutrient use efficiency, and constitute a potential adverse impact on continuing related management practices (Alley and Vanlauwe 2009). Many of the nutrients contained in imported feed stuffs are eventually exported from the farm in meat and dairy products. Others may be applied to the land in the form of animal manure, and this needs to be carefully managed to avoid exceeding the crop's needs.

In Europe and North America, nutrient budgets have been used to raise awareness on of potential environmental problems associated with nutrient accumulation from high levels of applied manure. Graphic representations of nutrient balances help farmers to understand the implications of their decisions on nutrient management (Goodlass et al. 2003; Alley and Vanlauwe 2009).

Climate change is a major issue for agricultural sustainability. It threatens plans to reduce poverty and achieve sustainable development in Africa. The net balance of changes in the potential cereal production for sub-Saharan Africa is projected to be negative over the next few decades, with net losses of up to 12%. About half of the sub-Saharan African countries will be at risk of significant declines in food crop and pasture production as a result of climate change (AfDB 2010). Progress in promoting agriculture and delivering food security for Africa will be significantly compromised by the negative impacts of climate change. The challenge of doubling the world's food grain production by 2030 is even more daunting because of the decrease in the per capita arable land area and renewable fresh water resources; increases in risks of soil and environmental degradation; and threats of a decrease in use efficiency of inputs (Lal 2009b). Therefore, if it is not tackled head on, the effects of climate change could erase the modest economic gains that Africa has achieved over the past decade. Adjustments in farming practices will be necessary to reduce emissions and adapt to the changing climate and new social expectations (Fleming and Vanclay 2010). However, through carbon sequestration, organic amendments play a positive role in mitigating the effects of climate change. The quantity of carbon sequestrated depends on the type of organic input and the rate and frequency of application (Diacono and Montemurro 2009).

The use of organic fertilizers has not received adequate attention in sub-Saharan Africa although some efforts have been made. During the past 25–30 years, the African Development Bank (AfDB) has financed a number of agricultural sector projects, focusing mainly on productivity improvement. Efforts have generally promoted the use of mineral and organic fertilizers, modern agronomic techniques, and improved planting materials. AfDB has financed projects designed to improve the production and use of manure, promote the planting of N-fixing crops and trees, enhance the acquisition and use of mineral fertilizers, build the capacity of agricultural sector institutions, improve irrigation and water management practices, and repair and construct feeder roads. By extending lines-of-credit to independent development banks as well as to private banks through the credit components of several agricultural projects, the Bank Group has also indirectly promoted the availability and use of fertilizers. In Ethiopia, the Bank financed a National Fertilizer Sector Project, through loans provided in partnership with other donors to support the effort of the Government of Ethiopia to increase the availability and accessibility of fertilizers to agricultural producers on a sustainable basis. There is an untapped potential existing in the deposits of fertilizer raw materials in Africa and the Bank has promoted the intra-continental production of fertilizers by financing a feasibility study for establishing a fertilizer plant in Mauritania and by having similar projects currently in the pipeline in some other African countries (AFFM 2009). China is also helping in the effort to promote fertilizer production in Africa by establishing fertilizer plants in Nigeria and Angola.

15 Lessons on Use of Organic Resources

Although organic fertilizers are unfortunately not yet widely and intensively used in sub-Saharan Africa, some important facts are already emerging. For instance, policy-makers are increasingly recognizing the important role of organic fertilizers in the farming systems. The other emerging lessons concern the need to ensure efficiency in the use of organic resources, the consequences of poor management of organic resources, and the synergy in crop-livestock integration.

Policymakers in Africa and their partners in development are finally acknowledging the potential and critical roles of organic resources. As a result, they are increasingly supporting activities in the areas of integrated soil fertility management, and integrated plant nutrient management in the farming systems (Sanginga and Woomer 2009; Alley and Vanlauwe 2009). New fertilizer strategies, where the science of integrated soil fertility management plays a critical role, are being designed following the Fertilizer Summit for African Heads of State and Governments held in Abuja, Nigeria, in June 2006 (Africa Fertilizer Summit 2006).

Organic resources are scarce. They must be used prudently and in a manner to maximize the benefits from their use. In sub-Saharan Africa, the climate is generally warm and moist in many areas, causing plant residues and livestock manures to decompose rapidly, resulting in nutrient release that is poorly timed with the crop's nutrient demand (Myers et al. 1994). The alley farming system was widely tested in the tropics for its potential to sustain food production under low external inputs. Large quantities of N (~300 kg N ha^{-1} $year^{-1}$) are harvested from hedgerow prunings. However, the N contribution to crops in the system is commonly in the range of 40–70 kg N ha^{-1} $season^{-1}$, representing ~20% of N applied as prunings and N recoveries as low as 5–10% have been reported (Vanlauwe et al. 2006; Sanginga and Woomer 2009).

Meeting even modest objectives for food production and rural development in sub-Saharan African countries requires the strategic use of the limited available resources (Savala et al. 2003; IFDC 2002). It is, therefore, essential to analyze the nutrient content of plant-based organic materials to properly determine their contribution to the crop's nutrient needs. The timing and placement of organic resources must be carefully considered. Estimating the decomposition rates of organic materials under localized conditions is essential to accurately determine the proper time of application (Alley and Vanlauwe 2009).

Organic resources vary in their nutrient contents and mineralization characteristics. The use of some organic resources results in the short-term immobilization of soil nutrients if improperly applied. As a result, those who practice integrated soil fertility management are often concerned because the processing of different organic resources of varying quality requires the specialized knowledge that most of them do not presently possess (Sanginga and Woomer 2009).

The consequence of poor organic resource management is the decline of soil organic matter. This results in a decline in soil nutrient retention, water holding capacity, and mineral fertilizer use efficiency (Manu et al. 1991). For example, a decline of 1.0 g of soil carbon kg^{-1} of soil results in the reduction of Cation Exchange Capacity by 0.25 cmol. If this effect is extrapolated, in a sandy soil, it may result in the reduced retention of the base nutrients by between 80 and 150 kg ha^{-1}. This is under the assumption of a bulk density of 1.5 kg L^{-1} and base saturation of 50% (De Ridder and Van Keulen 1990). Many Sahelian soils are sandy and so more dependent upon soil organic matter than clay soils for their nutrient and water buffering capacities (Bationo 2008).

Poorer households tend to manage organic resources well within their farms in a manner consistent with integrated soil fertility management. They make better use of manure and legume intercrops. However, their ability to combine these practices with top-dressed mineral fertilizer is considerably limited. Without proper nutrient additions and crop residue management, agricultural soils lose organic matter content and productivity (Alley and Vanlauwe 2009).

Data from a long-term cropping system experiment at the University of Illinois showed that with initial cultivation, the organic carbon content of the soil rapidly declined from 3.75% to 2.1% in 20 years, and further to 1.25% in the next 90 years (Fenton et al. 1999). This new equilibrium (1.25% organic carbon content) corresponds to organic materials that are very resistant to decomposition and provide few nutrients for annual crop plants (Alley and Vanlauwe 2009). Similar trends have been observed in Australia (Dalal and Mayer 1986) and England (Johnston and Poulton 2005). Thus, as soil organic matter declines, the availability of nutrients from this source also declines. Practices that hasten organic matter decomposition, such as tillage, should therefore be used sparingly.

In the Sahel drylands, fertilizer consumption remains among the lowest in the world, with only 1.1 kg ha^{-1} $year^{-1}$ applied in Niger and about 9.0 kg ha^{-1} $year^{-1}$ applied in Mali. Livestock operations are closely integrated with cropping; cattle feed upon the crop residues and provide sources of traction and manure. Indeed, given the severe soil limitations in agricultural lands, manure management offers farmers a seasonal opportunity to improve soils through collection, storage, and application (Powell et al. 1996). It is important to, however, note that the management of organic resources within cereal-based cropping systems is conditioned by the competing demand for crop residues and by the importance of livestock (Sanginga and Woomer 2009).

16 Conclusion

Notwithstanding the soil fertility challenges they face, farmers in Sub-Saharan Africa are not giving up on their desire for increased agricultural productivity. Besides seeking for ways to increase their access to and use of organic fertilizers to optimize the productivity of their agricultural systems, they have continued to make necessary adjustments, including shifting to crops that tolerate low fertility.

In addition, the era of low adoption of organic fertilizers in the farming systems of Africa is about becoming a thing of the past. This is because policy makers in Africa are increasingly recognizing the importance of organic fertilizers, the consequences of poor organic resources management, the need for efficiency in the use of organic resources, and the consensus that the highest and most sustainable gains in crop productivity are achieved from combined application of organic and mineral fertilizers. This will create the avenues to engender increased adoption of proven integrated soil fertility management technologies, many of which have been developed, tested, finalized and kept on the shelf. It is by so doing that the fertilizer equivalency values of organic inputs, noted to be quite high in sub-Saharan Africa, can be tapped for increased human welfare.

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Biofuel Production Byproducts as Soil Amendments

Khaled D. Alotaibi and Jeff. J. Schoenau

Abstract Attempts to reduce reliance on fossil fuel as the sole source of energy has resulted in production of energy from different organic materials. Due to increasing demand worldwide, production of energy from renewable sources has been growing rapidly, and it was estimated in 2002 to contribute to 14% of the world's energy supply. Several technologies such as biochemical, fermentation, thermo-chemical, gasification and pyrolysis, chemical extraction, and transesterification processes have been employed to convert organic materials to energy. These technologies produce not only energy, but also valuable byproducts which include distillers grain, thin stillage, glycerol, ash and biochar. Due to the growing bioenergy production industry, there will be an abundance of byproducts being generated. Recently, some of these byproducts are disposed of by incineration, e.g. glycerol, or landfilling, e.g. ash. This disposal may have adverse effects on the environment. Therefore, a proper method, which can be economically sound and environmentally safe, needs to be sought. As these byproducts are organic and contain carbon and plant nutrients that are potentially valuable to soils and production of crops, consideration of potential uses of the byproducts must include their application to soil. Carbon and other plant essential nutrients in the byproducts can be added to soil and recycled. If fed to animals, such as in the case of distillers grain and thin stillage byproducts, manure is produced containing a higher content of nutrient compared to animals fed regular grain. This type of manure may hurt the environment if not properly managed.

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The potential for recycling nutrient in soil-plant system through direct or indirect application of bioenergy byproducts is not widely covered in the literature. This review covers relevant information on the potential use of bioenergy production byproducts as soil amendments and organic fertilizers in agricultural lands, and considers opportunities for future applications.

We found that direct application of distillers grain to soil benefited crop growth, suppressed weeds, and was accessible by soil microorganisms, resulting in organic matter decomposition and therefore contributing to nutrient release and availability for plant uptake. Thin stillage use as a soil amendment has not widely been practiced, and there is a lack of documented information in this regard. It was found to be a viable source of nutrient and provided plant essential nutrient; however, its residual effect on crop production was more evident than its direct application effect. This indicates the slow release of nutrients from thin stillage organic matter persisting into the following growing seasons. Compared to the other byproducts covered in this review, glycerol was the least studied bioenergy production byproduct as a soil amendment. It was found that glycerol application to soil at a high rate of 1,000 kg ha^{-1} reduced the yield and N uptake and related this to a possible immobilization of available N by soil microorganisms. It was demonstrated in the most reviewed studies that ash application to soil increased crop yield and nutrient uptake, especially P and K. Biochar addition to soil contributed to crop yield increase, and this was attributed to reduction of nutrient losses, resulting in enhancement of nutrient use efficiency. Besides its agronomic benefits, it was reported in some studies that biochar application could have environmental benefits through its ability to reduce nutrient loss by leaching and runoff, absorb pesticides and mitigate greenhouse gas emissions. Inclusion of distillers grain in animal diets was found to have a significant effect on manure nutrients content and forms. This will promote including this type of manure in farm management plan and make it more valuable as organic fertilizer.

Keywords Bioenergy • Byproducts • Distillers grain • Thin stillage • Glycerol • Ash • Biochar • Soil • Amendment • Manure

1 Introduction

Fluctuation in petroleum prices and uncertainty about oil reserves have created a concern about the sustainability of petroleum commodity supply. In addition, use of fossil fuel has raised environmental concerns regarding its effect on greenhouse gas emissions and global warming (Lehmann 2007). Therefore, alternative sources of energy have been sought and investigated in recent years. Production of energy from organic materials is an example of an alternative source of energy that can reduce complete reliance on fossil fuels.

Various technologies have been implemented to produce different types of bioenergy. Some of these technologies are not new, but their application to certain types of organic materials as feedstock has not been widely evaluated or adopted. These technologies can be classified into three main categories: (1) biochemical (2) mechanical/chemical and (3) thermochemical process (McKendry 2002a). Biochemical conversion embraces two processes: fermentation and anaerobic digestion. Mechanical/chemical process includes transesterification of vegetable oil such as canola that results in production of biodiesel (McKendry 2002a). The thermo-chemical conversion technology includes four processes: combustion, gasification, pyrolysis and liquefaction.

In addition to the bio-energy produced, each conversion process results in a specific byproduct. The value and characteristics of these byproducts vary according to the type of conversion process and feedstock converted (Cayuela et al. 2010). Bioenergy production byproducts include, but are not limited to, distillers grain and thin stillage generated from fermentation of sugar crops and starch crops, glycerol produced from transesterification of plant oil during biodiesel manufacture, ash resulting from gasification process and biochar/charcoal produced from pyrolysis conversion. The composition of each byproduct, including its carbon, plant nutrient (nitrogen (N), phosphorus (P), potassium (K), sulfur (S) and others.) content is dependant on the method of processing. Therefore, biochar produced from pyrolysis and glycerol produced from biodiesel production via transesterification of vegetable plants are materials that are rich in carbon, while byproducts generated from ethanol manufacturing contain considerable amounts of nitrogen and phosphorus and other nutrients along with C. Ash materials produced from gasification process are rich in their content of phosphorus, potassium, calcium and magnesium but contain relating little carbon as it is lost as carbon dioxide during combustion.

Production of energy from renewable sources has been growing rapidly, and it was estimated in 2002 to contribute to 14% of the world's energy supply (McKendry 2002b). Biofuel manufacturing, especially ethanol, is the most common type of bioenergy product commercially produced on a large scale worldwide. In 2008, world ethanol production reached 66 billion L (RFA 2010a). In 2009, US ethanol refineries plants produced over 40.2 billion L of ethanol (RFA 2010a) and nearly two billion L of biodiesel (NBB 2010). About 1.4 billion L of ethanol was produced in Canada (CRFA 2010), with 0.512 billion L produced in western provinces. Canadian biodiesel production was also estimated to reach about 0.2 billion L in 2010 (CRFA 2010). The ethanol is derived from fermentation and distillation facilities that use sugar and starch crops as feedstock. It is also believed that ethanol will eventually be produced on a wide scale from lignocellulosic feedstocks, which are referred to as second generation feedstocks, including crop residues, processing wastes and biomass energy crops like willow and poplar (Gronowska et al. 2009). It was predicted that lignocellulosic feedstocks could produce approximately 229 billion L of ethanol in the U.S. by the year 2030 (De La Torre Ugarte et al. 2007). However, the advanced conversion technologies required to produce ethanol from lignocellulosic feedstocks are not available yet on a commercial scale, but are being researched and undergoing rapid development (Gronowska et al. 2009). The second generation biofuel production byproducts are not included in this review because they have not been produced in large quantities yet on a large scale.

As a function of the growing bioenergy production industry, there will be an abundance of byproducts being generated in their production. As these byproducts are organic and contain carbon and plant nutrients that are potentially valuable to soils and production of crops, consideration of potential uses of the byproducts must include their application to soil.

Utilization of bioenergy production byproducts as soil amendments can be a good strategy for recycling nutrient associated with production of feedstock, and thereby reduce reliance on mineral fertilizers requirements for food production. Additionally, this potential use can help offset any negative impact on soil when crop residues are harvested for bioenergy production. Harvesting crop residues for bioenergy production is suggested to have implications on soil quality and may jeopardize soil productivity through organic matter and nutrient loss (Lal 2009). To compensate for the loss in nutrients that are harvested in crop and to maintain optimum crop production, there will be increased need for external organic matter and nutrient inputs, such as animal manures, compost, or organic waste to help maintain and improve physical and chemical properties of soil.

There is a myriad of research work that has been completed on land application of organic materials such as compost and manure (e.g. Eghball 2002; Gale et al. 2006; Lithourgidis et al. 2007; Singer et al. 2004; Schoenau and Davis 2006), paper mill biosolids (Aitken et al. 1998; Curnoe et al. 2006; N'Dayegamiye 2006), and oily food wastes (Rashid and Voroney 2004) and their effects on soils and crop growth. However, there has not been an attempt to collate and review the recent body of work conducted on application of first generation bioenergy byproducts to soil. Therefore, the objective of this paper is to provide a state of the knowledge compendium of the documented information on direct or indirect; e.g. through animal manure, application of bioenergy byproducts to soil. The selected byproducts considered in this review included distillers grain, thin stillage, glycerol, ash, and biochar, in addition to manure that is derived from animals fed bioethanol byproducts.

2 Bioenergy Production Byproducts

2.1 Biofuel Production Byproducts

2.1.1 Ethanol Production

Distillers Grain

Bio-ethanol can be produced from grain using two milling processes: wet milling and dry-grind processing. In wet milling, the corn kernel, in case the feedstock used is corn, is fractionated into primary components of germ, fiber and starch, resulting in several process streams and coproducts (Rausch and Belyea 2006). The coproducts associated with wet milling processes of corn are: corn gluten meal, corn gluten

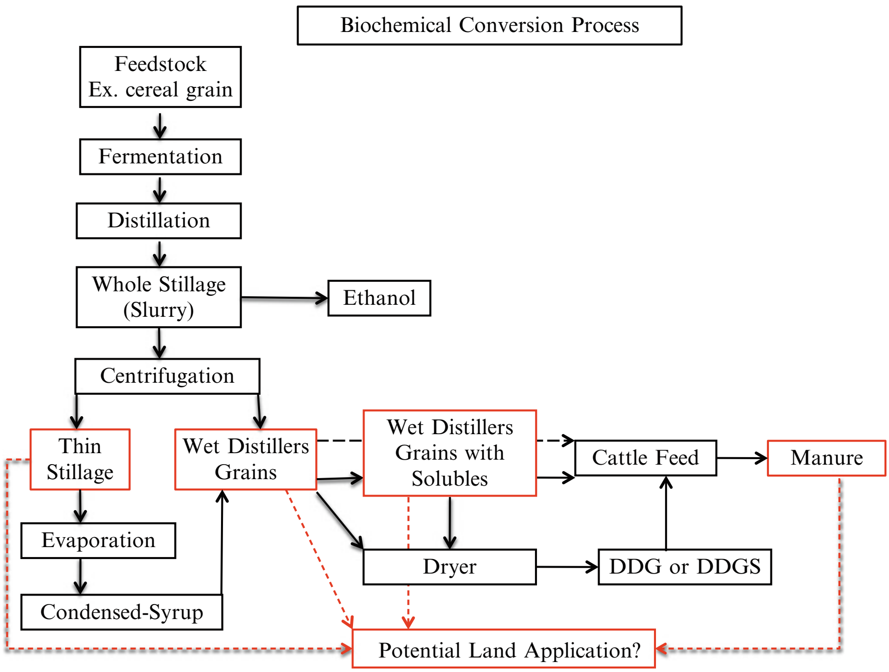

Fig. 1 Simplified process flow chart of cereal grain conversion to ethanol and associated byproducts of distillers grain and thin stillage. *DDG* dried distillers grain, *DDGS* dried distillers grain with solubles, *EX* example

feed, crude corn oil and germ meal. In contrast to dry-grind mills, wet mills are corporate-owned because they require high capital investment and extensive equipment (Belyea 2004). In the dry-grind process, the entire corn is subjected to fermentation; corn is not separated into individual fractions (Rausch and Belyea 2006). Dry-grind mills require less equipment, have lower capital investment, can be owned by producers and therefore can have a significant contribution to local economies (Singh et al. 2001). Since dry-grind mills were recently reported to represent approximately 90% of total ethanol production in the USA (RFA 2010a) and are the most common ethanol production facilities in western Canada, the focus in this review is on the byproducts generated from dry milling-based ethanol production.

In dry-grind milling as shown in Fig. 1, cereal grain is processed by grinding and fermenting via yeast addition where grain starch is converted into ethanol and carbon dioxide. Then, ethanol is distilled off followed by centrifugation to remove the remaining liquid. The byproducts that are left over after fermentation, distillation and centrifugation include a liquid fraction named thin stillage and the solid fraction termed wet distillers grains. Thin stillage can be partially dried/evaporated and become condensed distillers solubles. Condensed distillers solubles can be added back to the wet distillers grains resulting in wet distillers grains with solubles byproduct. The wet distillers grains with solubles can also be dried, making dried distillers grains with solubles. These byproducts can differ slightly in terms of their nutrient content, partly as a function of heating/drying in the case of condensed distillers solubles and dried distillers grain with solubles. However, all these byproducts contain nearly all the nutrient originally present in the processed grains, but are now concentrated due to the starch removal. They contain fiber, fat, protein and minerals. Wet distillers grain has a high moisture content; approximately 70%, affecting the time it can be stored without spoilage and the economic viability of transporting long distances from the ethanol production plant (Bonnardeaux 2007). Unlike wet distillers grain with solubles, dried distillers grain with solubles has less moisture content; approximately 12%, making its shelf life indefinite and economically viable to ship to longer distances. However, drying wet distillers grain requires further energy and adds extra cost to ethanol production. Additionally, possible changes can occur during drying which might reduce nutritional value of distillers grain when fed to animals (Ham et al. 1994).

The amount of distillers grains resulting from the conversion of cereal grain to ethanol varies according to the types of grains and the processes used. For example, 1 t of wheat generates 372 L of ethanol and 457 kg wet distillers grain or 295 kg of dried distillers grain with solubles whereas 1 t of corn produces 378 L of ethanol plus 479 kg wet distillers grain or 309 kg of dried distillers grain with solubles (Bonnardeaux 2007). In 2009/2010, USA ethanol biorefineries produced more than 30 million Mg of distillers grains (RFA 2010b). In 2009, ethanol plants in western Canada generated 0.46 million Mg of dried distillers grain with solubles (University of Saskatchewan 2009).

As a result of starch removal, the nutrient concentration in distillers grains are approximately three times that in the original grains (Spiehs et al. 2002). Therefore, the distillers grain has been traditionally used as animal feed due to its higher content of protein and nutrient (Ham et al. 1994; Rausch and Belyea 2006; Gibb et al. 2008; Harris et al. 2008). Use of distillers grain as animal feed accounts for the second largest source of income for ethanol-producing plants, after ethanol marketing (Bonnardeaux 2007). However, high concentrations of fiber and nutrient, especially phosphorus may impede the expansion of this market. High fibre concentration can limit the use of distillers grain mainly to ruminant diets, and similarly high phosphorus content could pose manure disposal challenges for cattle producers (Rausch and Belyea 2006), due to a greater land area required for application to avoid phosphorus loading in the soil. This higher content of P, fiber and protein is greater than that needed in the animal diets (Noureddini et al. 2009), and the excess nutrient in animal diets will be excreted in the urine and fecal material. Therefore, it is sometimes recommended to restrict inclusion of distillers grain in animal diets to a certain ration, for example 20% of the diet (Hao et al. 2009). As a result, feeding distillers grain to animals may not accommodate continued rise in distillers grain production, as the rapid growth in the ethanol industry is expected to create a surplus of dried distillers grain with solubles (Erickson et al. 2005; Rausch and Belyea 2006). Therefore, alternative approaches to their utilization need to be considered, including direct land application as a fertilizer and soil amendment. This may create another outlet for utilization of ethanol byproducts, as this is critical to sustain ethanol industry and could be another source of income to offset the expenses in ethanol production.

The option of land application of ethanol production byproducts has received little attention, and very few studies have looked at this option in the past. In a pot study conducted with horticultural plants, dried distillers grain with solubles was reported to suppress weeds when applied to the soil surface and incorporated (Boydston and Collins 2008). In a field study conducted near Novelty, Missouri, Nelson et al. (2009) concluded that dried distillers grain with solubles might be utilized as a valuable fertilizer to supply nutrient to corn crops. They reported that application of dried distillers grain with solubles at a rate of 140 kg N ha^{-1} resulted in similar corn yield to urea and anhydrous ammonia applied at the same rate of N. The dried distillers grain with solubles did not have a significant effect on selected soil chemical properties such as soil organic matter, P, K, Ca or Mg content. In a growth chamber study carried out to determine the N mineralization rates and the amount of available N to plants from different types of organic amendments over a 120-day growing season, it was found that N availability from dried distillers grains for the 210-day period of incubation was 56%, equivalent to 251 kg plant-available N ha^{-1} (Moore et al. 2010). This study also indicated that the mineralization rate of dried distillers grain organic N was slower compared to poultry litter amendment, and attributed this to compounds that are present in dried distillers grain that may have delayed the nitrification process and thereby increased NH_4-N accumulation in the soil.

Soil respiration and N release from soil amended with first generation biofuel byproducts, including dried distillers grain with solubles, have also been recently investigated under controlled environment conditions (Cayuela et al. 2010). In this study, soil amended with dried distillers grain with solubles and incubated for 60 days showed that more than 80% of dried distillers grain with solubles added C was mineralized after 2 months. Soil treated with dried distillers grain with solubles did not show a significant increase in extractable N when sampled at day 7 and 15 and was only significant after 60 days of incubation. This indicates a slow release of dried distillers grain with solubles-contained N into plant available inorganic forms, and suggests a potential for distillers grain byproducts being utilized as a soil amendment that releases nutrient more slowly than mineral fertilizers when directly applied to arable soil. However, field studies are needed to verify their performance under different environmental conditions.

In summary, the reviewed scientific studies showed that distillers grain application to soil benefited crop growth, suppressed weeds, and was accessible by soil microorganisms, resulting in organic matter decomposition and therefore contributing to nutrient release and availability for plant uptake.

Thin Stillage

Thin stillage is another major coproduct associated with ethanol production. It can be defined as the aqueous byproduct generated from the distillation of ethanol following fermentation of starch or sugar crops (Mustafa et al. 2000). The whole stillage, which contains solids from the grain along with added yeast and liquid from the water added during the process, is generated from fermentation and distillation

Fig. 2 Liquid manure application equipment (*left*) used during thin stillage injection (*right*) in a field trial in east-central Saskatchewan, Canada

processes (Fig. 1). The whole stillage is then centrifuged to separate the liquid components called thin stillage and the solid components called wet distillers grain. The thin stillage is then further processed by evaporation to produce syrup which can be blended with wet distillers grain resulting in wet distillers grain with solubles wet distillers grain with solubles (Bonnardeaux 2007). However, the evaporation process is costly and adds more expense to the cost of producing ethanol. Currently, one of the potential uses of thin stillage is that it can be used as a partial or complete drinking water replacement for cattle (Mustafa et al. 2000). Approximately 6 L of thin stillage is produced from 1 L of ethanol produced; a 190-million-L ethanol plant can produce about one to three million L of thin stillage per day (AURI 2008). It was also previously reported that up to 20 L of thin stillage may be generated for each liter of ethanol produced (van Haandel and Catunda 1994). There is growing interest in finding alternative uses for thin stillage, including digestion to produce biogas; e.g. methane which can be used to power the ethanol plant, replacing natural gas, and recovering phosphate, ammonia and magnesium contained in thin stillage to produce struvite pellets as a slow release 5-21-1 fertilizer (AURI 2008). More research is required to investigate alternative methods to utilize this significant byproduct stream associated with biofuel production. As thin stillage contains all essential plant nutrients which can promote crop production, and soluble organic matter that can stimulate soil biological activity, its direct application to agricultural soil might be a practical alternative. Equipment for land application of liquid byproducts such as liquid manure is readily available and works well for direct injection of thin stillage into soil (Fig. 2).

However, the chemical characteristics of thin stillage are variable, and will differ according to feedstock type and the treatments used in the biofuel production plant. For example, thin stillage generated from fermentation of cereal crops; e.g. corn or wheat, is different in its chemical properties to distillery wastewater generated from sugar cane or also known as vinasse, the most common feedstock in Brazil which has been investigated more extensively (Gemtos et al. 1999; Resende et al. 2006; España-Gamboa et al. 2011). Chemical composition of thin stillage collected from

Table 1 Wheat-based thin stillage properties

Element	Value	Units
NH_4-N	0.09	%
Total-N	0.47	%
Total P	0.09	%
Total S	0.06	%
Dry matter	7.5	%
Moisture	92.5	%
pH	3.8	
EC	5,160	μS cm^{-1}

The thin stillage was collected from an ethanol plant located in Saskatchewan, Canada

a local ethanol production plant located in Saskatchewan, Canada showed that this byproduct contains essential plant nutrients (Table 1). A significant portion, which was about 20% of total N, is in immediately plant available ammonium form, similar to that of liquid manure. The high content of soluble forms of nutrient in this byproduct would promote rapid availability of nutrients to plants, as well as enable better ability to predict the availability when added to soil.

In an early field study carried out to investigate land application of thin stillage generated from a sorghum grain feedstock in Texas, application of thin stillage at a rate of 334 and 1,040 kg N ha^{-1} provided essential macronutrients to the soil, but not to levels that were thought to pose plant or animal toxicity issues (Jenkins et al. 1987). It was also reported in this study that thin stillage application did not have a negative effect on grain sorghum yield. Residual effects of thin stillage on wheat grown on the same plots after the grain sorghum harvest resulted in wheat yield on the thin stillage-treated plots that was equal to or higher than plots treated with mineral fertilizer, indicating the slow release of N and the availability of nutrient from stillage organic matter persisting into the second season. In a parallel incubation experiment to examine thin stillage N mineralization rates in comparison to composted cattle manure and fresh swine manure, it was shown that 27% of the applied N was mineralized, and this was about twice the amount of N mineralized from the composted cattle manure, but not as high as the mineralization rate of swine manure (Jenkins et al. 1987). However, there is limited documented information in recent years regarding fertilizer value of thin stillage, especially as a soil amendment in prairie soils. A comprehensive understanding of the effects of thin stillage application on soil properties, crop growth and nutrient recovery under field conditions is needed to provide recommendations about the potential use of this material as a soil amendment.

In summary, thin stillage use as a soil amendment has not widely been practiced, and there is lack of documented information in this regard. Thin stillage was found to be a viable source of nutrient and provided plant essential nutrient; however, its residual effect on crop production was more evident than its direct application effect. This indicates the slow release of nutrients from thin stillage organic matter persisting into the following growing seasons.

2.1.2 Biodiesel Production Byproducts

Glycerol

Biodiesel is a biofuel that can be produced from renewable sources such as vegetable oils, animal fats or waste cooking oils. As a response to the increasing demand, biodiesel production has been growing rapidly over the past several years (Thompson and He 2006). It has some advantages over conventional diesel, including the sustainability of its feedstocks and lower emissions. Although biodiesel is considered as a sustainable, renewable and environmentally sound alternative to petroleum-based diesel fuel, its economic viability remains a major concern (Fan et al. 2010). Biodiesel manufacturing generates a principal byproduct called glycerol, also known as glycerin, (Fig. 3). It is generated during the manufacture of biodiesel via transesterification of vegetable oils that have been remained from oilseeds by crushing (Fig. 3). The glycerol constitutes 10% of biodiesel production: every t of biodiesel generates 100 kg of glycerol. The global production of biodiesel is estimated to reach over 140 billion L by 2016 with an average annual growth of 42%, which will result in approximately 15 billion L of crude glycerol being generated (Fan et al. 2010).

The large anticipated global increase in biodiesel production will lead to a surplus of glycerol and will also affect the glycerol market. It has already been reported that the current increase in glycerol production has resulted in a tenfold decrease in crude glycerol prices (Yazdani and Gonzalez 2007). Recently, the surplus glycerol byproduct is regarded as a waste stream and is disposed of by incineration (The Glycerol Challenge 2007). There is a wide range of applications for pure glycerol in pharmaceutical, food, cosmetic industries and many others; however, the refining of crude glycerol to a high purity is costly and may not be profitable for small and medium size biodiesel production plants; especially when the market for glycerol is already saturated (Groesbeck et al. 2008). Glycerol has also been used as a feed ingredient in animal diets to reduce diet costs (Lammers et al. 2007; Groesbeck et al. 2008). Research is ongoing to explore alternative methods of crude glycerol utilization to improve the economic feasibility of the biodiesel industry. Some recent potential applications of crude glycerol have included combustion and thermo-chemical conversion (Kolesárová et al. 2010) and biological conversion or biological production of methane from crude glycerol using anaerobic sludge (Fountoulakis and Manios 2009; Ma et al. 2008). Despite the existing uses of crude glycerol, more applications of this versatile byproduct need to be developed to help sustain biodiesel production. One example of a potential use of glycerol is its direct application to soil as amendment. This potential has not been evaluated.

Glycerol has no fertilizer value due to its lack of essential nutrient content, such as nitrogen and phosphorus. However, it is a concentrated carbon source, and could be used as a soil amendment to increase soil carbon content and build organic matter, especially in degraded soils that contain low organic matter due to the lack of organic inputs. It might also be used to prevent N losses via leaching and volatilization when combined with mineral N sources or liquid manure. This related to its expected ability to tie up available N temporarily through microbial immobilization.

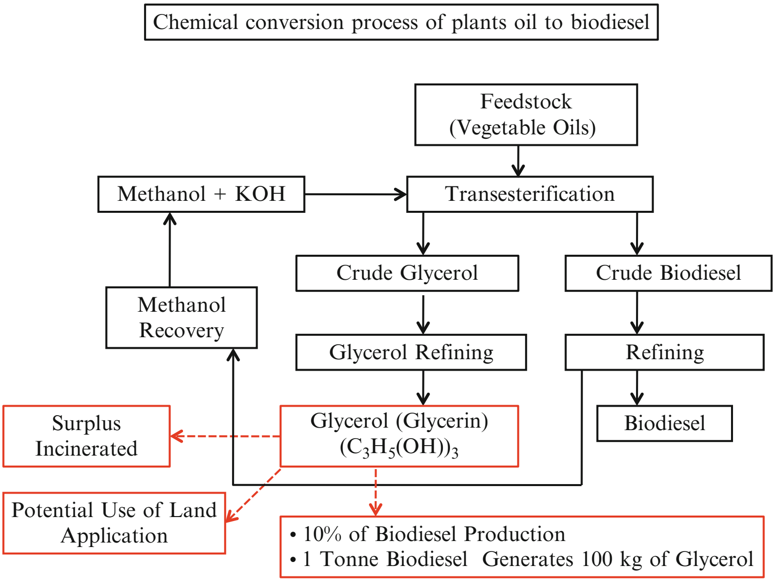

Fig. 3 Simplified process flow chart of vegetable oils conversion to biodiesel and associated byproducts of glycerol

In a study at the University of Saskatchewan, glycerol was obtained from a local biodiesel production plant and added to soil at a high rate (10,000 kg ha^{-1}). A reduction in wheat yield and N plant uptake was observed, and this was attributed to microbial immobilization of available N (Qian et al. 2009). Research into glycerol application as soil amendment should be expanded to include its effects on soil physical, chemical and biological properties, including effects on microbial populations and activity along with plants growth.

In summary, compared to the other byproducts covered in this review, glycerol was the least studied bioenergy production byproduct as a soil amendment. A study that investigated the impact of glycerol on wheat yield and N plant uptake found that glycerol application to soil at a high rate (1,000 kg ha^{-1}) reduced the yield and N uptake and related this to a possible immobilization of available N by soil microorganisms.

2.2 *Gasification and Pyrolysis Process Byproducts*

Gasification and pyrolysis thermo-chemical technologies can be used to convert organic materials to energy. Thermal conversion such as incineration, combustion or gasification, of organic materials; e.g. wood to energy is not a new technology; however, its application to some types of organic materials is new and may be an effective strategy for organic waste recycling. There is a growing interest worldwide to develop

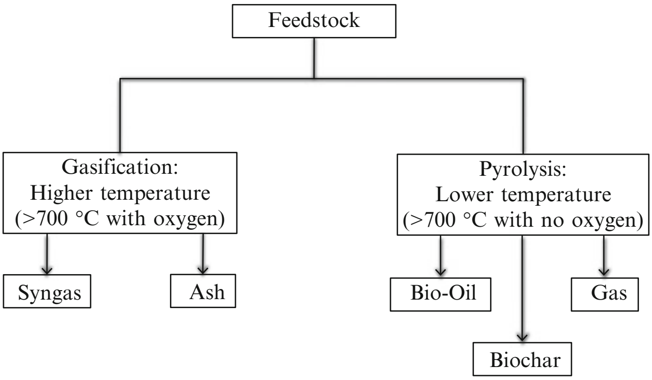

Fig. 4 Flow chart of conversion of organic materials to bioenergy through gasification and pyrolysis processes and associated byproducts produced (ash and biochar)

such technologies to produce energy and at the same time reduce waste volume (McKendry 2002a). Besides generating energy, gasification and pyrolysis technologies produce valuable byproducts of ash resulting from gasification process and biochar resulting from pyrolysis process that can be utilized as soil amendments (Fig. 4).

2.2.1 Ash

The gasification process is defined as the thermo-chemical decomposition of organic materials under high temperature (800–900°C) and in presence of oxygen (Ferreira et al. 2009). As shown in Fig. 4, this process does not only produce biogas or syngas, such as CO, H_2, CH_4, CO_2, but it also produces ash as another end product. The ash contains all the P and K originally present in the gasified materials (Kuligowski and Poulsen 2009), and the ash fraction comprises only about 1% of the raw waste mass. As such there is a significant reduction in processed waste volume and nutrient is significantly concentrated, especially P and K in ash generated, lowering cost of transport. The ash generated from gasification of organic materials contains a relatively high P content. Kuligowski et al. (2008) reported a P content of approximately 5.4% P; however, this is influenced by the type of materials gasified and their original P content. In our laboratory testing, ash from gasification of dried distillers grain and meat and bone meal were found to contain 16% and 13% of total P, respectively (Table 2).

Growing interest in producing bioenergy from sustainable sources through gasification has lead to a large quantity of ash byproduct being generated. For example, a power plant fueled with turkey litter in Minnesota, USA has capability to burn approximately 227,000 Mg of turkey litter each year, resulting in approximately 45,000 Mg ash being produced (Pagliari et al. 2010). It was estimated in Denmark that 1.5 million tons of pig manure gasified can result in 420,000 tons of ash being produced if all the pig manure is thermally gasified (Kuligowski and Poulsen 2009).

Table 2 Elemental analysis of oat hull-derived biochar, glycerol from canola biodiesel product and ash from distillers grain and meat & bone meal gasification

Parameter	Biochar	Glycerol	Distillers grain ash	Meat and bone meal ash
N%	1.54	0.095	0.12	0.02
P%	2.92	ND	15.58	12.70
S%	0.12	0.025	2.99	0.00
C%	71.40	56.6	0.87	0.09

The byproducts were chemically characterized in our laboratory, University of Saskatchewan
ND Not determined

In the light of the shrinking global phosphate rock reserves and increasing demand for P fertilizer in agricultural production, recycling P-rich ash would be a better option to replenish P-depleted soil. Therefore, there is a renewed interest in using ash as phosphorus fertilizer source. In the northeastern United States, most of the ash produced is land-applied (Campbell 1990). The effects of ash on crop production and P nutrition vary depending on ash sources, gasified feedstock, tested crop and soil properties.

In a growth chamber study, alfalfa stem (*Medicago sativa*) gasification ash application to soil was found to be a potentially useful source of K and positively affected extractable soil P, but did not improve plant P nutrition (Mozaffari et al. 2002). Similarly, Schiemenz and Eichler-Löbermann (2010) concluded that, based on results from pot experiments, crop biomass ashes can be effective source of P comparable to that of highly soluble triple superphosphate P fertilizer. Wood ash application to soil increased K content in corn and winter wheat (*Triticum aestivum* L.) in greenhouse studies (Erich and Ohno 1992; Etiegni et al. 1991) and alfalfa in field studies (Meyers and Kopecky 1998). Plant P uptake and the most plant available resin extractable P fraction was increased in soil amended with poultry litter ash generated from combustion process, indicating the ashes may adequately substitute for mineral P fertilizers (Bachmann and Eichler- Löbermann 2010). On a low-P soil, corn dry matter and shoot P uptake increased with increasing rate of turkey manure ash addition (Pagliari et al. 2010). However, by 52 days after emergence, corn dry matter in soil amended with turkey manure ash was lower compared to that of inorganic P fertilizer, and this was attributed to the initial slow release of plant available forms of P present in ash. In a 2-year field study, it was indicated that turkey manure ash can be an effective source of nutrients, especially P and K, for alfalfa production (Pagliari et al. 2009). Positive yield responses of alfalfa, bean (*Phaseolus vulgaris*), and fescue (*Festuca elatior*) to wood ash application were reported (Krejsl and Scanlon 1996; Meyers and Kopecky 1998; Muse and Mitchell 1995). Ryegrass (*Lolium perenne* L.) yield was found to be higher in soil fertilized with coal ash (Matsi and Keramidas 1999), and similarly sewage sludge ash addition increased yield of field corn and sweet corn (Bierman and Rosen 1994). When applied at 12 or 25 $t\,ha^{-1}$ to an acid soil and with N fertilizer, wood ash significantly increased barley and canola seed yield by 50% and 124%, respectively in a field trial conducted northeast of Edmonton, Canada (Patterson et al. 2004). In addition to noted positive effects on crop production, ash application also influences soil chemical, physical and biological properties. Acid agricultural soils treated with wood ash in northwestern Alberta, Canada was found to have higher soil pH, microbial biomass content, C mineralization and also a change in the functional structure of bacterial communities was noted (Lupwayi et al. 2009).

Despite the observed positive responses of crop yields to ash application, there may be concern associated with ash application to agricultural soils related to content of heavy metals which might limit its use as a soil amendment. However, several studies reported no adverse effect of ash application on soil and plant content of heavy metals (Mozaffari et al. 2002; Schiemenz and Eichler-Löbermann 2010; Pagliari et al. 2009, 2010; Codling et al. 2002; Mandre et al. 2010). This might be also clarified by conducting a long-term study with repeated application of different doses of ashes, and monitoring heavy metal toxicity and accumulation in soil and their potential transfer to the food and feed chain.

In summary, it was demonstrated in the most reviewed studies that ash application to soil increased crop yield and nutrient uptake, especially P and K. It was also reported that ash application did not have any adverse effect on plant or soil at various rates of application.

2.2.2 Biochar

Pyrolysis is the thermal breakdown of organic materials in absence of oxygen (O_2) and at relatively low temperature (< 700°C) (Lehmann and Joseph 2009). As shown in Fig. 4, this process converts organic materials into three coproducts: (1) a liquid product called bio-oil (pyrolysis oil), (2) a non-condensable gas product called syngas or pyrolysis gas containing carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4) and higher molecular weight volatile hydrocarbon, and (3) a solid inert residue rich in carbon known as biochar when intended for soil application (McCarl et al. 2009). The biochar generated during pyrolysis processes as a charcoal can be used as a fuel to produce heat, and as activated carbon used in purification processes (Horne and Williams 1996), or as a soil amendment. The latter option for biochar utilization is not a new concept, but it has recently received more attention. Research studies examining the agronomic and environmental potential benefits of biochar application to soil have been reported, but studies on the effects of biochar addition on agricultural productivity is still limited, especially in dry and temperate climates, as the majority of studies have been conducted in tropical regions (Blackwell et al. 2009). Biochar application is reported to improve plant production directly through supply of essential nutrient, or indirectly through improving soil quality and fertility. The ability of biochar to retain nutrients in the soil and improve fertilizer use efficiency are regarded as examples of indirect biochar nutrient value (Chan and Xu 2009). The Amazonian Terra Preta soils containing high amounts of biochar-like pyrogenic carbon were found to be more fertile compared to adjacent infertile soils, and this was related to their ability to retain nutrients (Glaser et al. 2001). The benefit of biochar amended-soils will therefore be related at least in part to reduction in nutrient losses via volatilization, leaching and runoff.

In a pot experiment conducted near Manaus, Brazil, application of biochar derived from wood applied at rates of 68–135 $t\,ha^{-1}$ increased rice biomass production and cowpea by 17% and 43%, respectively, and this was attributed to improved P and K nutrition provided by the biochar (Lehmann et al. 2003). It should be noted that rates of 100 $t\,ha^{-1}$ would limit the distance such material could be economically transported. In a field trial conducted in Japan, biochar addition increased height and volume of tea trees by 20% and 40%, respectively, and this was partly attributed to the ability of bamboo biochar to keep the soil pH within the range suitable for tea tree growth (Hoshi 2001). Biochar produced from paper mill sludge added at a rate of 10 $t\,ha^{-1}$ to an acidic soil from northern New South Wales, Australia in a pot experiment resulted in a 40% increase in wheat height (Van Zwieten et al. 2007). The liming effect of biochar may have promoted wheat growth by eliminating the toxic effects of soluble and exchangeable aluminium (Al) dominant in the acidic soils (Chan and Xu 2009).

The chemical and physical characteristics of biochar vary according to temperature used during pyrolysis and the type of feedstocks used. In our laboratory testing (Table 2), biochar derived from oat hull showed a high content of C (71%), with low N (1.5%) and P (3%) content. The positive effects of biochar application on plant production are not necessarily related to plant nutrition; it has been reported that biochar behaved as sorptive agent and removed organic compounds such as phenolics released from humus (Wardle et al. 1998); improved soil physical properties, like water holding capacity (Iswaran et al. 1980) and reduced soil strength (Chan et al. 2007).

Green waste biochar applied at rates up to 100 $t\,ha^{-1}$ in a combination with 100 kg N ha^{-1} increased radish dry matter by up to 266%, but this increase was not observed at the same rate of N in absence of biochar (Chan et al. 2007). This indicates an ability of biochar to improve N fertilizer use efficiency. It was also demonstrated in another study that biochar was able to protect applied fertilizer against leaching, resulting in increased fertilizer use efficiency (Lehmann et al. 2003).

Despite the positive response of different crops to biochar addition that has been documented in studies recently published, it was reported earlier that biochar addition at 5 and 15 $t\,ha^{-1}$ resulted in soybean yield reductions of 37% and 71%, respectively (Kishimoto and Sugiura 1985). This reduction in soybean yield was attributed to micronutrient deficiency as a consequence of pH increases. It was also shown that long-term productivity of woody plants was inhibited on charcoal hearths, and this was mainly attributed to higher pH and exchangeable base cations that were observed in charcoal hearth soils compared to nonhearth soils (Mikan and Abrams 1995).

In addition to agronomic potential benefits observed with biochar application, biochar might be considered as part of the solution for existing environmental issues such as reduction of mineral fertilizer losses through leaching and runoff, mitigation of greenhouse gases emissions, carbon sequestration, and potential application as sorbents in remediation of contaminated soils, and managing agricultural, urban and industrial wastes.

It has been shown that biochar was capable of retaining nutrients from applied mineral fertilizers due to a high sorptive surface area, reducing leaching and thereby increasing fertilizer use efficiency (Lehmann et al. 2003). Therefore, biochar application could have environmental benefit through reduction of nutrient losses by its ability to absorb nutrients such as phosphate and ammonium that would cause eutrophication and pose pollution risks (Lehmann et al. 2003; Lehmann 2007). Biochar was also found to absorb pesticides before they reached water bodies (Takagi and Yoshida 2003). As for its effect on greenhouse gas emissions reduction, biochar addition to soil could help mitigate greenhouse gas emissions through its ability to reduce N_2O emissions and increase CH_4 uptake from soil (Rondon et al. 2006; Yanai et al. 2007; Singh et al. 2010). In a 7-day incubation study, addition of biowaste charcoal at a rate of 10% wt/wt (approximately equivalent to 180 $t\,ha^{-1}$) to a grassland soil rich in organic matter suppressed N_2O emissions by 90%, but the emission of N_2O increased when the same soil was rewetted (Yanai et al. 2007). In a parallel trial in the same experimental set, these authors applied ash derived from the same biochar feedstock (pH 11.6) to the same soil and found no N_2O suppression when ash was added, suggesting that alkalinity properties of biochar (pH factor) was not the reason behind reduced N_2O emissions reduction. The mechanism responsible for N_2O emissions reduction when biochar was added is still unclear (Yanai et al. 2007; Van Zwieten et al. 2009; Singh et al. 2010). Despite the few short-term incubation studies conducted under controlled conditions (Yanai et al. 2007; Singh et al. 2010), there is, however, a dearth of field studies on the potential of biochar to mitigate greenhouse gas emissions.

In summary, biochar addition to soil was found to contribute to crop yield increase, and this was attributed to reduction of nutrient losses, resulting in enhancement of nutrient use efficiency. Besides its agronomic benefits, it was reported in some studies that biochar application could have environmental benefits through its ability to reduce nutrient loss by leaching and runoff, absorb pesticides and mitigate greenhouse gas emissions.

3 Manure Derived from Cattle Fed Ethanol Byproducts

Ethanol production byproducts including distillers grains and thin stillage can be an excellent source of protein and nutrients when included in livestock diets (Mustafa et al. 2000). However, unlike distillers grains, thin stillage has not routinely been used in animal diets.

Distillers grains have commonly been used as animal feed in the wet or dry form and are recognized as an excellent source of protein and phosphorus (Erickson et al. 2005; Harris et al. 2008). Similarly thin stillage can be fed alone or in a combination with distillers grains (Mustafa et al. 2000). However, due to it is liquid nature and for better utilization by beef cattle, thin stillage can replace water as a fluid source for animals (Mustafa et al. 2000). The co-location of an ethanol plant with a feedlot, such as exists near Lanigan, Saskatchewan, allows thin stillage to be used as a cattle watering source and wet distillers grain to be used as feed.

In cattle feeding, only about 10% of the nitrogen and only about 20% of the phosphorus in the feed is retained in the beef animal, and the rest is excreted in feces and urine (Bierman et al. 1999). Therefore, it is expected that manure produced from animals fed distillers grains will have different characteristics compared to that derived from animals fed regular grains. In particular, owing to higher contents of N and P in distillers grains, the distillers grain derived manure will also have higher content of nutrients, especially N, P and S (Hao et al. 2009). Recycling these nutrients back to soil through manure application will partially compensate for nutrients removed from the soil (Benke et al. 2010). This option will then, to some extent, help maintain soil quality and productivity.

In general, animal manure has been shown to be a valuable source of plant nutrients, making an effective contribution to improved chemical and physical properties of soil as well as biological activity and plant nutrition (Schoenau and Davis 2006; Edmeades 2003). Many manure characteristics and its agronomic value are influenced by livestock diet (Eghball 2002; Hao et al. 2009). For example, the capacity of manure to increase pH of acid soils is affected by the addition of $CaCO_3$ to the diet (Eghball 1999). Diet modification could also influence odor by affecting the various volatile fatty acid content (Hao et al. 2005). Reduction in protein and P intake was shown to result in a significant reduction in N and P concentration in manure and therefore decrease ammonia volatilization and P accumulation in manure amended soils (Satter et al. 2002; Maguire et al. 2007). In a study at Lethbridge, Alberta to evaluate the effect of including wheat dried distillers grains with solubles in finishing feedlot cattle diets on composition of manure, Hao et al. (2009) concluded that including 40% and 60% wheat DDGS in feedlot cattle diets resulted in significant increases in water soluble NH_4^+-N, total N, and total P in animal manure. Similarly, Spiehs and Varel (2009) reported that increasing amount of wet distillers grains with solubles in feedlot cattle diets resulted in increased P, N and S content in cattle manure. Increased inclusion of distillers grains in animal diets from 0% to 40% (DM basis) increased diet crude protein from 13% to 18.7% and P in the diets from 0.29% to 0.49% (Bremer et al. 2008). This increased the excreted N and P by 51% and 90%, respectively, as a consequence. It was also previously documented that cattle consuming dietary N (Cole et al. 2005; Archibeque et al. 2007), P (Benson et al. 2006; Luebbe et al. 2008), and S (Fron et al. 1990) in excess of nutrient needs will result in extra nutrients being excreted in urine and feces. In terms of thin stillage-derived manure, there is a lack of studies examining manure composition as affected by thin stillage inclusion in animal diets.

Distillers grain inclusion in animal diets does not only increase the amount of nutrient excreted, but it also can influence the forms of these nutrient. Water soluble P tended to increase when WDGS was included in the diet (Spiehs and Varel 2009). Similarly, Ebeling et al. (2002) revealed that higher dissolved reactive P was observed in manure obtained from animals fed higher P concentration diets. Therefore, this could enhance nutrient availability and crop growth response when manure is land-applied, but also increase potential for transport of P in runoff.

Greater concentration of nutrient in manure produced by animal fed distillers grain can increase animal manure value as organic fertilizer by reducing handling and transportation costs per unit of nutrient. Moreover, recycling these nutrients back to soil through manure application will partially compensate for nutrients removed with grains and straw sent for biofuel production and that otherwise will have to be replaced by mineral fertilizers. Land application will help maintain soil quality and productivity especially in land areas experiencing high demand for biofuel and food production. However, application rates need to be adjusted for higher nutrient content that may be encountered to avoid excessive application rates of nutrients which can have environmental implications including water quality degradation through nutrient runoff and leaching.

In summary, inclusion of distillers grain in animal diets was found to have a significant effect on manure nutrients content and forms. This will promote including this type of manure in farm management plan and make it more valuable as organic fertilizers.

Even though manure application effects on soil quality and plant production have been long studied and are well-documented, there have been no scientific studies conducted in the field to identify the behavior of manure from distillers grain fed cattle in comparison with original grain ration fed cattle when land-applied.

4 Conclusion

Several factors and concerns including dwindling fossil fuel supply, energy security, and adverse effects of fossil fuel use on the environment, including climate change have stimulated production of energy from renewable bioresources. Technologies for bioenergy production include biochemical; fermentation, mechanical/chemical extraction; transesterification and thermochemical; gasification and pyrolysis processes. These conversion processes convert the organic materials into different types of energy, such as liquid fuel or gases, depending on the type of feedstocks and energy required. In addition to the energy product produced, each conversion process generates byproducts.

Soil is a natural resource and key component of natural and managed systems that in an agricultural setting that plays a major role in food and feed production. Nutrients and soil organic matter that are exported from agricultural fields in food and bioenergy production have to be compensated for by adding mineral fertilizer or organic amendments to maintain soil productivity. Addition of extra mineral fertilizers is a concern because commercial fertilizers require energy for production and may not compensate for reduced soil biodiversity and microbial activity due to reduced organic matter inputs.

A promising solution for the need to effectively recycle nutrients used in biofuel production is to return the residues generated during bioenergy production to the soil to help keep the balance between the inputs through bioenergy residue addition; carbon and nutrients and the outputs via biomass harvested for bioenergy production; carbon and nutrients. The scientific studies reviewed in this paper support this potential for utilization of bioenergy production byproducts as soil amendments. Their application to agricultural soil as a source of carbon and nutrients appears to be a viable alternative to their “disposal” as a waste material. Among the byproducts covered in this review, biochar is the amendment that has received most attention recently, mostly related to its ability to retain nutrient rather than as a direct supply of nutrient to plants. Ash addition to soil has also showed positive effects on crop yield. Distillers grain application to soil has received less attention, but the few studies conducted have shown a potential of using this byproduct as a slow release source of nutrients. Still, further studies on this byproduct are needed to provide sound guidelines on its use. The other byproducts, such as thin stillage and glycerol have been rarely studied and require further investigation. These byproducts can potentially be used as a source of carbon in the case of glycerol and all essential nutrients in case of thin stillage amendment. The effects of repeated long-term land application of bioenergy byproducts need to be monitored to ensure that soil, air and water quality is not adversely affected.

5 Future Research

Some identified future research needs related to utilization of bioenergy byproducts as soil amendments are listed below:

- Biochar research should to be extended geographically to include arid and semi-arid regions.
- Long-term effects of application of biochar in combination with mineral fertilizers need to be carried out to investigate its ability to conserve mineral N and reduce losses to environment through volatilization, denitrification and leaching over the long term; e.g. several years.
- Evaluation of combinations of biochars with other amendments like manure and stillage.
- Effect of pyrolysis conditions, such as feedstocks, temperature and oxygen status on biochar physical and chemical characteristics and efficacy when added to soil. This can be conducted by comparing several biochar types produced from different feedstocks under different conditions and examining their effect in the field.
- Engineered solutions and technology for handling and application of chars and ashes to soil in an efficient manner.
- Most studies with ashes and chars are either conducted under controlled environment conditions or under field conditions but only for a short-term (usually ~2 years). This does not give an appropriate period to make inferences about the potential for heavy metal accumulation in soils and phytotoxicity.
- Land application of glycerol is unexplored but has a potential to conserve N fertilizer through microbial immobilization as well as its ability to increase organic matter content. This should be investigated under controlled environment and field conditions. Glycerol might also be used as composting additive as a source of carbon.
- Application of distillers grain and thin stillage to land directly as organic fertilizers needs to be further studied. These materials are rich in nutrient and their

application to soil might open a new path for their utilization. Thin stillage is an acidic material and its application might better benefit alkaline soils. If soil applied, appropriate rate, method, time of application has to be determined to avoid soil and water pollution while providing crop benefit.

- Distillers grain derived manure is richer in nutrient compared to conventional manure, and its decomposition and nutrient availability may be different. Manure management practices specific to distillers grain fed animals need to be established.

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Pseudomonas and other Microbes in Disease-Suppressive Soils

Martina Kyselková and Yvan Moënne-Loccoz

Abstract Soil-borne phytopathogens cause extensive damage to cultivated plants worldwide, resulting in yield loss worth billions of Euros each year. Soil fumigation is the most effective chemical treatment but is too expensive for many crops, and fumigants like methyl bromide are being phased out for environmental reasons. In this context, much is to be learned from disease-suppressive soils, where susceptible plants are protected from soil-borne pathogens by the indigenous microbiota, because these microbial interactions may be exploited to design sustainable crop protection strategies for ordinary farm soils. However, our knowledge of plant-protecting microorganisms and biocontrol mechanisms involved in soil suppressiveness remain very fragmented, as most knowledge on disease suppressive soils comes from studies restricted to individual plant-protecting microbial populations, mostly fluorescent *Pseudomonas* species. The phenomenon of disease suppressiveness remains therefore poorly understood, even in the most studied cases such as suppressiveness to wheat take-all.

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We reviewed the respective biocontrol contributions of fluorescent pseudomonads and other plant-protecting microorganisms in disease-suppressive soils. The ability to inhibit soil-borne pathogens and to protect plants occurs both in *Pseudomonas* and non-*Pseudomonas* microorganisms, including diverse bacteria and fungi, and both play important roles in soil suppressiveness. In *Pseudomonas*, antibiosis and competition were shown to be important mechanisms of pathogen suppression, though direct effects on plant, e.g. induced systemic resistance, phytohormone interference and plant-growth promotion, were also reported. These types of mechanisms occur also in non-*Pseudomonas* biocontrol microbes, some of them also displaying hyperparasitism in certain types of suppressive soils.

This review shows that in suppressive soils where *Pseudomonas* play an important role, the roles of non-*Pseudomonas* microorganisms were often neglected, and *vice versa*. Yet, *Pseudomonas* and other microorganisms may interact with each other in the rhizosphere and with the plant, and some recent studies indicate that disease suppressiveness is an emerging soil property that can typically result from these multiple interactions. In conclusion, we propose that a parallel assessment of *Pseudomonas* and non-*Pseudomonas* microorganisms in suppressive soils, e.g. using microarrays or metagenomics, may bring a better understanding of disease suppressiveness.

Keywords Biocontrol • Disease-suppressive soil • Plant pathogen • *Pseudomonas* • Rhizosphere

1 Introduction

Crop plants are faced with a wide range of bioagressors, including pests, parasites and pathogens (Agrios 1997). Among them, phytoparasitic microorganisms are responsible for hundreds of billons Euros in crop loss worldwide. Many of them infect plant shoots and may be managed via chemical control. However, microorganisms affecting crop health and yield may also reside inside agricultural soils, where they infect the plant via the root. These soil-borne phytoparasitic microorganisms can be harder to control by chemical means, because they are physically protected by soil particles. Soil fumigation is the most effective chemical treatment but is expensive, has adverse effects on beneficial microbes involved in soil fertility and quality, and may cause other environmental problems in relation to global change.

Soils harbour a wide range of phytoparasitic microorganisms, including pathogenic fungi, oomycetes, nematodes and bacteria (Raaijmakers et al. 2009), and these phytoparasites may cause extensive damage to crops (Agrios 1997). However, the survival, infectivity and/or pathogenicity of plant-parasitic microorganisms in soil is generally reduced due to competition and other negative interactions exerted by the rest of the microbial community, and this common soil property is referred to as general disease suppression (Cook and Baker 1983). In addition to general disease suppression, certain soils exhibit specific disease suppression towards a particular parasite (Haas and Défago 2005). In these soils, disease incidence in presence of virulent

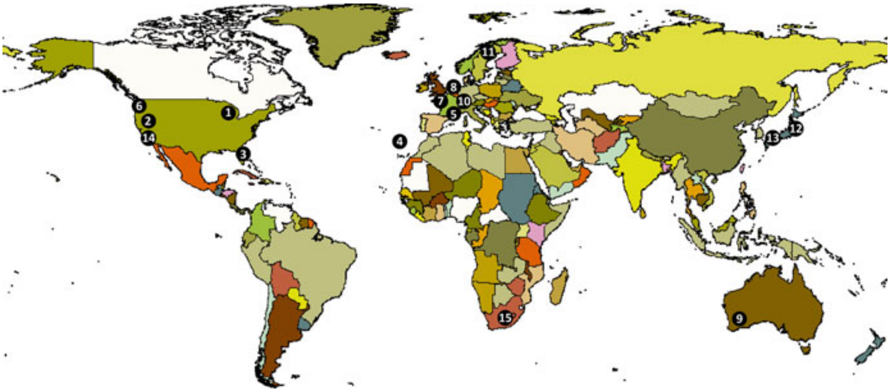

Fig. 1 Countries with emblematic case studies of soils with specific suppression towards soil-borne phytoparasites. **1** *Streptomyces scabiei* (potato scab); **2–5** *Fusarium oxysporum* (Fusarium wilt of watermelon, banana and flax); **6–9** *Gaeumannomyces graminis* var. *tritici* (wheat take-all); **10** *Thielaviopsis basicola* (black root rot of tobacco); **11–12** *Plasmodiophora brassicae* (clubroot disease of cabbage); **13** *Ralstonia solanacearum* (tomato wilt); **14** *Heterodera schachtii* (endoparasitic nematode; damage to sugarbeet roots); **15** *Xiphinema elongatum* and *Paratrichodorus minor* (ectoparasitic nematodes; damage to sugarcane roots)

pathogen, susceptible plant and pathogen-favorable environmental conditions is much lower than expected, unlike in disease-conducive soils (i.e. allowing plant infection and spread of the disease; Baker and Cook 1974; Weller et al. 2002; Mazzola 2002; Borneman and Becker 2007; Janvier et al. 2007). The microbial basis of suppressiveness has been shown in experiments where this property was eliminated by soil sterilization/pasteurisation, and acquired by conducive or sterilized/pasteurised suppressive soil following the addition of small amount of suppressive soil (Baker and Cook 1974; Weller et al. 2002; Mazzola 2002; Haas and Défago 2005).

The focus of this review is on specific disease suppressiveness, which has been documented for several phytoparasitic bacteria (Becker et al. 1997; Shiomi et al. 1999), nematodes (Rimé et al. 2003; Borneman and Becker 2007), oomycetes (Persson et al. 1999; Murakami et al. 2000) and especially fungi (Stutz et al. 1986; Weller et al. 2002; Janvier et al. 2007). Soils specifically suppressive towards a pathogen occur worldwide (Fig. 1). They were originally defined by Baker and Cook (1974) as soils in which the pathogen does not establish, establishes but causes no or little disease, or causes disease that subsequently diminishes with continuous culture of the crop. The definition comprises two recognized types of specific suppressiveness, i.e. natural (long-standing) suppressiveness and suppressiveness induced by monoculture. Induced disease suppressiveness develops as a result of crop monoculture, and is well documented especially for take-all disease of wheat (caused by the fungus *Gaeumannomyces graminis* var. *tritici*), potato scab (caused by the actinobacterium *Streptomyces scabiei*), Rhizoctonia root rot of wheat and cauliflower (caused by *Rhizoctonia solani*) and damage caused by the cereal-cyst nematode *Heterodera avenae* (Kerry 1982; Roget 1995; Weller et al. 2002; Postma et al. 2010). Often, repeated growth of a same crop favours the pathogen, and disease severity increases year after year. In the case of induced disease suppressive soils, however, rhizosphere populations of plant-protecting microorganisms build up after a few years, and they lead then to disease suppressiveness, which explains why this phase is often referred to as disease decline (Weller et al. 2002). Induced disease suppressiveness lasts as long as the monoculture is not interrupted using a non-host plant. In contrast, natural disease suppressiveness does not require monoculture (Haas and Défago 2005), although it is likely that the extent of disease suppression may be influenced by past conditions of crop rotation (Ramette et al. 2003a). It has been extensively studied for several soil-borne diseases, such as *Thielaviopsis basicola*-mediated black root rot (Stutz et al. 1986) and Fusarium wilt caused by *Fusarium oxysporum* (Alabouvette 1986). Although microrganisms play the key role in disease suppressiveness, soil physicochemical properties may also contribute to the phenomenon (especially in the case of natural disease suppressiveness, e.g. Höper et al. 1995). Indeed, soil factors such as pH and clay mineral composition may favour the establishement of plant-protecting populations or expression of plant-beneficial traits (Höper et al. 1995; Keel et al. 1992; Ramette et al. 2006).

In a majority of studies, the assessment of disease-suppressive soils has focused on the role of the fluorescent *Pseudomonas* spp. (Lemanceau et al. 2006), especially in a context of antibiosis (Haas and Défago 2005; Weller 2007), without considering the potential role of other microorganisms in specific disease suppression. This is particularly the case for soil suppressiveness to take-all or black root rot disease. However, it is likely that non-pseudomonads contribute also to disease suppression in many cases (Rimé et al. 2003; Ramette et al. 2006; Borneman and Becker 2007). In a smaller number of studies, other plant-protecting microorganisms have been considered, e.g. *Bacillus*, *Streptomyces*, *Pasteuria penetrans*, *Trichoderma* or non-pathogenic *Fusarium oxysporum* (Weller et al. 2002; Janvier et al. 2007), but typically without parallel analysis of fluorescent *Pseudomonas* populations.

Both *Pseudomonas* and non-*Pseudomonas* microorganisms display a range of biocontrol traits that are likely to be involved in specific suppression. This review therefore aims at assessing current knowledge on the biocontrol properties and respective role of fluorescent pseudomonads versus non-*Pseudomonas* microorganisms in specific disease suppressiveness of soils. We believe that this is a prerequisite for understanding the phenomenon of specific disease suppressiveness with its implications for sustainable soil management and prospecting for suppressive soils and novel biocontrol microorganisms.

2 Role of Fluorescent *Pseudomonas* in Disease-Suppressive Soils

2.1 Modes of Action of Fluorescent Pseudomonas

2.1.1 Antibiosis

Several modes of plant protection are known for fluorescent pseudomonads (Fig. 2; Couillerot et al. 2009). The main one documented is antagonism mediated by the production of secondary antimicrobial metabolites, noticeably 2,4-diacetylphloroglucinol

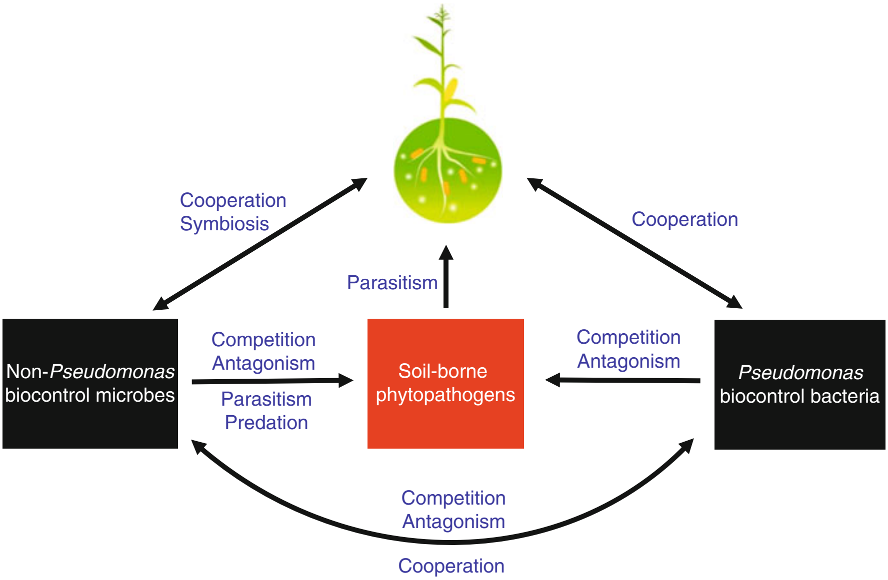

Fig. 2 Interplay between *Pseudomonas* and non-*Pseudomonas* biocontrol microorganisms and protection of plant roots from soil-borne phytopathogens (Modified from Couillerot et al. 2009)

(DAPG), phenazines, and hydrogen cyanide (Chin-A-Woeng et al. 2000; Raaijmakers et al. 2002; Haas and Défago 2005; Weller 2007). Antimicrobial metabolites also include pyrrolnitrin, pyoluteorin, lipopeptides and others, but they have been comparatively less studied. Only fragmented information is available on the mode of action of these compounds. In phytopathogenic fungi and oomycetes, DAPG can target the cell membrane, phenazines and pyrrolnitrin the electron transport chain, while hydrogen cyanide affects copper-containing cytochrome c oxidases (Haas and Défago 2005; Raaijmakers et al. 2009; Schouten et al. 2008). Evidence for the implication of antimicrobial secondary metabolites in biological control has been obtained using mainly two different approaches. First, non-producing mutants protected less than the corresponding parental strains, which has been shown for instance in the case of DAPG (Fenton et al. 1992; Keel et al. 1992), hydrogen cyanide (Voisard et al. 1989), pyoluteorin (Maurhofer et al. 1994) and phenazines (Thomashow and Weller 1988). However, the loss of the ability to produce a given metabolite is compensated in certain strains by excess production of another metabolite (Haas and Keel 2003), which complicates data interpretation. Second, the introduction into non-producing wild-type strains of genes conferring the ability to produce antimicrobial secondary metabolites conferred (or enhanced) plant protection ability (Fenton et al. 1992; Timms-Wilson et al. 2000). Similarly, the development by genetic means of overproducing derivatives could also result in improved biocontrol (Haas and Keel 2003; Mark et al. 2006).

Quantification of antimicrobial secondary metabolites in the rhizosphere is tricky. DAPG has been detected at levels up to 250 ng/g root in bulk samples from the wheat rhizosphere (Raaijmakers et al. 1999), but it is likely that the actual concentration faced locally by pathogens in root surface micro-habitats is higher. Concentrations needed for *in vitro* inhibition of phytopathogenic bacteria, oomycetes, fungi and nematodes vary according to the target, from a few μg/ml to more than 100 μg/ml (Keel et al. 1992; de Souza and Raaijmakers 2003), and biocontrol pseudomonads are more effective against highly-sensitive pathogenic strains than less sensitive ones (Mazzola et al. 1995). Often, pseudomonads with plant-protection ability can produce more than one antimicrobial secondary metabolite (Raaijmakers et al. 2002; Haas and Keel 2003), certain compounds being more effective in some pathosystems than in others. Parallel analysis of the plant-protection efficacy of several biocontrol pseudomonads indicated that strains producing hydrogen cyanide protected better than the others in a pea-*Pythium ultimum* pathosystem (Ellis et al. 2000), whereas strains producing DAPG protected better overall than non-producing strains in cucumber-*P. ultimum* and tomato-*F. oxysporum* f. sp. *radicis-lycopersici* pathosystems (Sharifi-Tehrani et al. 1998). In the latter pathosystems, the ability to produce DAPG was more influential than the one to produce hydrogen cyanide when a much larger collection of biocontrol pseudomonads was used (Rezzonico et al. 2007).

The role of antimicrobial metabolites of *Pseudomonas* in antagonism is in fact difficult to ascertain, because these compounds can have multiple effects. Indeed, they may inhibit non-pathogens as well (Keel et al. 1992; Walsh et al. 2003), which in turn might interfere with phytopathogens. Furthermore, certain antimicrobial metabolites may have a direct impact on plant physiology. For instance, DAPG can modify root system architecture (Brazelton et al. 2008) and stimulate root exudation of amino acids (Phillips et al. 2004), which in turn affects perhaps the rhizosphere microbial community including phytopathogens, and it triggers an induced systemic response in the plant (see below). In addition to biocontrol functions, the ability to produce secondary antimicrobial metabolites may also contribute to ecological fitness, as shown for DAPG on potato (Cronin et al. 1997b) (but not on sugarbeet; Carroll et al. 1995) and phenazine on wheat (Mazzola et al. 1992). It has been hypothesized that certain genes encoding antimicrobial secondary metabolites in the fluorescent *Pseudomonas* spp. noticeably *phlD* (DAPG synthesis) could have been acquired from the plant, where perhaps they were also involved in plant defense functions (Cook et al. 1995; Ramette et al. 2001).

2.1.2 Other Biocontrol Mechanisms

Certain fluorescent pseudomonads may antagonize phytopathogens via the production of lytic enzymes or effectors (Raaijmakers et al. 2009). Data are scarce on the possible role of cell wall-degrading extracellular lytic enzymes e.g. β-1,3-glucanase and chitinase in *Pseudomonas* antagonism (Lim et al. 1991), and they seem to play a minor role in the plant-protection ability of pseudomonads (Sharifi-Tehrani et al. 1998). Another type of antagonistic interaction, in which pathogen virulence is targeted, implicates putative effectors. Indeed, mutation of type III protein secretion gene *hrcV* lowered the ability of *P. fluorescens* KD to reduce both polygalacturonase activity in *Pythium ultimum* and Pythium damping-off of cucumber (Rezzonico et al. 2005). Type III secretion system genes are a basic feature of many biocontrol pseudomonads (Preston et al. 2001; Mazurier et al. 2004), but in *P. fluorescens* KD they may have been acquired horizontally in more recent time, apparently from pathogenic *Pseudomonas syringae* (Rezzonico et al. 2004).

In addition to antagonism, competition by pseudomonads is thought to contribute to pathogen control (Fig. 2), although to a lesser extent than antagonism (Haas and Défago 2005). Competition may take place for nutrients (Kamilova et al. 2005), especially organic carbon and/or iron (Lemanceau et al. 1992; Paulitz et al. 1992; Duijff et al. 1993). Besides conferring protection from disease (noticeably Pythium damping-off and Fusarium wilt), competition is also important for successful establishment of biocontrol pseudomonads in the rhizosphere (Moënne-Loccoz et al. 1996) and expression of antagonistic traits (Chin-A-Woeng et al. 2000).

Even if biocontrol fluorescent pseudomonads are effective at inhibiting phytopathogens, direct effects on the plant are also documented (Fig. 2), noticeably induced systemic resistance (ISR; Pieterse et al. 2003). During ISR, several plant defence mechanisms are activated and the plant resists better to a range of pathogens (van Loon 2007). ISR can be triggered by different surface constituents of *Pseudomonas* cells, such as the O-antigenic sidechain of lipopolysaccharides and flagella (Pieterse et al. 2003), and by metabolites released by these bacteria, e.g. the siderophore pyoverdine (Maurhofer et al. 1994), a benzylamine derivative (Ongena et al. 2007), and the antimicrobial metabolite DAPG (Iavicoli et al. 2003).

In addition to ISR, certain pseudomonads can also act on the plant by phytohormone interference, as follows. Ethylene levels in roots may be influenced by bacterial deamination of its precursor 1-aminocyclopropane-1-carboxylate (ACC), which is thought to diminish the quantity of plant ACC left for ethylene synthesis (Glick et al. 1998). This can contribute to plant health by promoting growth and alleviating stress (Glick 2005). Transfer of the ACC deaminase locus into *Pseudomonas protegens* CHA0 (previously *P. fluorescens* CHA0; Ramette et al. 2011) enhanced biocontrol of Pythium damping-off of cucumber (Wang et al. 2000). Unlike strain CHA0, a large range of biocontrol pseudomonads display ACC deaminase activity (Blaha et al. 2006), but whether this trait actually contributes to biocontrol in any of these strains remains to be established. Phytohormone interference may also result from production of the phytohormone indole-3-acetic acid (IAA), a trait occurring in many plant-beneficial pseudomonads including several biocontrol strains (Kamilova et al. 2005). Certain IAA-producing pseudomonads can stimulate root growth (Lippmann et al. 1995; Patten and Glick 2002), and overproduction of IAA has the potential to enhance plant growth promotion effects (Dubeikovsky et al. 1993; Beyeler et al. 1999). However, spontaneous or controlled mutations that reduced IAA synthesis ability or genetic modifications enhancing this ability did not have a significant impact on the biocontrol efficacy of pseudomonads (Oberhansli et al. 1991; Beyeler et al. 1999; Suzuki et al. 2003).

Finally, a few plant growth-promoting pseudomonads are thought to act on the plant by enhancing nutrient availability, noticeably via nitrogen fixation for

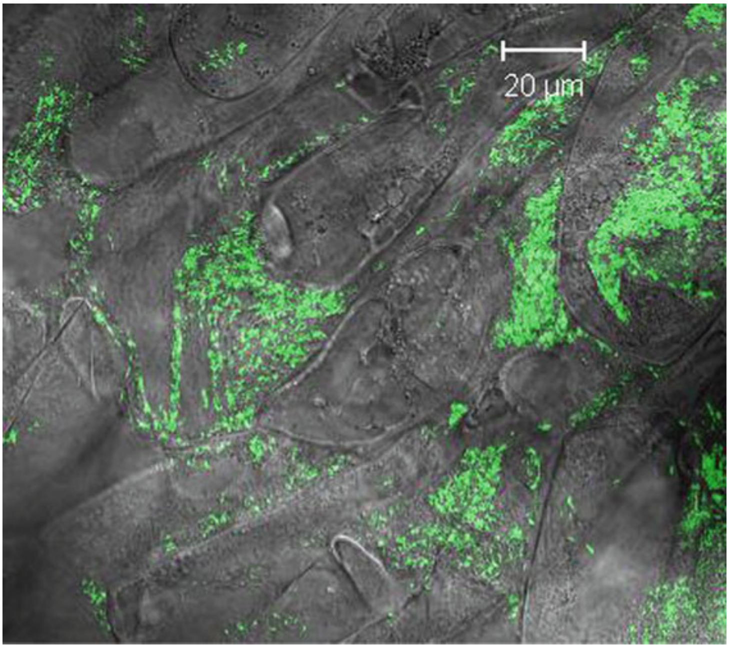

Fig. 3 Colonization of wheat roots by the biocontrol strain *Pseudomonas protegens* CHA0 labelled with a P_{lac}-*egfp* plasmid fusion, which makes the cells green (they appear in light grey when printed in black and white) via the expression of autofluorescent green protein EGFP. Plants were grown under gnotobiotic conditions and roots assessed by confocal laser scanning microscopy. Results show that *P. protegens* CHA0 colonized roots extensively. It was found as a combination of individual cells and cell patches, forming discontinued biofilms prevalent in the intercellular spaces between epidermal cells (Source: C. Prigent-Combaret)

P. stutzeri strains and relatives (Mirza et al. 2006) or phosphate solubilization (Rodriguez and Fraga 1999; Peix et al. 2003). However, its significance in terms of plant protection from disease is unknown.

2.2 *Prevalence and Biogeography of Pseudomonas in Soil*

Fluorescent pseudomonads are often found at rather high population levels in bulk soil (e.g. 10^6 CFU/g soil; Troxler et al. 1997a) and the rhizosphere (10^{5-7} CFU/g root; Troxler et al. 1997b), where they may represent 0.1–1% of the total culturable bacterial community (Haas and Défago 2005). These population levels are in accordance with estimates obtained using quantitative PCR (Johnsen et al. 1999) and are consistent with their high root-colonization ability (Fig. 3). Certain types of fluorescent pseudomonads have been monitored in greater detail, especially those producing DAPG. The latter may represent 10–15% of all culturable fluorescent pseudomonads from the rhizosphere (Picard et al. 2004), and from less than 1%

(McSpadden Gardener and Weller 2001) to up to 30% of all culturable fluorescent pseudomonads in certain suppressive soils (Ramette et al. 2003b). The prevalence of *phlD*+ isolates in the rhizosphere depends on plant genotype and growth stage (Picard et al. 2004).

Soil fluorescent pseudomonads display a cosmopolitan distribution worldwide when considering broad groups of strains defined by restriction of 16S rRNA gene *rrs* (Cho and Tiedje 2000). At (almost) strain level, however, endemism was evidenced when assessing isolates from large geographic distances (based on BOX-PCR clusters; Cho and Tiedje 2000) as well as within a same field (based on RAPD markers; Moënne-Loccoz et al. 2001). The same may apply to the case of plant-protecting pseudomonads based on analysis of strains producing DAPG (Wang et al. 2001; Ramette et al. 2006) and/or HCN (Ramette et al. 2003b), in that they have been documented across several continents, climatic regions and soil types, yet with a rather endemic distribution (except pyoluteorin-producing DAPG+ strains; Wang et al. 2001) when considering strain properties and/or population structure (Ramette et al. 2006; Weller et al. 2007). In addition, the genetic diversity of *phlD*+ *Pseudomonas* populations from a given site may fluctuate with plant genotype and development (Picard et al. 2004).

2.3 Suppressive Soils Where Plant Protection Is Attributed Mainly to Pseudomonas

2.3.1 *Pseudomonas* and Take-All Suppressive Soils

Soil suppressiveness to take-all disease is largely attributed to antagonistic root-colonizing fluorescent pseudomonads (Smiley 1979; Sarniguet and Lucas 1992; Weller et al. 2002), especially those producing antimicrobial compounds such as phenazines or DAPG (reviewed by Weller et al. 2007). Work in Washington State and elsewhere showed that rhizosphere DAPG+ pseudomonads were recovered at higher levels in take-all decline soils (i.e. at or above the threshold population density of 10^5 CFU/g root necessary for disease suppression) than in conducive soils (Raaijmakers and Weller 1998), where they remained below this threshold, both in greenhouse experiment (Raaijmakers and Weller 1998) and in the field (Weller et al. 2007). The amount of DAPG recovered from the rhizosphere of wheat was proportional to cell number of inoculated DAPG+ *P. fluorescens* Q2-87, and accordingly DAPG was detected in the rhizosphere of plants colonized by indigenous DAPG+ pseudomonads in take-all-suppressive soil but not in conducive soil (Raaijmakers et al. 1999).

Wheat monoculture is thought to enrich selectively for certain types of antagonistic *Pseudomonas* during take-all decline (Chapon et al. 2002; Weller et al. 2007). Comparison of neighboring fields under crop rotation of wheat or flax monoculture showed that DAPG+ pseudomonads were enriched in the two monoculture soils, but that distinct *Pseudomonas* genotypes predominated on wheat versus flax roots

(Landa et al. 2006). In western France, the decline of wheat take-all correlated with changes in the prevalence of two major *Pseudomonas* (sub)populations (Sanguin et al. 2008). Evidence was also obtained for parallel modifications in the genetic structure of the *G. graminis* var. *tritici* population, leading to predominance of less aggressive genotypes once suppressiveness was reached (Lebreton et al. 2004). The relation between antagonistic pseudomonads and *G. graminis* var. *tritici* is complex, as multiple changes in gene expression take place in the bacterium when it is in presence of the pathogen (Barret et al. 2009).

When DAPG⁺ isolates from take-all decline soil were tested, inoculation into conducive soil resulted in take-all suppression (Raaijmakers and Weller 1998), whereas DAPG-deficient *Pseudomonas* mutants displayed reduced biocontrol. In addition, the DAPG⁺ strain *P. fluorescens* Q2-87 controlled DAPG-sensitive strains but not DAPG-tolerant strains of *G. graminis* var. *tritici* (Mazzola et al. 1995).

2.3.2 *Pseudomonas* and Black Root Rot Suppressive Soils

Natural soil suppressiveness to *T. basicola*-mediated black root rot of tobacco is thought to result from antagonistic effects of root-colonizing fluorescent pseudomonads, especially strains producing DAPG and/or HCN (Stutz et al. 1986; Voisard et al. 1989; Keel et al. 1992). DAPG⁺ strains isolated from black root rot suppressive soil inhibited *T. basicola in vitro*, and one of them (*P. protegens* CHA0) protected tobacco from the pathogen when inoculated to a conducive soil (Stutz et al. 1986). The percentage of root-associated DAPG⁺ pseudomonads among the total culturable fluorescent *Pseudomonas* spp. was higher for suppressive versus conducive soils (Ramette et al. 2003a), but the difference was not extensive and fluctuated from one sampling to the next. In addition, the number of culturable *phlD*⁺ rhizosphere pseudomonads was comparable or even sometimes higher with black root rot conducive soils than in suppressive counterparts (Ramette et al. 2003a; Frapolli et al. 2010).

Analysis of *phlD*⁺ rhizosphere isolates from black root rot suppressive and conducive soils indicated that their population structure depended more on field location than soil suppressiveness status (Ramette et al. 2006), but as many as a quarter of *phlD* DGGE bands and one third of *phlD* alleles identified by band sequencing were only found in suppressive soils (Frapolli et al. 2010). Whether these differences in *phlD*⁺ *Pseudomonas* population structure are important for disease suppression remains to be determined, but results raise the possibility that suppressiveness could require particular consortia of DAPG⁺ pseudomonads interacting with one another (Haas and Défago 2005).

In the Swiss region of Morens, black root rot suppressive soils are developed on morainic deposits and conducive soils on molasse sandstone (Stutz et al. 1989). Although both types of soil display very similar physicochemical properties, they differ in clay mineralogy. Indeed, vermiculite (which releases iron during weathering) is prevalent in suppressive soils and illite (of lower iron content) in conducive soils (Stutz et al. 1989). Iron availability is important for production of biocontrol metabolites such as HCN by Morens isolate *P. protegens* CHA0 (Keel et al. 1992), and DAPG+ HCN+ pseudomonads from conducive soils did protect tobacco from black root rot when inoculated in artificial vermiculitic soil (Ramette et al. 2006), pointing to the importance of gene expression conditions specific to suppressive soils.

3 Role of Non-*Pseudomonas* Microorganisms in Disease-Suppressive Soils

3.1 Non-Pseudomonas Microorganisms with Plant Protecting Abilities

A large number of studies have documented the ability of non-*Pseudomonas* microorganisms to protect plants from soil-borne disease when used as inoculants (Fig. 2). These biocontrol microorganisms include Gram-negative and Gram-positive bacteria, as well as oomycetes and fungi (Table 1). Bacteriophages were also considered for their biocontrol properties (Goodridge 2004), but they are out of the scope of this review. Biocontrol Gram-negative bacteria (*Proteobacteria*) are mainly documented in the eight families *Pseudomonadaceae*, *Xanthomonadaceae*, *Enterobacteriaceae* (*Gammaproteobacteria*), *Burkholderiaceae*, *Comamonadaceae* (*Betaproteobacteria*), *Rhizobacteriaceae*, *Rhodospirillaceae* and *Acetobacteraceae* (*Alphaproteobacteria*). Biocontrol Gram-positive bacteria belong to the *Firmicutes* (genera *Bacillus*, *Pasteuria* and *Paenibacillus*) or the *Actinobacteria* (genera *Streptomyces*, *Rhodococcus*, *Cellulomonas*, *Kocuria*, *Actinoplanes* and *Nocardioides*). Most plant-protecting fungi are documented among the mitosporic *Ascomycetes*, e.g. non-pathogenic *Fusarium*, *Coniothyrium*, *Phoma*, *Arthrobotrys* and especially *Gliocladium* and *Trichoderma* (Howell 2003), as well as several arbuscular mycorrhizal fungi (the *Glomeromycota* genus *Glomus*). A smaller number of reports are available on biocontrol *Basidiomycetes* (e.g. binucleate *Rhizoctonia*) and oomycetes (particularly non-pathogenic *Pythium*). Nevertheless, knowledge on the biogeography, diversity and mode of action of non-*Pseudomonas* biocontrol microorganisms is often fragmented. In addition, there is rather limited information on their possible role in soil disease suppressiveness (Mazzola 2002; Borneman and Becker 2007; Janvier et al. 2007).

3.2 Modes of Action of Non-Pseudomonas Plant-Beneficial Microorganisms

3.2.1 Antibiosis

Antimicrobial secondary metabolites that can affect plant pathogens are produced by a wide range of non-*Pseudomonas* microorganisms from the *Proteobacteria*, *Firmicutes*, *Actinobacteria* and *Ascomycetes* (Table 1). Among *Gammaproteobacteria*,

Table 1 Some recent examples of fungal, oomycete and non-*Pseudomonas* bacterial strains that suppressed plant pathogens in pot and/or field experiments

Taxonomic affiliation of strain	Species	Strain	Pathosystem	Experimental conditions	Antimicrobials	Other mode of action	Reference
Bacteria							
Alphaproteobacteria							
Rhizobacteriaceae	*Agrobacterium vitis*	F2/5	*Agrobacterium tumefaciens* on grapevine	Greenhouse		Bacteriocin	Burr and Reid (1994)
Acetobacteraceae	*Gluconacetobacter diazotrophicus*	35–47	*Meloidogyne incognita* on cotton	Field		Ammonia and volatile fatty acids	Bansal et al. (2005)
Betaproteobacteria							
Burkholderiaceae	*Burkholderia cepacia*	BC11	*Rhizoctonia solani* damping-off of cotton	Gnotobiotic system	Lipopeptide AFC-BC11		Kang et al. (1998)
		5.5B	*Rhizoctonia solani* stem rot of poinsettia	Greenhouse	Pyrrolnitrin		Hwang and Benson (2002)
	Burkholderia ambifaria	BC-F	*Pythium ultimum* damping-off of cucumber and soybean	Pot experiment (soilless mix)		unknown	Li et al. (2002)
Comamonadaceae	*Comamonas acidovorans*	HF42	*Magnaporthe poae* summer patch of Kentucky bluegrass	Field		unknown	Thompson et al. (1998)
	Delftia tsuruhatensis	HR4	*Pyricularia oryzae* rice blast, *Xanthomonas oryzae* rice bacterial blight, *Rhizoctonia solani* rice sheath blight	Greenhouse		unknown	Han et al. (2005b)

Gammaproteobacteria							
Pseudomonadaceae	*Azotobacter armeniacus*	RC2	*Fusarium verticillioides* root rot of maize	Greenhouse	unknown	unknown	Cavaglieri et al. (2004)
Xanthomonadaceae	*Lysobacter enzymogenes*	C3	*Bipolaris sorokiniana* leaf spot of tall fescue	Greenhouse		ISR, lytic enzymes	Kilic-Ekici and Yuen (2003)
	Stenotrophomonas maltophilia	34 S1	*Magnaporthe poae* summer patch of Kentucky bluegrass	Pot experiment		Chitinase	Kobayashi et al. (1995, 2002)
		PD3533	*Ralstonia solanacearum* potato brown rot	Greenhouse		unknown	Messiha et al. (2007)
Enterobacteriaceae	*Enterobacter cloacae*	EcCT-501R3	*Pythium ultimum* on cotton seedlings	Pot experiment		Competition for seed exudates	van Dijk and Nelson (2000)
	Pantoea agglomerans	Eh252	*Erwinia amylovora* fire blight of pear	Orchand	mccEh252	unknown	Stockwell et al. (2002) and Anderson et al. (2004)
	Pantoea dispersa	SB1403	*Xanthomonas alibilineans* leaf scald disease of sugar cane	Pot experiment		Albicidin hydrolysis	Zhang and Birch (1997a, b)
	Serratia plymuthica	R1GC4	*Pythium ultimum* in cucumber	Pot experiment		ISR	Benhamou et al. (2000)

(continued)

Table 1 (continued)

Taxonomic affiliation of strain	Species	Strain	Pathosystem	Experimental conditions	Antimicrobials	Other mode of action	Reference
		A21-4	*Phytophthora capsici* blight of pepper	Greenhouse	Macrocyclic lactone A21-4		Shen et al. (2007)
		IC14	*Botrytis cinerea* gray mold and *Sclerotinia sclerotinum* white mold of cucumber	Greenhouse	Pyrrolnitrin	Enzymes, siderophores	Kamensky et al. (2003)
	Rahnella aquatilis	HX2	*Agrobacterium tumefaciens* in grapevine	3-year field experiment	unknown	unknown	Chen et al. (2007)
Firmicutes							
Paenibacillaceae	*Paenibacillus polymyxa*	18191	*Botrytis cinerea* grey mold of strawberry	Field	unknown	unknown	Helbig (2001)
		E681	*Fusarium oxysporum* and *Rhizoctonia solani* damping-off of sesame	Greenhouse and field	unknown	unknown	Ryu et al. (2006)
Bacillaceae	*Bacillus* sp.	Sunhua	*Streptomyces scabiei* potato scab	Pot experiment	Iturin A, macrolactin A		Han et al. (2005a)
		CRS7	*Botrytis cinerea* gray mold of chickenpea	Prophylactic foliar spray application in greenhouse		Chitinase	Kishore et al. (2005)
	Bacillus thuringiensis	COT1	*Pectobacterium carotovorum* potato soft rot	Gnotobiotic system		AHL-lactonase	Dong et al. (2004)
	Bacillus subtilis	RB14	*Rhizoctonia solani* damping-off of tomato	Pot experiment	Iturin A, surfactin		Asaka and Shoda (1996)

		BS 107	*Pectobacterium carotovorum* potato soft rot	Gnotobiotic system	unknown		Sharga and Lyon (1998)
		GBO3 (Kodiac)	*Fusarium solani* f. sp. *phaseoli* dry bean root rot	Field		unknown	Estevez de Jensen et al. (2002)
		CE1	*Fusarium verticil-lioides* root rot of maize	Greenhouse		unknown	Cavaglieri et al. (2005)
	Bacillus pumilus	SE34	*Phytophthora infestans* late blight of tomato	Greenhouse		ISR	Yan et al. (2002)
	Bacillus amyloliquefa-ciens	RC-2	*Colleotrichum dematidum* mulberry anthracose	Culture filtrate tested in greenhouse	Iturins		Yoshida et al. (2001) and Hiradate et al. (2002)
Alicyclobacillaceae	*Pasteuria penetrans*	P-20	*Meloidogyne arenaria* damage on peanut	Microplot field experiment		Parasitism	Chen et al. (1996)
Actinobacteria							
Micromonosporaceae	*Actinoplanes* sp.	25844	*Pythium ulimum* damping-off of table beets	Field		Parasitism	Khan et al. (1997)
Streptomycetaceae	*Streptomyces violaceusniger*	YCED-9	*Pythium ultimum* damping-off of lettuce	Greenhouse	Guanidylfungin A, nigericin, geldanamycin	β-1,3-glucanase, chitinase	Crawford et al. (1993) and Trejo-Estrada et al. (1998)

(continued)

Table 1 (continued)

Taxonomic affiliation of strain	Species	Strain	Pathosystem	Experimental conditions	Antimicrobials	Other mode of action	Reference
	Streptomyces lydicus	WYEC108	*Pythium ultimum* damping-off of pea	Greenhouse		Mycoparasitism	Crawford et al. (1993) and Yuan and Crawford (1995)
	Streptomyces sp.	CR-43	*Meloidogyne incognita* root galling of tomato, *Pratylenchus penetrans* black root rot of strawberry	Greenhouse and field		unknown	Dicklow et al. (1993)
		A15, A20, A22, STL	*Macrophomina phaseolina* charcoal stem rot of melon	Greenhouse	unknown	unknown	Etebarian (2006)
		AMG-P1	*Phytophthora infestans* tomato late blight	Greenhouse	Paromomycin		Lee et al. (2005)
		201	*Fusarial wilt* of *Brassicaceae*	Pot experiment	2-methylheptyl isonicotinate		Bordoloi et al. (2002)
		96 and 63	*Pratylenchus penetrans* in roots of alfalfa	Pot experiment		unknown	Samac and Kinkel (2001)
	Streptomyces diastochromogenes	PonSSII	*Streptomyces scabiei* potato scab	4-year field-pot experiment	unknown	Competition	Liu et al. (1995), Lorang et al. (1995), and Neeno-Eckwall et al. (2001)

	Streptomyces scabiei	PonR	*Streptomyces scabiei* potato scab	4-year field-pot experiment	unknown	Competition	Liu et al. (1995), Lorang et al. (1995), and Neeno-Eckwall et al. (2001)
		PonSSII, GS93-23, 15	*Phytophthora medicaginis* root rot of alfalfa	Field	unknown		Xiao et al. (2002)
		Di-944	*Rhizoctonia solani* damping-off of tomato	Greenhouse	unknown	unknown	Sabaratnam and Traquair (2002)
	Streptomyces argenteolus	EN60	*Gaeumanomyces graminis* var. *tritici* take-all of wheat	Field	unknown		Coombs et al. (2004)
	Streptomyces caviscabies	EN23, EN28, EN35	*Gaeumanomyces graminis var. tritici* take-all of wheat	Field	unknown		Coombs et al. (2004)
	Streptomyces galilaeus	EN4, EN39	*Gaeumanomyces graminis var. tritici* take-all of wheat	Field	unknown		Coombs et al. (2004)
Nocardioidaceae	*Nocardioides albus*	EN47	*Gaeumanomyces graminis var. tritici* take-all of wheat	Field	unknown		Coombs et al. (2004)

(continued)

Table 1 (continued)

Taxonomic affiliation of strain	Species	Strain	Pathosystem	Experimental conditions	Antimicrobials	Other mode of action	Reference
Fungi							
Ascomycetes	*Trichoderma harzianum*	T39	*Sphaerotheca fusca* powdery mildew on cucumber	Greenhouse		ISR	Elad et al. (1998)
		2413	*Phytophthora capsicii* root rot of pepper	Pot experiment and field		Mycoparasitism	Ezziyyani et al. (2007)
		T-203	Root galling of tomato caused by *Meloidogyne javanica*	Greenhouse		Protease	Sharon et al. (2001)
		T-203	*Pseudomonas syringae* pv. *lachrymans* in cucumber	Hydroponic system		Induced resistance	Yedidia et al. (2003)
	Trichoderma virens	Gv29-8	*Pseudomonas syringae* pv. *lachrymans* in cucumber	Hydroponic system		Induced resistance	Viterbo et al. (2007)
	Coniothyrium minitans	LRC 2137	*Sclerotinia sclerotiorum* alfalfa blossom blight	Field		Mycoparasitism	Li et al. (2005)
	Verticillium biguttatum	M73	*Rhizoctonia solani* sclerotia formation on potato	Field		Mycoparasitism?	Jager and Velvis (1986)
	Phoma sp.	GS8-1, GS8-2	*Colletotrichum orbiculare* in cucumber	Pot experiment (soilless mix)		ISR	Meera et al. (1995)
	Arthrobotrys oligospora	ORS 18692 S7, ORS 18692 S5	*Meloidogyne mayaguensis* on tomato	Pot experiment and field		Predation	Duponnois et al. (1995)

	Fusarium oxysporum	Fo47	Fusarium wilt of tomato	Hydroponic system, pot experiment (soilless mix)	Competition, ISR	Fuchs et al. (1997) and Larkin and Fravel (1999)
	Dactylella oviparasitica	50	*Heterodera schachtii* on beet	Greenhouse	Parasitism	Olatinwo et al. (2006)
Basidiomycetes	binucleate *Rhizoctonia*	P9023	*Rhizoctonia solani* stem rot in poinsettia	Pot experiment	ISR	Hwang and Benson (2003)
Chromista						
Oomycetes	*Pythium nunn*	P9023	Sweet orange and azalea root rots caused by different *Phytophthora* species	Pot experiment	Mycoparasitism	Fang and Tsao (1994)

Pantoea (previously *Enterobacter*) *agglomerans* may produce pyrrolnitrin (Chernin et al. 1996), *Serratia* pyrrolnitrin (Kamensky et al. 2003), prodigiosin (Kalbe et al. 1996), chlorinated macrolides (Shen et al. 2007) and surfactants (Roberts et al. 2007), *Stenotrophomonas* and *Lysobacter* the macrocyclic lactams xanthobaccins (Islam et al. 2005) and maltophilin (Jakobi et al. 1996; Li et al. 2008). Within the *Betaproteobacteria*, species from the *Burkholderia cepacia* complex are well known for synthesis of pyrrolnitrin (Cartwright et al. 1995; El-Banna and Winkelmann 1998), phenazines (Cartwright et al. 1995) and lipopeptide AFC-11 (Kang et al. 1998). Antimicrobials affecting phytopathogens are much less documented in the other proteobacterial subdivisions. In the *Alphaproteobacteria*, *Azospirillum brasilense* may release phenylacetic acid (Somers et al. 2005) and *Rhizobium* hydrogen cyanide (Antoun et al. 1998). Among the *Deltaproteobacteria*, *Myxococcus fulvus* may produce pyrrolnitrin (Gerth et al. 1982) and other myxobacteria (e.g. *Sorangium*, *Chondromyces*) a range of antimicrobials (Reichenbach 2001).

The *Firmicutes* produce a variety of antimicrobials that can affect phytopathogens, particularly non-ribosomally synthesized peptides and lipopeptides (Donadio et al. 2007). Thus, *Paenibacillus* may produce polymyxins, fusaricidins, gasaverin and saltavalin (Pichard et al. 1995; Kajimura and Kaneda 1996), and *Bacillus* several amphiphilic cyclic lipopeptides from the iturin, fengycin and surfactin families (Asaka and Shoda 1996; Touré et al. 2004), the macrolide macrolactin A (Han et al. 2005a), and (noticeably in the well-studied biocontrol strain *B. cereus* UW85) the aminopolyol zwittermycin A (Silo-Suh et al. 1994) and kanosamine (Milner et al. 1996). *Actinobacteria* are well known for production of a very wide range of antimicrobial metabolites, and many of them are used as antibiotics in medical and veterinary contexts. However, several antimicrobials from the *Actinobacteria* (generally not used against animal or human pathogens) are active against plant pathogens. In *Streptomyces*, they include the polyketide geldanamycin, the polyether nigericin, the polyene-like compounds guanidylfungin A (all three documented in the biocontrol strain *Streptomyces violaceusniger* YCED-9; Trejo-Estrada et al. 1998) and faerifungin (in *Streptomyces griseus*; Smith et al. 1990), the aminoglycoside paromomycin (Lee et al. 2005), the macrolide oligomycin A (Kim et al. 1999), as well as 1-propanone,1-(4-chlorophenyl) and 2-methylheptyl isonicotinate (Bordoloi et al. 2002; Ezziyyani et al. 2007).

Among *Ascomycetes*, antimicrobials relevant for plant protection are best documented in *Trichoderma* and include gliovirin (Stipanovic and Howell 1982), gliotoxin (Lumsden et al. 1992) and (lipo)peptaibol peptides (Szekeres et al. 2005; Xiao-Yan et al. 2006). Terreic acid and butyrolactons are reported in *Aspergillus terreus* (Cazar et al. 2005).

Although a wide range of phytopathogen-inhibiting metabolites are known in many non-*Pseudomonas* microorganisms, the contribution of a given compound to plant protection is often not established, especially for biocontrol strains producing several of them. The importance of antibiosis in biological control was evidenced by gene deletion (and in some cases, gene complementation) for iturin A produced by *B. subtilis* (biocontrol of *Rhizoctonia solani*-mediated damping-off of cotton; Asaka and Shoda 1996), zwittermycin A produced by *B. cereus* (biocontrol of

Phytophthora medicaginins-mediated damping-off of alfalfa; Silo-Suh et al. 1994), pyrrolnitrin (biocontrol of Rhizoctonia stem rot of poinsettia; Hwang and Benson 2002) and AFC-BC11 (biocontrol of *Rhizoctonia solani*-mediated damping-off of tomato; Kang et al. 1998) produced by *B. cepacia*, and Eh252 produced by *Pantoea agglomerans* (biocontrol of *Erwinia amylovora*-mediated fire blight of pear; Stockwell et al. 2002). The mode of action is documented for only some of these antimicrobial metabolites. Lipopeptides (e.g. iturins, fengycins and surfactins from *Bacillus*) act on cell membranes as surfactants (Deleu et al. 1999), lipopeptaibols (produced by *Trichoderma*) form tunnels in cytoplasmic membrane (Cosette et al. 1999), nigericin acts on membrane as an ionophore exchanging K^+ for H^+ (Bergen and Bates 1984), aminoglycosides (produced by *Streptomyces* spp.) affect prokaryotic and mitochondrial translation (Recht et al. 1999), while oligomycin inhibits mitochondrial ATPase (John and Nagley 1986).

3.2.2 Other Biocontrol Mechanisms

As in the case of *Pseudomonas*, antagonism in non-*Pseudomonas* biocontrol agents is not restricted to production of antimicrobial metabolites, as it can also be mediated by lytic enzymes that act against pathogen cell wall or virulence factors (enzymes and signal molecules). A variety of cell wall-degrading chitinases, glucanases, proteases and lyzozymes are produced by plant-protecting bacteria, such as in the *Proteobacteria Lysobacter* (Palumbo et al. 2005), *Pantoea agglomerans* (Chernin et al. 1995), *Serratia* (Kalbe et al. 1996) and *Gluconacetobacter diazotrophicus* (Pinon et al. 2002), the *Firmicutes Bacillus* (Leelasuphakul et al. 2006), *Brevibacillus* (Huang et al. 2005) and *Paenibacillus* (Budi et al. 2000), the *Actinobacteria Streptomyces* (Trejo-Estrada et al. 1998), as well as several fungi such as *Trichoderma* biocontrol strains (Metcalf and Wilson 2001; Djonovic et al. 2007). In contrast to *Pseudomonas*, production of cell wall-degrading extracellular lytic enzymes seems to be one of the major modes of action of many non-*Pseudomonas* biocontrol strains against phytopathogens. Their chitinases act on several fungal (Chernin et al. 1995; Metcalf and Wilson 2001) and nematode phytoparasites (Cronin et al. 1997a; Kishore et al. 2005), their β-1,3- and β-1,6-glucanases on the oomycete *Pythium ultimum* (Palumbo et al. 2005; Djonovic et al. 2007), their lysozyme-like enzymes on the *Proteobacteria Xanthomonas albilineans* (Pinon et al. 2002), and their proteases on phytoparasitic nematodes (Sharon et al. 2001; Huang et al. 2005; Lian et al. 2007), oomycetes (Dunne et al. 1997) and fungi (De Marco and Felix 2002).

Certain enzymes operate instead on the pathogen enzymes or toxins, resulting in lower disease severity (Elad and Kapat 1999; Zhang and Birch 1997a, b), although this is mainly documented for shoot pathogens. Others interfere with pathogen signalization, such as the lactonase AiiA from *Bacillus* sp. 240B1, which cleaves *N*-acylhomoserine lactone quorum sensing signals of *Pectobacterium carotovorum*, thus decreasing production of extracellular enzymes by the pathogen and the extent of soft rot disease on potato and other plants (Dong et al. 2000). *N*-Acylhomoserine lactone degradation has been found in other soil bacteria (Uroz et al. 2005; Yoon et al. 2006; Medina-Martinez et al. 2007) and may play a role in biocontrol of bacterial phytopathogens (Dong et al. 2004).

Like their *Pseudomonas* counterparts, non-*Pseudomonas* biocontrol agents compete with plant pathogens for space and nutrients. Competition for root colonization sites is documented for non-pathogenic *F. oxysporum* (against pathogenic *F. oxysporum*; Eparvier and Alabouvette 1994) and arbuscular mycorrhizal fungi (against fungal, oomycete and nematode pathogens; Azcón-Aguilar and Barea 1996). Competition for carbon and nitrogen usually concerns biocontrol microorganisms closely related to the pathogen e.g. non-pathogenic *F. oxysporum* (for suppression of Fusarium wilt; Lemanceau et al. 1993) or *Streptomyces* (for suppression of potato scab; Neeno-Eckwall et al. 2001), but sometimes also microorganisms that are unrelated e.g. the fungi *Trichoderma* (Howell 2003) and *Collimonas* (Kamilova et al. 2007), as well as *Enterobacter cloacae* (van Dijk and Nelson 1998, 2000). Siderophores were found in several biocontrol strains from e.g. *Enterobacter* (Loper et al. 1993), *Serratia* (Kamensky et al. 2003) and *Burkholderia* (Bevivino et al. 1998), but competition with phytopathogen for iron has not been evidenced.

Certain non-*Pseudomonas* biocontrol agents can act on phytopathogens via hyperparasitism (Fig. 2), a mode of action not documented with *Pseudomonas* counterparts. The *Firmicute Pasteuria penetrans* is an obligate (hyper)parasite of root-knot nematodes (Siddiqui and Mahmood 1999). It occurs worldwide and displays a wide host range (Siddiqui and Mahmood 1999), but individual *P. penetrans* isolates seem to be mainly adapted to one or a few nematode species (Dutky and Sayre 1978) or even nematode strains (Duponnois et al. 2000). Among hyperparasitic fungi, the mitosporic *Ascomycete Dactylella oviparasitica* may survive saprophytically and sporulate in soil (Stirling and Mankau 1979), and it parasites fourth stage juveniles, females, and eggs of different nematodes, including *Heterodera schachtii* (Borneman and Becker 2007). A related phenomenon occurs with predation of phytoparasitic *Meloidogyne* spp. by the fungus *Arthrobotrys oligospora* (Duponnois et al. 1995). Mycoparasitic *Trichoderma* penetrate and disrupt the mycelium of phytopathogenic fungi and oomycetes (Chet et al. 1981; Gupta et al. 1999) whereas *Acremonium* targets oospores of *Pythium ultimum* (Khan et al. 1997). Mycoparastism was also reported in oomycetes *Pythium oligandrum* and *Pythium nunn*, which may penetrate mycelia of plant-pathogenic *Pythium* species as well as of certain fungi (Lifshitz et al. 1984; Berry et al. 1993).

Many non-*Pseudomonas* strains may enhance plant health by acting directly on plant physiology and growth (Fig. 2). The induction of resistance in the plant is documented in the case of bacteria, e.g. *Bacillus pumilus* (Yan et al. 2002) and *Serratia* (Press et al. 1997; Benhamou et al. 2000), and fungi, e.g. *Trichoderma* (Yedidia et al. 2000), *Phoma* (Meera et al. 1995), *F. oxysporum* (Fuchs et al. 1997) and binucleate *Rhizoctonia* (Hwang and Benson 2003). Only few studies, however, focused on molecular mechanisms involved (inducers implicated, possible involvement of salicylate/jasmonate/ethylene, pathogenesis-related protein production in plant), so the knowledge about induced resistance mediated by non-*Pseudomonas* microorganisms remains fragmented. In *Trichoderma virens*, an 18-mer peptaibol was shown to trigger ISR (Viterbo et al. 2007). *T. harzianum* induced resistance in cucumber, which was accompanied by production of typical pathogenesis-related (PR) proteins such as chitinases and ß-1,3-glucanases (Yedidia et al. 2000). ISR in cucumber, mediated by *S. marcescens*, is independent from the salicylic acid pathway (Press et al. 1997).

Production of phytohormones corresponding to cytokinins, gibberellins and auxins has been shown in a large range of plant-beneficial *Proteobacteria*, such as *Azospirillum* (Dobbelaere et al. 1999), *Phyllobacterium* (Larcher et al. 2003), and *Herbaspirillum* (Bastián et al. 1998), as well as *Firmicutes* such as *Paenibacillus* (Timmusk et al. 1999) and *Bacillus* (Gutierrez-Manero et al. 2001). This can result in enhanced plant development and growth (Dobbelaere et al. 1999; Larcher et al. 2003). ACC deaminase activity has been reported in various plant-beneficial strains from the *Alphaproteobacteria* (*Azospirillum*, *Mesorhizobium*, *Bradyrhizobium*, etc.), *Betaproteobacteria* (*Burkholderia*, etc.) and *Gammaproteobacteria* (*Enterobacter*, etc.) (Shah et al. 1998; Glick 2005; Blaha et al. 2006), but evidence for a role of this trait in biological control is lacking in the case of non-*Pseudomonas* microorganisms.

Various plant growth-promoting properties, such as symbiotic (by nodulating bacteria *Rhizobium* and *Frankia*; Mylona et al. 1995) and associative nitrogen fixation (by endophytic or rhizosphere bacteria from *Alpha*-, *Beta*-, *Gammaproteobacteria*, *Firmicutes* and *Cyanobacteria*; Ghosh and Saha 1993; Kennedy et al. 2004), nitrogen mineralization (Griffiths and Robinson 1992), phosphorus solubilization (by several *Proteobacteria*, *Firmicutes*, and *Actinobacteria*, as well as *Trichoderma* and *Aspergillus*; Banik and Dey 1982; Altomare et al. 1999; Rodriguez and Fraga 1999) and enhanced mineral uptake (by arbuscular mycorrhizal fungi, George et al. 1995) are extensively documented. These properties are considered as important for plant vigor and health, with the potential to help plants to overcome disease, but direct experimental evidence is often missing (Bally and Elmerich 2007). However, several plant growth-promoting microorganisms display biocontrol effects, for example *Gluconacetobacter diazotrophicus* (against *Meloidogyne incognita* in cotton; Bansal et al. 2005), *Azospirillum brasilense* (against *Rhizoctonia* spp. in *Prunus*; Russo et al. 2008), *Burkholderia cepacia* (against *Fusarium* spp. in maize; Bevivino et al. 1998) or *Delftia tsuruhatensis* (against rice blast, rice bacterial blight and rice sheath; Han et al. 2005b), but their biocontrol properties have been generally less studied than their plant growth-promoting traits.

3.2.3 Conclusion

The distribution of plant-protecting traits in non-*Pseudomonas* microorganisms is rather contrasted, regardless of whether bacteria or fungi are considered. Some of these traits are rather widespread, such as the synthesis of particular types of lytic enzymes involved in antagonism, or bacterial constituents triggering induced resistance (Neilands 1995; van Loon 2007). Other traits are restricted to a limited number of genera, such as the ability to produce pyrrolnitrin in *Proteobacteria* including certain pseudomonads (de Souza and Raaijmakers 2003) or to certain species within a particular genus, as illustrated by the case of the antifungal metabolite zwittermycin A in *Bacillus cereus* (Stabb et al. 1994). In many cases, however, plant-beneficial properties are not found in all members of the species but rather in selected strains or groups of strains (Berg 2000).

As for pseudomonads, certain non-*Pseudomonas* species are comprised of both biocontrol strains and pathogens, e.g. *F. oxysporum* (Fravel et al. 2003; Bolwerk et al. 2005) and *S. scabiei* (Liu et al. 1995). In addition, some traits contributing to plant-beneficial effects can occur both in biocontrol strains and in deleterious or pathogenic strains. This is for instance the case for ACC deaminase activity (Blaha et al. 2006), auxin production (Spaepen et al. 2007) and synthesis of hydrogen cyanide (Schippers et al. 1990). The unexpected distribution of several plant-beneficial traits is sometimes related to the fact that the corresponding genes may have been subjected to horizontal gene transfer (de Souza and Raaijmakers 2003; Hopwood 2003; Hontzeas et al. 2005; Blaha et al. 2006).

3.3 Suppressive Soils Where Plant Protection Is Mainly Attributed to Non-Pseudomonas Microorganisms

Plant protection by non-*Pseudomonas* microorganisms is documented for several types of suppressive soils. These microorganisms include bacteria (mostly *Firmicutes* and *Actinobacteria*), fungi and nematodes. In contrast, disease suppressiveness due to bacteriophages has not been evidenced so far. Plant protection effects often stem from negative interactions with the pathogen, which are implemented by avirulent strains of the same species (e.g. soils suppressive to Fusarium wilt) and/or genus (e.g. soils suppressive to potato scab), or hyperparasitic microorganisms (for certain soils suppressive to nematodes). Some of the best understood cases are presented below.

3.3.1 Non-*Pseudomonas* Microorganisms and Potato Scab Suppressive Soils

While potato scab is caused by *Streptomyces scabiei* strains that produce the phytotoxin thaxtomin (Kinkel et al. 1998), potato scab suppressiveness, which is induced by potato monoculture, is attributed to non-pathogenic strains from *Streptomyces scabiei*, *Streptomyces diastatochromogenes* or *Streptomyces albogriseolus* (Liu et al. 1995; Lorang et al. 1995). The pathogenic and non-pathogenic strains are genetically close. They could not be separated by repetitive intergenic DNA fingerprinting (rep-PCR; Sadowsky et al. 1996), but were distinguished based on fatty acids profiling (Kinkel et al. 1998). The introduction of two biocontrol *Streptomyces* strains into infested soil negatively affected the population size of pathogenic strains, with no impact on the whole microbial community (as assessed with PLFA; Bowers et al. 1996). This correlated with a reduction of potato scab incidence.

Experiments with spontaneous non-inhibitory mutants of *Streptomyces* biocontrol strains and spontaneous pathogen mutants resistant to at least one antimicrobial produced by the biocontrol strains revealed that both antibiosis and competition contributed to suppression of pathogenic strains (Schottel et al. 2001; Neeno-Eckwall et al. 2001). The composition of the *Streptomyces* soil subcommunity can be modified according to the type of organic soil amendment, suggesting that the biocontrol potential of suppressive indigenous strains could be enhanced via appropriate choice of farming practices (Schlatter et al. 2009). So far, the assessment of potato scab suppressive soils has focused on biocontrol *Streptomyces* strains, and the potential role of non-*Streptomyces* microorganisms (including *Pseudomonas*) in these soils has been neglected.

3.3.2 Non-*Pseudomonas* Microorganisms and Fusarium Wilt Suppressive Soils

Soil suppressiveness to Fusarium wilt implicates non-pathogenic strains of *F. oxysporum*. In soils from southern France naturally suppressive to the disease, competition was identified as an important mode of action of non-pathogenic *F. oxysporum* against pathogenic *F. oxysporum* strains (Alabouvette 1986). The establishment of a *Pueraria* cover crop in an oil palm grove increased the size of the *F. oxysporum* population in soil (without changing its genetic structure) and the level of soil suppressiveness to Fusarium wilt of oil palm, strengthening the competition hypothesis (Abadie et al. 1998). In the case of Fusarium wilt suppressiveness induced by monoculture, which is documented for certain watermelon cultivars, protection by non-pathogenic *F. oxysporum* strains is attributed to induced resistance in host plant (Larkin et al. 1996). Indeed, the possibility of induced resistance was shown for a non-pathogenic *F. oxysporum* strain using tomato in split-root and other systems (Fuchs et al. 1997). The dose of non-pathogenic strain necessary for tomato protection differed according to its main mode of action, i.e. high for strains effective at competing with the pathogen and low for strains whose main mode of action was induced resistance (Larkin and Fravel 1999).

So far, non-pathogenic *F. oxysporum* strains cannot be distinguished from pathogenic ones unless plant inoculation tests are performed, which complicates monitoring of their dynamics in soil. There is a high intraspecies diversity in *F. oxysporum*, but pathogenic strains did not form a separated clade based on molecular phylogeny (Baayen et al. 2000). High diversity was also found within natural populations of *F. oxysporum* (Steinberg et al. 1997). Indigenous field populations of *F. oxysporum* remained stable for years and differed across fields of different geographical locations in France (Edel et al. 2001), which is compatible with a functional implication of these microorganisms in long-standing disease suppressiveness.

Interestingly, antagonistic properties of certain non-pathogenic *F. oxysporum* strains may depend on their bacterial ectosymbionts (e.g. *Serratia, Bacillus* and *Achromobacter*), which are attached to the hyphae. For instance, *F. oxysporum* strain MSA 35 (isolated from an Italian suppressive soil) lost its antagonistic properties and even became pathogenic when it was cured of its ectosymbionts (Minerdi et al. 2008). The original strain produced volatile compounds that repressed the expression of virulence genes in the pathogenic strain tested while the cured strain did not, showing a new potential long-distance mechanism of *F. oxysporum* antagonism mediated by volatile compounds (Minerdi et al. 2009).

The importance of certain soil abiotic properties, e.g. smectite clay, soluble sodium, sodium adsorption ratio and soil aggregate stability, has been shown for several Fusarium wilt suppressive soils (Stotzky and Martin 1963; Höper et al. 1995; Domínguez et al. 2001, 2003). It is likely that these properties may influence antagonistic populations and gene expression, but this has not been clearly shown so far.

3.3.3 Non-*Pseudomonas* Microorganisms and Rhizoctonia Suppressive Soils

Though a non-pathogenic *Rhizoctonia* strain could be used for biocontrol of Rhizoctonia rot in a pot experiment (Hwang and Benson 2003), the potential role of indigenous non-pathogenic *Rhizoctonia* spp. in Rhizoctonia suppressive soils is unknown. In the case of Rhizoctonia damping-off of radish, soil suppressiveness was induced by repeated culture of radish and was attributed to *T. harzianum*. Hyperparasitism was suggested as the mode of action by which *T. harzianum* suppressed *R. solani* (Chet et al. 1981). In addition, suppressiveness to Rhizoctonia potato rot correlated with the extent of *Bacillus* genetic diversity, raising the possibility that these bacteria could also play a part (Garbeva et al. 2006), while on cauliflower suppressiveness correlated with the abundance of *Lysobacter* (Postma et al. 2010).

3.3.4 Non-*Pseudomonas* Microorganisms and Soils Suppressive to Endoparasitic Nematodes

Soil suppressiveness towards the endoparasitic nematodes *Heterodera schachtii* or *Meloidogyne* spp. was shown to be associated with nematode-parasitic microorganisms. In the case of soils suppressive to the beet cyst nematode *H. schachtii* (which may be induced by monoculture), suppressiveness could be transferred to a conducive soil using solely nematode cysts isolated from a suppressive soil (Westphal and Becker 1999, 2000). rRNA gene analysis of microorganisms associated with these cysts identified *Rhizobium*-like bacteria and the fungus *Dactylella oviparasitica*, which were consistently associated with highly-suppressive soils (Yin et al. 2003a, b). *D. oviparasitica* can parasite eggs of *H. schachtii*, and one *D. oviparasitica* strain protected Swiss chard against the nematode when inoculated to conducive soil (Olatinwo et al. 2006). Other microorganisms that can act on *H. schachtii*, e.g. *Bacillus megaterium* and *F. oxysporum*, were isolated from nematode cysts or beet roots in suppressive soils, but their importance in suppressiveness is debated (Jorgenson 1970; Neipp and Becker 1999; Yin et al. 2003a).

Soil suppressiveness towards root-knot-causing *Meloidogyne* spp. is induced by monoculture, and is associated with hyperparasitim by *Pasteuria penetrans*.

The *Firmicute P. penetrans* is an obligate nematode parasite. Its endospores adhere to second-stage juveniles and germinate, the germ tube penetrating the cuticle (Sayre and Wergin 1977), and it is also found in mature females (Weibelzahl-Fulton et al. 1996). *P. penetrans* sporulates within the nematode and prevents its reproduction (Sayre and Wergin 1977).

3.3.5 Non-*Pseudomonas* Microorganisms and Soils Suppressive to Ectoparasitic Nematodes

In the case of sugarcane monoculture soils suppressive to ectoparasitic nematodes, such as *Xiphinema elongatum* and *Paratrichodorus minor*, no hyperparasite has been identified so far. Rather, soil suppressiveness was associated with a higher soil content in weak ectoparasitic nematodes, especially *Helicotylenchus dihystera* (Rimé et al. 2003), whose competitive interactions with the more aggressive ectonematodes limit the ability of the latter to parasite roots (Spaull and Cadet 1990; Mateille et al. 2008). In addition, sandy soils suppressive and conducive to ectoparasitic nematodes from the same South African region differed in sugarcane rhizobacterial community structure (Rimé et al. 2003), indicating a possible beneficial role for root bacteria. Interestingly, *Burkholderia tropica* correlated positively with the less pathogenic species *Pratylenchus zeae* (endoparasite) and *H. dihystera*, and negatively with aggressive *X. elongatum*, and it was hypothesized that the rhizobacterium could be one factor influencing the composition of the ectonematode community towards a lower prevalence of aggressive species (Omarjee et al. 2008).

3.3.6 Conclusion

Several non-*Pseudomonas* microorganisms play a major role in different suppressive soils, the most studied ones being the *Firmicute Pasteuria*, the *Actinobacteria Streptomyces*, and the mitosporic *Ascomycetes Fusarium*, *Dactyllela* and (to a lesser extent) *Trichoderma*. A substantial amount of information is available on their possible mode(s) of action, e.g. antibiosis, competition, induced resistance or parasitism, but relatively few detailed studies have targeted the implementation of these modes of action in suppressive soils. In comparison with *Pseudomonas*, less is known about root colonization by non-*Pseudomonas* biocontrol strains, their population levels in soil necessary to achieve suppressiveness, and their diversity within and between suppressive soils. Furthermore, it is striking to note that most information on the role of non-*Pseudomonas* microorganisms originates from suppressive soils for which the ecology and role of *Pseudomonas* biocontrol strains is poorly documented or unknown. Similarly, it appears that the potential role of non-*Pseudomonas* microorganisms remains neglected in suppressive soils where plant protection by fluorescent pseudomonads has been extensively studied (Lemanceau et al. 2006), e.g. take-all decline soils and soils suppressive to *T. basicola*-mediated black root rot. This limits our ability to compare and contrast the relative importance of *Pseudomonas* versus non-*Pseudomonas* microorganisms in soil suppressiveness.

4 Interactions Between *Pseudomonas* and Non-*Pseudomonas* Microorganisms

4.1 Interactions Between Pseudomonas and Non-Pseudomonas Microorganisms from Biocontrol Studies

Pseudomonas and non-*Pseudomonas* biocontrol microorganisms are present in the same rhizosphere environment, where they have coevolved with the plant, its guild of phytoparasites, and perhaps also with one another. On this basis, it is likely that multiple rhizosphere interactions take place between *Pseudomonas* and non-*Pseudomonas* biocontrol microorganisms (Couillerot et al. 2009). Some of these interactions may be indirect, as plant-associated microorganisms may influence plant development and behaviour, which in turn will determine ecological conditions for the other plant-beneficial populations in the rhizosphere (Fig. 2). This is documented for *Pseudomonas* strains and/or metabolites (especially DAPG), in terms of root system architecture and plant growth (Patten and Glick 2002; Brazelton et al. 2008), plant physiology (Iavicoli et al. 2003) and root exudation (Phillips et al. 2004). Similar effects are also known with non-*Pseudomonas* plant-beneficial microorganisms (Heulin et al. 1987; Dobbelaere et al. 1999).

The direct interactions between *Pseudomonas* and non-*Pseudomonas* plant-beneficial microorganisms may range from antagonism and competition to cooperation (Fig. 2; Couillerot et al. 2009). On one hand, rhizosphere incompatibility was shown for some *Pseudomonas* and non-*Pseudomonas* strains (e.g. *Bradyrhizobium*; Siddiqui and Ehteshamul-Haque 2001). In addition, various root bacteria were inhibited *in vitro* by the *Pseudomonas* metabolites DAPG and/or pyoluteorin (Natsch et al. 1998). Certain pseudomonads may inhibit *T. harzianum* (de Boer et al. 2007), a fungal species playing an important role in disease suppression, and compound(s) produced by biocontrol *P. protegens* CHA0 reduced expression of chitinase genes *nag1* and *ech42* in *T. atroviride* (Lutz et al. 2004). Similarly, *P. fluorescens* A506 produced a protease that cleaved an antimicrobial metabolite of *P. agglomerans* Eh252 involved in *Erwinia amylovora* antagonism (Anderson et al. 2004), but it is not known whether this metabolite is also active against root pathogens.

On the other hand, positive effects may also take place. *P. fluorescens* F113 can stimulate mycelial growth of the symbiotic fungus *Glomus mosseae* and mycorrhization of tomato roots (Barea et al. 1998). Combining *Pseudomonas* and non-*Pseudomonas* microorganisms with complementary modes of action lead often to enhanced biological control (Mazzola 2002), as shown using wild-type strains and mutants. This was for instance the case for proteolytic *Stenotrophomonas maltophilia* W81 and DAPG-producing *P. fluorescens* F113 against *Pythium*-mediated damping-off of sugarbeet (Dunne et al. 1997), as well as non-pathogenic *F. oxysporum* Fo47 and iron-competing *Pseudomonas putida* WCS358 against Fusarium wilt of flax (Duijff et al. 1993), although combining *Pseudomonas* and non-pathogenic

Fusarium did not lead to improved tomato protection from Fusarium wilt (Larkin and Fravel 1998). Co-inoculation of *Pseudomonas alcaligenes* with *Glomus intraradices* and *Bacillus pumilus* improved control of a chickpea root-rot disease complex caused by the root-knot nematode *Meloidogyne incognita* and the root-rot fungus *Macrophomina phaseolina* (Sayeed and Siddiqui 2008), but the biocontrol mechanisms involved were not determined. DAPG$^+$ *P. protegens* CHA0 and *Trichoderma atroviride* P1 displayed enhanced expression of respectively DAPG biosynthetic gene *phlA* (in presence of P1 culture filtrate) and chitinase gene *nag1* (in presence of DAPG) (Lutz et al. 2004), illustrating the potential of molecular interactions between *Pseudomonas* and non-*Pseudomonas* biocontrol microorganisms. The importance of such interactions is also illustrated by the observation that certain soil bacteria (including one *Pseudomonas* strain related to *P. koreensis*) unable alone to interfere with growth of fungal phytopathogens did inhibit the latter when they were used in combination (presumably via antibiosis), which also means that their potential role in soil suppressiveness could have been easily overlooked in previous investigations (de Boer et al. 2007).

4.2 Interactions Between Pseudomonas and Non-Pseudomonas Microorganisms in Suppressive Soils

The significance of microbial interactions between *Pseudomonas* and non-*Pseudomonas* microorganisms in suppressive soils is very poorly documented. The only clear example of such interaction is from a French soil suppressive to Fusarium wilt. Here, plant protection implicated both non-pathogenic *F. oxysporum* and fluorescent *Pseudomonas* spp., and competition between non-pathogenic and pathogenic *F. oxysporum* strains was enhanced following iron sequestration effects mediated by *Pseudomonas* siderophores (Lemanceau and Alabouvette 1991). The remaining studies focused either on *Pseudomonas* or non-*Pseudomonas,* or assessed both but without considering the significance of their interactions for disease suppression (reviewed below in Sects. 4.3 and 4.4).

4.3 Importance of Pseudomonas in Suppressive Soils Where the Suppression Is Attributed Mainly to Non-Pseudomonas Microorganisms

4.3.1 *Pseudomonas* and Rhizoctonia Suppressive Soils

Suppression of *Rhizoctonia* and *Pythium* damage to apple in orchard replant soils was induced by repeated culture of wheat, which also changed the population structure of fluorescent pseudomonads towards a higher prevalence of *Pseudomonas putida* (Mazzola and Gu 2000). In addition, a correlation was found between the ability of wheat cultivars to recruit antagonistic pseudomonads and the efficacy of replant disease control (Mazzola 2002). These results pointed to fluorescent pseudomonads as a likely factor accounting for (at least part of) disease suppressiveness. Similarly, suppressiveness to *Rhizoctonia solani* AG3-mediated potato rot might implicate antagonistic *Pseudomonas* populations (Garbeva et al. 2006). Antagonistic pseudomonads were also recovered from soils suppressive to *Rhizoctonia solani* AG 2-1 in cauliflower, but their abundance (in contrast to that of antagonistic *Lysobacter*) did not correlate with soil suppressiveness level (Postma et al. 2010).

4.3.2 *Pseudomonas* and Fusarium Wilt Suppressive Soils

Fluorescent pseudomonads have been extensively considered in relation to Fusarium wilt control, especially in California (Scher and Baker 1982) and southern France (Alabouvette 1986), and competition for iron (Scher and Baker 1982) and phenazine production (Mazurier et al. 2009) were identified as mechanisms by which these bacteria suppressed the disease in these soils. ISR is also an important mode of action of biocontrol pseudomonads against *F. oxysporum* (Lemanceau and Alabouvette 1991, 1993), but evidence for a role of ISR in soil suppressiveness is lacking. On greenhouse tomato, *Pseudomonas* isolates were not as effective as non-pathogenic isolates of *F. oxysporum* and *F. solani* collected from a Fusarium wilt-suppressive soil (Larkin and Fravel 1998).

Antagonistic DAPG$^+$ pseudomonads have been isolated from Fusarium wilt suppressive soils from different continents (Wang et al. 2001), and they reached significant population levels on pea roots in a pea-monoculture soil suppressive to Fusarium wilt in Washington State (Landa et al. 2002). The analogy with the case of monoculture-induced take-all decline of wheat suggests that a similar phenomenon, resulting in pea protection by DAPG$^+$ pseudomonads, might take place in this Fusarium wilt suppressive soil. At another location, culturable fluorescent pseudomonads were recovered in higher numbers from the watermelon rhizosphere after monoculture induction of Fusarium wilt suppressiveness, but only non-pathogenic *F. oxysporum* strains seemed able to play a major role in this case (Larkin et al. 1996).

4.3.3 *Pseudomonas* and Soils Suppressive to Ectoparasitic Nematodes

In South African sandy soils suppressive or conducive to damage caused by ectoparasitic nematodes, fluorescent pseudomonads were recovered at levels below 10^4 CFU/g rhizosphere soil (Rimé et al. 2003). Therefore, it is very unlikely that these bacteria could play a significant role in the suppressiveness of these soils. The production of DAPG can affect phytoparasitic *Globodera* (Cronin et al. 1997c) but DAPG$^+$ pseudomonads have not been considered so far in soils suppressive to such nematodes.

4.4 Importance of Non-Pseudomonas Microorganisms in Suppressive Soils Where the Suppression Is Attributed Mainly to Pseudomonas

4.4.1 Non-*Pseudomonas* Microorganisms and Take-All Suppressive Soils

In take-all decline soils, the potential role of non-*Pseudomonas* microorganisms has been considered, and a rather wide range of bacteria and fungi have been proposed as being implicated in suppressiveness (reviewed by Weller et al. 2002). Certain studies pointed at a possible role of *Trichoderma*, especially *T. koningii*, in take-all suppressive soils (Simon and Sivasithamparam 1989; Duffy et al. 1997). A *T. koningii* strain affecting *G. graminis* var. *tritici* probably via mycoparasitism and antibiosis was isolated from a take-all suppressive soil in Australia (Simon and Sivasithamparam 1989), but little was done since to assess the ecological role of *T. koningii* in soil suppressiveness to take-all. Similarly, a fungal isolate from *Phialophora* originating from a take-all suppressive field protected wheat in conducive soil (Mathre et al. 1998), but its significance in take-all decline remains unknown.

In western France, the bacterial rhizosphere community of field-grown wheat at the start of wheat monoculture, during take-all outbreak and after take-all decline was assessed using a 16S rRNA gene-based taxonomic microarray (Sanguin et al. 2009). Changes in rhizobacterial community composition were evidenced during disease, as found elsewhere with *rrs* T-RFLP (McSpadden Gardener and Weller 2001). Significant differences were also observed when comparing the disease and the suppressive stages. Indeed, a wide range of bacterial taxa were less prevalent, i.e. *Bacteroidetes*, *Flavobacteria*, *Verrucomicrobia* and *Actinobacteria*, or more prevalent, i.e. *Planctomycetes*, *Nitrospira*, *Acidobacteria*, *Chloroflexi*, *Alphaproteobacteria* (including *Azospirillum*) and *Betaproteobacteria*, in the suppressive stage than in the disease stage. Similarly, differences in rhizobacterial community structure were observed by T-RFLP during the decline of barley take-all (Schreiner et al. 2010). Whether these taxa actually contribute to suppressiveness remains to be shown, but it is interesting to note that at least some of them are known to contain strains that display biocontrol or plant growth-promoting properties.

4.4.2 Non-*Pseudomonas* Microorganisms and Black Root Rot Suppressive Soils

For Swiss soils of Morens, in which black root rot is controlled, a possible functional role of non-pathogenic *T. basicola* strains in suppressiveness was discounted in early work (Stutz et al. 1986). However, the hypothesis of Ramette et al. (2006) that suppressiveness could also result from the contribution of non-*Pseudomonas* microorganisms was strengthened by 16S rRNA gene-based microarray observations that differences in rhizobacterial community composition were rather extensive in terms of abundance of a wide range of bacterial taxa between suppressive and conducive soils (Kyselková et al. 2009). Taxa associated with suppressiveness included *Alphaproteobacteria* (*Sphingomonadaceae*, *Gluconacetobacter* and *Azospirillum*), *Betaproteobacteria* (*Nitrosospira*/*Nitrosovibrio*, *Comamonas*, various *Burkholderia* species and *Herbaspirillum seropedicae*), *Gammaproteobacteria* (e.g. *Xanthomonadaceae* and *Stenotrophomonas*/*Xanthomonas*), *Deltaproteobacteria* (*Polyangiaceae*), *Actinobacteria* (*Agromyces* and *Collinsella*), *Firmicutes* (*Paenibacillus alginolyticus*), *Cyanobacteria* (*Lyngbia*), and *Acidobacteria*. The role of these taxa in black root rot suppression will be important to assess. The wheat take-all study of Sanguin et al. (2009) was performed using the same metho dology but with a smaller probe set, limiting possibilities of comparison. Yet, certain taxa (i.e. *Acidobacteria* and *Azospirillum*) were associated with disease suppressiveness in both types of suppressive soils.

5 Outlook

Soil suppressiveness to disease is not completely understood, in part because individual phytoprotecting populations have been studied rather in isolation from the rest of the rhizosphere community. Indeed, biocontrol capacities of microorganisms cannot always be predicted from the knowledge of their behaviour under simplified conditions (Kamilova et al. 2007). On one hand, the plant-protecting effects of certain biocontrol microorganisms was largely mediated by the impact they had on composition and functioning of the microbial community, whose members, in turn, were responsible for disease suppression (Ramos et al. 2003). On the other hand, even though plant protection in suppressive soils may result mainly from the contribution of one or a few prominent microbial groups, functional redundancy may be important and it could be also that interactions with the rest of the microbial community may influence significantly root colonization and expression of biocontrol traits in the former (McSpadden Gardener and Weller 2001; Weller et al. 2002).

It is likely that new ecogenomic approaches ('omics') assessing the relative importance of all community members and the *in situ* expression of microbial genes and functions implicated in plant protection will help reach a better comprehension of the mechanisms behind soil suppressiveness. Microbial community analysis carried out on soils of contrasted suppressiveness levels is a promising approach to identify taxa more prevalent or more active in suppressive situations, which represent candidate plant-protecting microbes (Borneman and Becker 2007; Benítez and McSpadden Gardener 2009). With this type of approach, it is likely that parallel changes in the prevalence of (antagonistic) *Pseudomonas* populations may correlate with other changes in rhizobacterial community composition, as already found in certain types of suppressive soils (McSpadden Gardener and Weller 2001; Hjort et al. 2007; Kyselková et al. 2009; Sanguin et al. 2009; Schreiner et al. 2010). In addition, metagenomic analyses (using microarrays or deep sequencing) of suppressive soils in combination with clever experimental set-ups may be useful to reveal novel biocontrol microorganisms and novel genes involved in plant protection (van Elsas et al. 2008; Hjort et al. 2010) while metaproteomics and metabolomics are promising for identifying molecular effectors.

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Conservation Tillage Impact on Soil Aggregation, Organic Matter Turnover and Biodiversity

Tek Bahadur Sapkota

Abstract Tillage is one of the oldest practices in agricultural production and offers many short term benefits in agro-ecosystem. These perceived benefits of tillage, however, have been gradually questioned because of its negative long-term consequences on soil and environment. Therefore conservation tillage systems have become the subject of intensive research among scientific communities and common practices among farming communities. However, scientific information on beneficial effects of conservation tillage systems on soil and environment is scattered. Critical analysis and synthesis of such information is helpful for scientific communities, farmers, students, and policy makers.

This chapter reviews the impact of conservation tillage on soil organic matter, soil structure stability and soil organisms. Based on the analysis of available literature, it can be concluded that conservation tillage increases soil organic matter content. Most studies state that conservation tillage decreases the loss of carbon from the soil by reducing soil erosion loss and minimizing carbon loss by microbial respiration thus increasing soil organic matter. Some studies also found increased carbon input under conservation tillage system mainly through increased moisture and nutrient use efficiency of plants thereby increasing crop biomass production and its subsequent incorporation into the soil. Conservation tillage also enhances soil structural stability through its positive effects on soil moisture, organic matter and microbial activities. Accumulation of crop residues and organic matter in the surface layer under conservation tillage creates favourable feeding conditions and also provides physical protection to various soil organisms, thereby increasing their abundance as well as diversity. Various studies have shown that conservation tillage increases microbial biomass in soil from 80% to 200% as compared with conventional tillage system. Less soil disturbance, which is the characteristics of conservation

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tillage, has positive effects on soil properties, soil processes and soil organisms which interact in a complex way and together, they all enhance soil quality for agro-ecosystem productivity.

Keywords Soil quality • Indicators • No-tillage • Conventional tillage • Soil organisms • Soil organic matter turnover • Conservation tillage

1 Introduction

Tillage is one of the oldest agricultural practices. The history tillage dates back many millennia when humans changed from hunting and gathering to more sedentary and settled agriculture mostly in the Tigris, Euphrates, Nile, Yangtze and Indus river valleys (Lal 2004). Ancient people used the tools such as digging stick and plow to place seeds in the soil in order to protect them against birds and rodents and vagaries of climate. With the advent of the industrial revolution in the nineteenth century, mechanical power and tractors became available to undertake tillage operations; today, an array of equipment is available for tillage and agricultural production. The main purposes of tillage in agricultural production are to: soften the soil and prepare seedbed, control weeds for better crop growth, release nutrient through enhanced mineralization and oxidation, temporarily reduce the soil compaction, control crop diseases/insects and so on (Hobbs et al. 2008). The advent of modern tillage implements greatly expanded the ability of agriculture to meet the food needs of growing populations. Cropland area in the world expanded dramatically over three centuries between 1700 and 2000, going from 265 million hectares in 1700 to about 1,360 million hectares in 2000 (Lal 2004).

The benefits of plowing on weed control and stand establishment are immediate, but it also has numerous long-term adverse impacts on soil and environments. For example, tillage rearranges the soil and affects the soil physical and chemical properties (Agbede 2010; Alvarez and Steinbach 2009). These changes in the soil physical environment brought about by tillage affect the organisms that live within that environment, with different soil organisms responding in different ways. Populations, diversity, and activity are adversely affected by frequent tillage operations (Wardle 1995) thus directly affecting soil biological properties. The changes in soil-dwelling organisms may interact with on-field and off-field ecosystems, for example, as food sources for species in adjacent hedgerows affecting the whole agro-ecosystem. Plowing down the crop residues and weed biomass into the soil and exposing loosened soil on the surface enhance the risks of accelerated erosion by water on sloping land and by wind on flat terrain. Pimentel et al. (1995) have reported that 75 billion metric tons of soil are removed from the land worldwide by wind and water erosion and estimated the global economic loss by such erosion at hundreds of billions of U.S. dollars per year. They further mention that most of such erosion comes from croplands because their soil is repeatedly tilled and left without a protective cover of vegetation. Soil erosion leads to preferential removal of the lighter soil fractions that

Photo 1 Soil inversion in preparation of planting in conventional tillage system (Photo courtesy: M. Mazzoncini)

include soil organic matter and unaggregated clay and silt-sized particles. Erosion causes breakdown of aggregates and exposure of encapsulated soil organic matter. Assuming that gross soil erosion worldwide is 75 billion Mega grams, the amount of erosion induced transport of soil carbon is 4–6 Pictogram per annum (Lal 2003). Loss of carbon from the soil has direct consequences on soil quality as it influences soil structure, retains water and plant nutrients, increases soil biodiversity and decreases risks of soil erosion and the related degradation (Lal 2009).

Therefore, the perceived benefits of cultivation have been increasingly questioned because of its negative long-term soil and environmental consequences. Furthermore, alternative chemical weed control measures have been developed since the middle of the twentieth century which make it possible to either completely eliminate the need for plowing or to greatly reduce its frequency and intensity (Lal 2004). Nowadays, it has been realized that the development of sustainable agricultural practices depends, among other factors, on decreasing the frequency and intensity of soil tillage. With this realization, various alternative tillage techniques have been developed (Baker et al. 1996) and reduced or conservation tillage systems have been the subject of intensive scientific investigation in past two decades (Photo 2). However, scientific information regarding effect of conservation tillage on soil quality parameters are scattered and limited efforts have been made to analyze and synthesize such information. This chapter tries to synthesize and summarize these information through analysis of scientific literatures.

Photo 2 Comparison of conventional tillage (*right plot*) and no-tillage (*left plot*) systems in the long-term tillage systems comparison trial of Interdepartmental Center for Agro-environmental Research, Pisa, Italy

2 Concept of Conservation Tillage in Agro-Ecosystem

Soil tillage is defined as the mechanical manipulation of soil for any purpose. In the context of agro-ecosystems, the purpose of tillage is to modify the soil conditions to nurture crops (El Titi 2003; Koller 2003). The history of tillage dates back many millennia when humans changed their lifestyle from hunting and gathering to more sedentary and settled agriculture (Hobbs et al. 2008). The tillage tool evolved from digging stick to spade to triangular blade and was made of wood, stone, and ultimately metal. With the advent of the industrial revolution in the nineteenth century, mechanical power and tractors became available to undertake tillage operations; today, an array of equipment is available for tillage and agricultural production. Conventional tillage, also called intensive tillage, which comprises all tillage practices that leave less than 15% of crop residues on the soil surface is still a predominant tillage system in today's agricultural production (Koller 2003).

Tillage offers a number of benefits to agricultural production and to farmers. For instance, tillage softens the soil ensuring uniform seed germination, helps the release of nutrients for plant growth and controls weeds, soil borne diseases and insect pests. These benefits of tillage to the farmer are, however, at a cost to him, to

Photo 3 Direct seed drilling over the residue of previous crop under no-tillage system. Layer of crop residues on the surface conserve soil moisture and nutrient and also reduce soil erosion

the environment and to the natural resource base on which farming depends. The results of various investigations suggest that ploughing often leads to common soil related problems such as soil compaction, soil erosion (Chatterjee and Lal 2009), deteriorated water percolation, decreased microbiological activities (Kladivko 2001) and high energy and time requirement (Fukushima and Chen 2009). In response to increasing costs of fossil energy and increasing concerns about the environment, the utility of intensive tillage in has been questioned and many alternative tillage techniques have been developed (Baker et al. 1996). As a consequence, there is an increasing tendency towards reduced or conservation tillage systems that use less fossil fuel, reduce run-off and erosion of soil and reverse the loss of soil organic matter.

The term conservation tillage refers to a number of strategies and techniques for establishing crops in a previous crop's residues (Photo 3), which are purposely left on the soil surface (Koller 2003). Various types of conservation tillage systems are prevalent throughout the world. No-tillage, ridge-tillage, strip-tillage and mulch tillage are some of the most common conservation tillage systems practiced so far. The principal benefits of conservation tillage are improved water conservation and reduction of soil erosion. Additional benefits include reduced fuel consumption, reduced compaction, planting and harvesting flexibility, reduced labor requirements, and improved soil tilth (Lal 2004).

Overall, plowing is one of the oldest agricultural practices which offers multiple benefits to crop production but also has some negative effects on soil quality and environment. To minimize the negative effects of tillage, conservation tillage practices have been evolved which have many benefits to soil and environment such as reduced soil erosion, water conservation, improved soil tilth and so on.

3 Soil Quality in the Context of Agro-Ecosystems

Simply, the soil quality is defined as its capacity to function. Therefore, soil quality is a concept of giving value to the soil related to a specific function. According to the USDA Natural Resources Conservation Service, soil quality is the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation. The specific definition of soil quality for a particular soil is, therefore, dependent on its inherent capabilities, intended land use, landscape and social environment thus giving rise to variety of definition and understanding (Doran and Parkin 1994; Harris et al. 1997; Mairura et al. 2007; Toth et al. 2007). Because of the multiple and complex function that soil provides, its quality has to be defined in context of its specific function, purpose or use. For example, the function, properties, and process necessary to hold up a physical structure are not the same as those needed to grow a crop and therefore soil quality for these two purposes will be very different. Soil quality can further be viewed as inherent or dynamic soil quality. The inherent soil quality is that aspect of soil quality relating to a soil's natural composition and properties which mainly includes static properties that show little change over time, such as mineralogy and particle size distribution. The dynamic soil quality, on the other hand, is the aspect of soil quality relating to soil properties that are subject to change over relatively short time periods and that respond to management.

Agro-ecosystems can be defined as land-use systems that produce food and fiber, a process that is governed by many factors and components such as soil type, cropping patterns and tillage management. In the context of agro-ecosystem, soil quality is, therefore, usually defined in terms of its productivity and specifically in regard to a soil's capacity to sustain and nurture plant growth. For example, better soil quality produces abundant, high quality crops. Thus, from the perspective of agricultural crop production, soil quality can be defined as "soil's capacity or fitness to support crop growth without resulting in soil degradation or otherwise harming the environment" (Carter et al. 1997). The crop production and ecosystem health are affected strongly by soil physical quality which are derived from physical properties such as soil porosity, soil strength and structure; chemical quality which are derived from chemical properties such as mineralogy, organic matter, pH, electrical conductivity and cation exchange capacity; and biological quality which are derived from biological properties that include living organisms and materials such as plants, microorganism, meso- and macro-fauna plus soil processes associated with living organisms such as C and N mineralization. Therefore, a good quality soil in an agro-ecosystem must have a strong foundation to provide adequate plant support and stable soil structure, provide nutrients for crop growth, support soil flora and fauna and minimize the loss of nutrients and pesticides out the root zones.

Assessment of soil quality involves the process of characterizing change in soil quality by comparative and dynamic means i.e. determining the changes continuously over time. Several approaches have been developed to assess soil quality with respect to specific function (Bastida et al. 2008; Doran and Parkin 1994; Kang et al. 2005; Karlen et al. 1994) but no generally acceptable methodology has been identified yet. Probably, the most convincing approach to evaluate soil quality for agricultural production is that developed by Karlen et al. (1994). These authors used the framework established by Karlen and Stott (1994) and proposed the critical soil functions for crop production as: (1) accommodate water entry; (2) facilitate water transfer, adsorption, and deliverance; (3) resist degradation; and (4) support plant growth. These functions of soil, and thus soil quality, can be assessed at the field, farm, ecosystem, pedosphere and global scale by using different indicators. Scanning through the literature, most commonly used indicators of soil quality in agro-ecosystems are: soil organic matter, aggregate stability, microbial biomass and respiration, pH, bulk density, soil total nitrogen and enzymatic activities. Changes in the populations, diversity and activity of biotic organisms living in the soil due to management effect on soil physical and chemical environment are also worth considering while talking about soil quality. Since organic matter, aggregate stability and biodiversity are the important parameters of soil quality, this chapter documents the effect of conservation tillage on these soil quality parameters in agro-ecosystem.

To sum up, in the context of agroecosystems, soil quality is its capacity to support plant growth by facilitating water movement and nutrient availability and to resist degradation.

4 Effect of Conservation Tillage on Soil Quality Parameters

Assessment of the effect of management practices including tillage system on soil quality involves the measurement of soil's productive quality in agro-ecosystem. However, many soil- agro-ecosystem-functions are difficult to measure directly and therefore, soil quality should often be inferred from easily measureable soil properties; the soil quality indicators (Weil and Magdoff 2004). Assessing soil quality by means of indicators involves observation of easy-to-measure soil properties that can provide an appraisal or estimate of a difficult-to-measure property or that can provide a substitute when specific data is missing or not available. For example in the abovementioned framework, Karlen et al. (1994) used porosity as an indicator of the soil's capacity to accommodate water entry and aggregates stability to reflect the ability of soil to resist degradation. Since then, several authors have used different indicators to evaluate the soil quality for agricultural production (Andrews et al. 2002; Erkossa et al. 2007; Kang et al. 2005; Marzaioli et al. 2010).

Tillage in an agro-ecosystem has complex effects on the soil physical, chemical, and biological environment. The soil disturbance performed by cultivation or tillage produce multiple effects on soil at farm, field, ecosystem, pedosphere and finally at global scale. Within field, tillage rearranges soil structure at varying intensity and accordingly affects the soil physical, hydrological and chemical features. These changes in the soil physical environment affect the organisms that live within that environment, with different soil organisms responding in different ways. Populations, diversity, and activity may all be affected by changes in tillage systems. The changes in soil-dwelling organisms may interact with on-field and off-field ecosystems, for example, as food sources for species in adjacent hedgerows. Tillage also exerts serious impacts on the nearby environment through runoff, erosion or pollution. In response to these deleterious effects of conventional tillage practices, various forms of conservation tillage have been developed and are being widely adopted throughout many parts of the world. The conservation tillage practices provide feasible soil-management options with fewer disturbances to soil agro- ecosystems (El Titi 2003). Minimum soil disturbance offers many benefits to soil through its effects on soil properties, soil processes and biodiversity.

Less soil disturbance, which is the characteristics of conservation tillage, has positive effects on soil properties, soil processes and soil organisms which altogether enhance soil quality.

4.1 Conservation Tillage and Soil Organic Matter

Soil organic matter (SOM) offers numerous and wide-ranging benefits to the soil and thus is an essential component to enhance soil quality. Some direct benefits of the SOM include improvement in soil structure, retention of water and plant nutrients, increase in soil biodiversity and decrease in risks of soil erosion and the related degradation (Lal 2009). Besides these direct benefits to soil, there are numerous ancillary benefits of SOM such as increase in use efficiency of input because of the reduction in losses of water and nutrients from the root zone, an increase in the soil's and ecosystem's resilience, and moderation of climate through sequestration of atmospheric CO_2 into stable SOM and oxidation of CH_4. There is a strong and positive relationship of SOM with soil and environmental quality and therefore increasing quality and quantity of SOM is essential for maintaining sustainable soil quality in agro-ecosystem. Thus, if a new practice increases SOM content, we conclude that it enhances soil quality; if the practice results in SOM depletion, we infer a decline in soil quality.

Changes in SOM occur whenever the rates of carbon input and loss diverge (Fig. 1). So, any technique that disproportionately affects C input into and output from the soil will elicit a change in SOM content. In order to bring positive changes in SOM, the management technique should favor C input relative to its loss (Janzen et al. 2004). Conservation tillage practices affect C input and its conservation in a number of fundamental ways. These include: (i) affecting the water storage

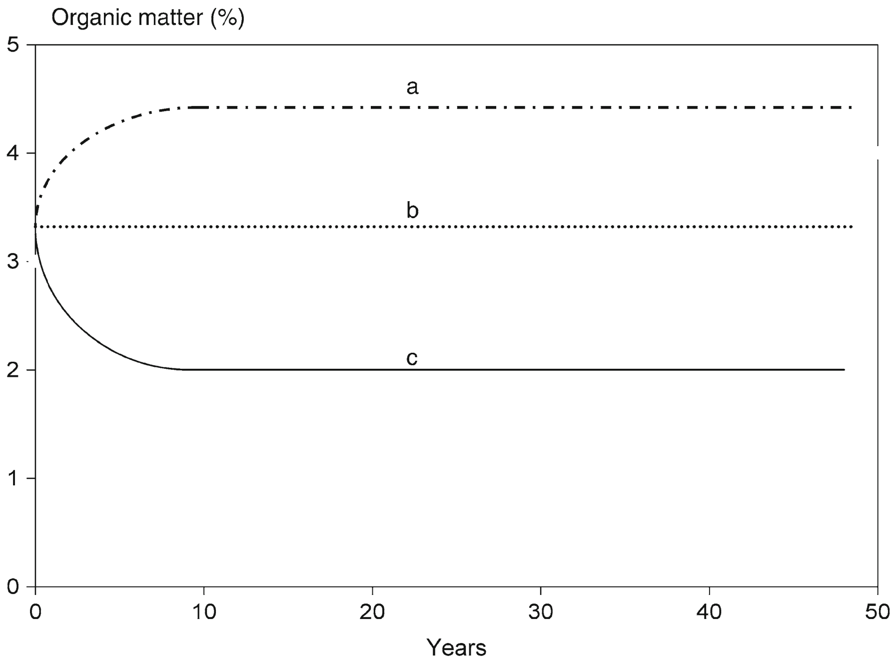

Fig. 1 Conceptual view of organic matter dynamics in an agro-ecosystem; (**a**) when carbon inputs exceed losses, soil organic matter increases for some time until it reaches in its equilibrium. (**b**) when carbon inputs equal losses there is no change in soil organic matter. (**c**) when carbon inputs are less than losses, soil organic matter decreases for some period until it is so low that soil will not lose it anymore (Modified from Magdoff and Weil 2004)

properties of a soil, thus affecting crop production and organic matter decomposition rates; (ii) reducing the physical disturbance that ruptures soil aggregates, thus keeping new organic matter from decomposition; (iii) returning all residues to the soil, causing a redistribution of organic matter from below ground to the surface soil layers; and (iv) reducing the soil-residue contact with decomposers that occurs when soil is tilled. Effects of conservation tillage on these fundamental processes of organic matter turnover are summarized in the following paragraphs.

The accumulation of SOM is greatly influenced by the amount of C inputs. Paustian et al. (1997) showed that the change in SOM over time is linearly related to the level of C inputs from seven long-term experiments. Increased water and nutrient use efficiency of plants, thereby increasing crop and residues production is one of the examples of practices that increase C inputs into the soil. Conservation tillage practices are known for their favorable effects on moisture and nutrient conservation thereby affecting crop production and crop residue input into the soil. Formation of a layer of crop residues on the soil surface reduces soil erosion and conserves significant amounts of plant nutrients. Crop residues on the surface layer also minimize water loss through evaporation. The conservation tillage system often builds a residue layer on the soil surface reducing aggregate disruption that contributes to reduced water loss from soil (Lal et al. 1980). Abid and Lal (2009) studied soil water characteristics, plant available water, and the water infiltration rate in no-tilled and conventionally-tilled silty loam soil of Ohio on a 14-year-old field study. From this study, they reported that the plant available water and water infiltration rate was significantly higher in a no-tillage system than in a conventional tillage system. Conservation of soil nutrients and water through conservation tillage along with better water infiltration improves the crop production and thus the C input into the soil.

Another important tactic of increasing SOM is decreasing its losses from the soil. Loss of SOM from the soil can be reduced by minimizing (1) removal of plant materials in harvest, (2) erosion losses by water and wind, and (3) C losses as CO_2 by accelerated microbial respiration (Magdoff and Weil 2004). Removal of C in plant materials in harvest can be minimized by careful retention of as much of the plant residues as possible into the soil. Large amount of SOM is lost through erosion of surface soil where SOM content is higher. Tillage on slopes tends to move topsoil enriched with organic matter downhill (Magdoff and Van Es. 2000). Conservation tillage practices that minimize erosion of surface soil will considerably reduce the loss of SOM and thus increase soil quality. For example, no-tillage management of 2.7 ha cropped watershed for 24 years on a Typic Kanhapludult in Georgia reduced water runoff to 22 mm $year^{-1}$ compared with 180 mm $year^{-1}$ under previous management of watershed under conventional inversion tillage (Endale et al. 2000). Soil loss was even more dramatically reduced with no-tillage than conventional tillage (3 vs. 129 kg ha^{-1} mm^{-1} runoff). Reductions of soil erosion by adoption of no-tillage and by growing cover crops have also been reported by different researchers from different parts of the world (Morris et al. 2010; Nyakatawa et al. 2007; Ulen et al. 2010; Wollni et al. 2010). Stevens et al. (1992) reported that without cover cropping, no-till can reduce soil erosion by 70% compared to conventional tillage system in cotton.

Rates of microbial respiration largely govern SOM losses. The SOM decomposition by microbial respiration is largely influenced by alternating drying and wetting cycles (Lal 2009) as well as degree of contact of the residues with diverse population of decomposers. Crop residues decay more rapidly when mixed into the soil, because the soil maintains conditions of moisture, and nitrogen availability, and temperature suitable for microbial decomposition. Therefore, the tillage system has great influence on soil microbial respiration and thus loss of SOM. Physical disturbance associated with ploughing accelerates these mechanisms and thus loss of SOM whereas conservation tillage practices greatly reduce SOM losses due to these mechanisms. For example, surface placement of crop residues in conservation tillage reduces the contact of residues with decomposing microorganisms thus slowing down the rate of decomposition and carbon loss (Havlin et al 1990). Sequestration of carbon by no-tillage and other forms of conservation tillage has been reported by different researchers around the world (Calegari et al. 2008; Lopez-Bellido et al. 2010; Sainju et al. 2009; Spargo et al. 2008; Photo 4).

In conclusion, conservation tillage increases carbon input into the soil mainly through increased biomass production and incorporation into the soil which is achieved with increased water and nutrient use efficiency of plants. Conservation tillage also

Photo 4 Severe soil erosion under conventional tillage system. It is estimated that about 75 billion Mega grams of soil is eroded leading to loss of 4–6 Pictogram carbon per annum from 1,600 million hectare of cropland around the globe

reduces carbon losses from soil by reducing soil erosion loss and minimizing C loss by microbial respiration. Both increased carbon input into and decreased carbon loss from the soil increase the amount of soil organic matter into the soil.

4.2 Conservation Tillage and Soil Structural Stability

Soil aggregation involves the formation of aggregates through the combination of sand, silt and clay particles, and their stabilization by organic and inorganic materials. As a consequence, soil consist of aggregates of different sizes and the pores between the aggregates. Soil aggregate stability is the ability of the aggregates to remain intact when subjected to stress. The maintenance of a "good" soil structure is critical for agricultural sustainability, and it depends on the stability of the aggregates. Aggregate stability of soil affects the movement and storage of water, aeration, erosion and biological activities in soil thus influencing a wide range of soil properties and growth of crops. Therefore, maintaining high soil aggregate stability is a requisite for the sustainable use of soil and for sustainable agriculture. Arshad and Coen (1992) proposed aggregate stability as one of the soil physical properties that can serve as an indicator of soil quality.

Crop management systems have a strong influence on soil aggregate stability; some agricultural practices decrease soil aggregate stability while others increase it. The effect of tillage on soil structural stability is somewhat controversial (Amezketa 1999). Tillage may increase porosity and thus the water infiltration when it loosens surface crusts, disrupts dense soil layers, or provides surface depressions for temporary storage of water (Unger 1992). Bronick and Lal (2005) pointed out that although tillage causes short-term increase in soil porosity, in the longer term it results in decrease in soil aggregation. In general, it is accepted that soils subjected to frequent and intensive cultivation suffer deterioration in structure which is reflected by a decrease in the stability of aggregates. Tillage breaks down the aggregates by smoothing the surface and by exposing organic matter to microbial attack.

Conservation tillage indirectly enhances soil aggregate stability mainly through its influence on soil moisture (Mahboubi et al. 1993), organic matter, microbial activity (Costantini et al. 1996) and population of soil fauna (Kladivko 2001). It has been shown that organic matter from different sources improves soil water-stable aggregation (Milne and Haynes 2004; Molina et al. 2001). Similarly, several biological binding agents have been recognized as responsible for aggregation and aggregate stability. Abiven et al. (2009), by reviewing the relationship between microbial binding agents and aggregate stability, observed good relationships in many cases while some studies showed no relationship. Direct drilling and reduced cultivation significantly increased organic carbon (Lopez-Bellido et al. 2010), microbial activities (Muruganandam et al. 2010; Purakayastha et al. 2009) and thus improved soil structural stability. Imaz et al. (2010) found aggregate stability positively correlated to soil water retention, earthworm activity and organic matter stratification, and all these soil properties were higher in conservation tillage system than in conventional tillage system under Mediterranean conditions. The absence of tillage has an important stabilizing effect on macroaggregation relative to conventional tillage system as the aggregates are less subject to slaking under no-tillage condition (Angers et al. 1993).

In sum, conservation tillage enhances soil structural stability through its positive effects on soil moisture, organic matter and microbial activities.

4.3 Conservation Tillage and Soil Organisms

4.3.1 Effect on Meso- and Macro-organisms

Use of soil organisms as an indicator of soil quality has received special attention in recent years due to their sensitivity to any change in the soil. Several authors have used soil mesofauna communities, particularly soil arthropods for the assessment of soil quality (e.g. Baldigo et al. 2009; Blocksom and Johnson 2009; Parisi et al. 2005). Some of these methods are based on a single taxon where several organisms such as Hymenoptera, Collembola and Carabidae are identified as indicators of different farming systems or anthropogenic impacts while others such as the Biological Quality of Soil (BSQ) takes into account whole soil micro-arthropod communities. As soil organisms respond sensitively to land management practices, they can be considered as good indicators to evaluate agro-ecosystem quality.

Agro-ecosystems under conventional tillage and no-tillage management experience vastly different physical and chemical environments. The changes in the physical and chemical environment brought about by tillage have large influence on the organisms living in the soil. Several researchers have explored the effects of tillage on soil organisms. These investigations on tillage impacts on soil biota reveal that soil biota respond in different ways to soil tillage regimes. Variations in responses found in different studies reflect different magnitudes of tillage disruption and residue burial, timing of the tillage operations, timing of the measurements, and different soil, crop, and climate combinations. For example, reductions in earthworm population and biomass due to tillage were higher in finer textured soils than sandy soils (Joschko et al. 2009). Nevertheless, both abundance and diversity tend to increase as tillage intensity is reduced.

Conservation tillage systems, in which soil conditions are usually presumed to be less disturbed, are supposedly more closely related to natural systems and support diverse organisms and biotic processes. In general, larger organisms appear to be more sensitive to tillage operations than smaller organisms, due to the physical disruption of the soil as they are either killed by tillage-induced abrasion or trapped in soil because of soil inversion. Conservation tillage practices tended to support higher densities of earthworms (Reeleder et al. 2006), soil fungi (Caesar-TonThat et al. 2010), phytopathogens (Pankhurst et al. 1995) and microarthropods (Miyazawa et al. 2002). In general, higher abundance and diversity of soil biota under conservation tillage systems can be attributed to the accumulation of crop residues/organic matter in topsoil, regulation of soil moisture and temperature (Kladivko 2001), its effects on plant rooting pattern and consequent distribution of root litter and rhizosphere exudates (Wardle 1995). Accumulation of crop residues and organic matter in surface layers under conservation tillage creates favourable feeding conditions for topsoil-dwelling species (El Titi 2003). The surface residues also provide physical protection to shallow-surface dwelling micro-arthropods. In addition, the surface residues serve as mulch thus slowing down the rate of soil drying in spring and freezing in winter. This lengthens the active periods of micro-arthropods. Regulation of soil moisture and temperature by conservation tillage favours many micro-arthropods including mites. On the contrary, cultivation and absence of mulch make the micro-climate and the resource levels less favourable for soil micro-arthropods. In various studies, highest earthworm abundance and biomass have been reported in no-tillage soil, in particular with cover crops whereas ploughed soil hosted the lowest worm populations, regardless of the crop grown (Birkas et al. 2004; Chan 2001; Eriksen-Hamel et al. 2009; Metzke et al. 2007). Similarly, various forms of conservation tillage have resulted in elevated abundances and diversity of various micro-arthropods compared with conventional tillage (Brennan et al. 2006; Davis et al. 2009; Wilson-Rummenie et al. 1999).

Thus, conservation tillage favours higher number of meso- and macro-organisms through regulation of crop residues, organic matter, soil moisture and making soil microclimate favourable for these organisms.

4.3.2 Effects on Micro-organisms

The microbial biomass has an important role in nutrient transformation and thus impacts on fertility status and nutrient supplying potential of soils. The microbial biomass of soil is a comparatively labile pool of soil organic matter and a substantial pool of soil nutrients (Roper and Gupta 1995). Microbial carbon content of surface soil has been shown to be a more sensitive indicator of changes in soil organic matter than total organic matter and also closely related to the proportion of water-stable aggregates (Sparling et al. 1992). Loss of microbial component of organic matter can adversely affect both the physical and biological as well as nutrient status of the soil and therefore it is one of the commonly used indices of the changes brought about by management practices including tillage systems.

Increase in soil microbial biomass due to conservation tillage, particularly no-tillage, has been reported by different authors. For example, Gonzalez-Chavez et al. (2010) found almost double microbial biomass carbon and nitrogen in no-tillage system than in conventional tillage system after 25 years of experimentation. Balota et al. (2004) studied the effect of 22 years of conventional and no- tillage system on soil microbial biomass in a Brazilian Oxisol and found that no tillage systems increased microbial biomass by 83% in 0–5 cm depth over conventional tillage. Higher microbial biomass due to no-tillage system has been also reported by Muruganandam et al. (2010) and Purakayastha et al. (2009). On the other hand, a decrease in microbial carbon of 0.76 mg g^{-1} has been reported after 11 years of cultivation (Mari and Changying 2006). Similarly, conversion to cropping with conventional tillage from permanent pasture resulted in a 45%, 53% and 51% decline in microbial nitrogen, potash and phosphorus, respectively, at 0–5 cm soil depth (Aslam et al. 1999). Greater microbial biomass under no-tillage system is likely due to significant residue layer build on the soil surface, reduced aggregate disruption and sometimes pore sizes, all of which contribute to reduce water loss from soil resulting in cooler and wetter conditions (Wardle 1995). The overall response of soil microbial biomass on soil moisture and temperature is poorly understood but part of microbial biomass is usually killed by extreme drying (Liu et al. 2009). Influence of conservation tillage on plant rooting patterns and consequent distribution of root litter and rhizosphere exudates also favours soil micro-organisms. Generally, plants in conservation tillage systems produce a greater proportion of roots nearer the soil surface compared with those in conventional tillage systems and therefore more microorganisms can be expected near the soil surface under former system. The abundance and diversity of arbuscular mycorrhizas is also higher under conservation tillage practices as tillage disrupts their mycelia network (Gao et al. 2010).

Increased microbial biomass by conservation tillage often parallels an increase in organic matter levels, especially in the surface 10 cm soil layer (Joergensen et al. 2010;

Laxminarayana 2010), reflecting that increased microbial biomass under conservation tillage is due to the positive effect on soil organic matter. However, the extent of stimulation of microbial biomass by adoption of conservation tillage is often greater than that would be expected by the elevation of organic matter levels alone, and the ratio of microbial biomass carbon to organic carbon is frequently higher in conservation tillage situations (Gajda 2010; Melero et al. 2009; Simon et al. 2009). This may be, in part, due to superior quality of organic matter in conservation tillage systems with higher levels of microbially-available carbohydrates and amino acids. At first glance, the higher microbial biomass with conservation tillage may appear to be contradictory to a build-up of soil organic carbon content. However, some studies have found a decrease in the efficiency of use of carbon sources by soil microorganisms under conventional tillage, as evidenced by greater carbon dioxide evolution per unit microbial biomass under conventional tillage compared with conservation tillage systems (Balota et al. 2004).

Although bacteria and fungi both appear to have greater biomass in the soil under no-tillage than under conventional tillage (Wardle 1995), the crop residues at the soil surface under no-tillage tend to be fungal-dominated. In six long-term tillage experiments in USA, the proportion of the total biomass composed of fungi ranged from 10% to 60% and was significantly higher in no-tillage compared to conventional tillage on surface soil at five of six sites (Frey et al. 1999). Thus one generalization often made is that the microbial biomass in no-tillage systems tends to be fungal-dominated whereas that in conventional tillage system tends to be bacterial-dominated, although this certainly depends on whether measurements are made near the soil surface or deeper in the soil profile.

To sum up, conservation tillage systems have been reported to increase microbial biomass in soil from 80% to 200% as compared with conventional tillage systems and these increases can mainly be attributed to reduced aggregate disruption, intact residue layer, increased organic matter and enhance crop rooting and rhizodeposition.

5 Conclusion

Conservation tillage practices have complex effects on soil properties. Assessment of these effects on soil quality for agro-ecosystem productivity, i.e., soil's capacity to sustain and nurture plant growth, involves observation of some easily measurable soil properties; the soil quality indicators. Various indicators of soil quality have been proposed so far but soil organic matter, structural stability and soil biodiversity are the most important and commonly used indicators of soil quality in agro-ecosystems. Besides reducing cost of production, conservation tillage also increases soil organic matter in long-term. It also increases diversity of micro-, meso- and macro-organisms in the soil and improves their efficiency of use of carbon sources. Increased organic matter and biological activities in the soil by conservation agriculture improves the soil structural stability and other soil properties and thus improves the agro-ecosystem productivity.

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Sustainable Agricultural NP Turnover in the 27 European Countries

Péter Csathó and László Radimszky

Abstract A deep contrast of NP balances, water nitrate contamination, soil P and rural development has appeared between Western and Eastern European countries since the implementation of the European nitrate directive in 1991 (91/676/EEC). In an economy ruled by free market rich countries become richer and poor countries become poorer from the point of view of water nitrate contamination and soil P overloads. There is a need for a paradigm shift in the European agro-environmental protection legislation. Instead of speaking about it, agro-environmental protection, social, and rural development principles should gain real priority. According to the principle of subsidiarity, the present problems can be solved only at the highest European-level, i.e., in the legislation and in the administration.

We reviewed the anomalies in the NP turnover of the European countries. The major points are: (1) instead of some agronomic factors such as soil NP status, added farmyard manure, and expected yield level, per capita gross domestic product and population density were the major factors affecting the magnitude of mineral and organic NP application. (2) Countries with the highest livestock densities do not take into account previous farmyard manure application and soil P status as mineral NP dose diminishing factors. This practice contradicts to the basic principles of sustainable crop nutrition. As a result, between 1991 and 2005, highest P surpluses, the most positive P balances were reached in the countries with the highest soil P level, further enhancing their agricultural P load to the environment. (3) Similarly, the European countries with the highest organic NP application, The Netherlands, and Belgium, were those who applied most mineral NP fertilisers reversely to the agronomic principles, and, resulting in most positive NP balances, and, as a consequence, the most severe environmental threat, the most severe agronomic NP

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load to the environment. (4) The major cause of heavy agricultural NP loads to the environment was livestock density exceeding 100 livestock units 100 ha agricultural land^{-1}. (5) A positive correlation was found in the European countries between cumulative N balances for the period of 1991–2005 and the degree of ground water nitrates contamination. The main added value of this paper is to compare NP balances values to groundwater nitrate contaminations as well as soil P status, and evaluate their correlation from both agronomic and environmental point of views. Former works evaluate these factors, although correlative to each other, separately (Steén I, A European fertilizer industry view on phosphorus retention and loss from agricultural soils. In: Tunney H, Carton OT, Brookes PC, Johnston AE (eds) Phosphorus loss from soil to water. CABI, Wallingford, pp 311–328, 1997; OECD, Environmental indicators for agriculture, vol 3. OECD, Paris, pp 117–139, 2001; OECD, OECD trends of environmental conditions related to agriculture. In: Environmental indicators for agriculture, vol 4. OECD, Paris, Chapter 3, www.oecd.org, 2008).

Keywords Agricultural NP loads • Polarization • Livestock density • Nitrates Directives • Inefficiency • New priorities in EU legislation

Abbreviations

EU	European Union
EU15 countries	The Western European EU countries including Austria Finland and Sweden
FER	Mineral fertiliser
FYM	Farmyard manure
GDP	Gross Domestic Product
NEU12 countries	The newly joined Central- and Eastern European countries including Bulgaria and Romania
STP	Soil test phosphorus

1 Introduction

In 2008, all the different sciences, related to planet earth, including disciplines dealing with agro-environmental sciences, receive special attention: as a mutual initiative of the International Union of Geological Sciences (IUGS) and United Nations Educational, Scientific and Cultural Organization (UNESCO), United Nations Organization declared the year 2008 as the "International Year of Planet Earth" (The International Year of Planet Earth. www.esfs.org). This event underlines the importance of sustainable crop nutrition and land use practice all over the world, including the EU.

According to Webster's Dictionary (Webster 1961), the description of "Union" is: "A uniting into a coherent and harmonious whole". The question emerges, whether how much is consistent the plant nutrition practice of the farmers in the different EU countries to this description? And how much does the EU agro-environmental protection legislation help the various

Directives:

- Nitrates Directives/91/676/EEC/;
- Water Framework Directives/2000/60/EC/, etc.

Strategies:

- Principle that environmental dimension should be integrated in all Community policies/The Cardiff European Council, June, 1998/;
- Integrating environmental dimensions into the Common Agricultural Policy/CAP/The Helsinki European Council, December, 1999/;
- EU Sustainable Development Strategy/The Göteborg European Council, June, 2001/;
- Environmental integration and sustainable development incorporated into CAP/The Agricultural Council, April, 2001/, etc.

and Policies:

- Common Agricultural Policy/Swinbank and Daugbjerg 2006/, etc.,

so that the farmers' plant nutrition practice be united "into a coherent and harmonious whole"?

Nutrient balances, especially those of nitrogen and phosphorus, are important environmental indicators. The approaches and methodology of these balance calculations may differ significantly, which is why there are limitations in the comparison of the data. In recognition of their importance, the countries belonging to the Organisation for Economic Co-operation and Development (OECD) group have an obligation to submit yearly calculations on soil surface N and P balances (OECD 2001, 2008). The advantage of OECD calculations is that the countries involved elaborate on their NP balances using the same methodology. Consequently, the NP balance calculations of these individual countries are comparable. As a new initiative, EUROSTAT has started a program of estimating NP balances in the EU countries on NUTS-2 level (TAPAS 2007). The magnitude of mineral and organic NP use has a major effect on NP balances. Therefore, it is essential to investigate the major factors affecting them, such as per capita GDP and population density.

As a synthesis of a literature survey, Johnston and Steén compared the soil P supply data of Western European countries, most of them long-term EU members (Steén 1997). Csathó et al. (2007) have done the same for Central and Eastern European countries, allowing comparisons to be made between NP balances and soil NP supplies within and between these two main European regions, i.e. the former 15 Western European (EU15) and the newly joined 12 Central and Eastern European (NEU12) EU countries.

For interpreting the agricultural OECD NP balances data from both agronomic and environmental points of view, it is essential to compare them to the actual soil NP status of the investigated area so that to evaluate them, whether they are sound from both agronomical and environmental points of view. As an example, strongly positive P balances in areas with very low P status, are justified from agronomic side, and are not a threat to the environment. These soil P statuses are characteristic for the Central and Eastern European EU countries. As an unfavourable phenomenon, opposite to the reasonable practice, these EU countries have the lowest P balances, having unfavourable agronomic, social, and rural development consequences (Csathó et al. 2007; OECD 2001, 2008). Oppositely, strongly positive P balances in areas with very high P status, are unfavourable from agronomic side, and are severe threat to the environment. These soil P statuses are characteristic for the Western European EU countries with the highest livestock densities, as The Netherlands, Belgium, and at some regions within the given countries, as in the Bretagne peninsula, and in the Po valley. As an unfavourable phenomenon, opposite to the reasonable practice, these EU countries and regions have the highest NP balances, having unfavourable environmental protection consequences (Steén 1997; OECD 2001, 2008).

The Göteborg European Council (2001) endorsed the EU Sustainable Development Strategy, which requires that the economic, social and environmental effects of all policies be taken into account in the decision-making processes. It also adopted the conclusion of the Agriculture Council (2001) on environmental integration, requiring that agricultural production must be done in an environmentally friendly way.

In 2008, for their new, environmentally friendly fertiliser recommendation system, elaborated in Institutions belonging to the network of the Hungarian Academy of Sciences, received the Year of 2007 Innovation Grand Prize for Hungary, the highest Prize on innovative research and development (Csathó et al. 1998, 2009; Várallyay 2008). Elements and approach of this fertiliser recommendation system also appear in the suggestions for improving agro-environmental protection legislation and practice in the EU.

The basic approach of this work is to evaluate factors affecting the intensity of organic and mineral NP application per agricultural land unit, and to collide with each other the environmental NP balances – using the OECD methodology – and groundwater nitrates contamination, as well as soil P supplies of the Western European former EU15 countries and new EU12 member countries, in Central and Eastern Europe.

The aim of this work is to answer these questions, and to give some suggestions for a way out from the unfavourable plant nutrition practice of the farmers both in the former EU 15 countries (the environmental problems), and the new EU12 countries (the agronomic, social and rural development problems), not fitting the description of the Webster's Dictionary (Webster 1961), on "Union". In 2001, a review book was published on the nutrient management legislation in the former EU15 countries, as well as in Norway (De Clercq et al. 2001).

In the first part of the paper, factors affecting the level of NP fertilization are discussed. In the next section, contrasts in NP balances and NP supplies between Western and Eastern Europe are evaluated, i.e. over fertilization and environmental problems in the western part, and under fertilization and related agronomic and social problems in the eastern part. In the last section, suggestions are made for altering EU NP turnover towards a sustainable way, either from environmental, or agronomic, social and rural development points of views.

2 Scientific Methods Used in the Chapter

Correlations between the national per capita income, the population density, the livestock density, and the quantities of N and P applied as mineral fertiliser and as organic manure were evaluated using the 2005 agricultural statistical database of the FAO (2005). For 2007 and 2008, the database of EUROSTAT was used (http://epp.eurostat.ec.europa.eu). The GDP per capita was estimated using the CIA (2001) database, which also took purchasing power into consideration. The data included in the FAO database were expressed in terms of the agricultural area of the given country. Set-aside areas in the EU15 countries, which have been temporarily removed from cultivation, were not included in the agricultural area. On the other hand, in countries where more than one crop a year is possible, areas harvested twice were counted twice as agricultural land. Countries with an agricultural area of less than a hundred thousand hectares were not included in the calculations. This left a total of 129 countries in the database.

When calculating the livestock units (LU), the following factors were used: cattle, bullock, horse 0.8; donkey, mule 0.213; pig 0.114; sheep 0.071; goat 0.1065; 1,000 rabbits 4.0; 1,000 chickens 2.0; 1,000 ducks 3.0; 1,000 geese 4.0; 1,000 turkeys 5.0 (Hajas and Rázsó 1969). One LU was considered to produce 10 metric tonnes of farmyard manure with 0.6% N, 0.3% P_2O_5, and 0.6% K_2O year^{-1} (Csathó and Radimszky 2005a).

For calculating environmental NP balances, the OECD methodology was used (OECD 1997), each country using their own crop and livestock specific nutrient contents, characteristic for their own countries. For evaluating the soil phosphorus status of the Western European countries, the review of Steén (1997), of the Central and Eastern European countries, the review of Csathó et al. (2007) was used as basis. For strengthening the reliability of the N balance calculations in the EU countries, ground water statuses of the same countries were used. For strengthening the reliability of the P balance calculations in the EU countries, in the other hand, soil P statuses of the same countries were taken into account.

3 Reviewing and Evaluating EU Agricultural NP Turnover

3.1 Factors Influencing the Use of Organic and Mineral NP

When investigating the reasons for differences in the quantities of N and P applied as organic manure or mineral fertiliser, it became clear that in countries with a higher national per capita income, combined with greater population density, the

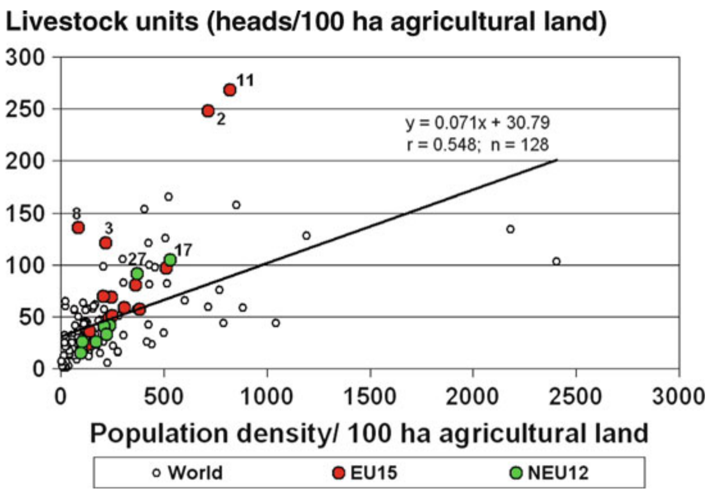


Fig. 1 Correlation between population density and livestock density in the countries of the world, as well as in the EU15 and NEU12 countries, in 2000. EU15: former western European countries, NEU12: new central-eastern European countries

agriculture was more intensive, involving greater quantities of N and P both from mineral fertiliser and from organic manure. Because of the fact, that organic and mineral N and P use change proportionally in the investigated countries, in Figs. 1, 2, and 3, the two potentially harmful elements appear usually together.

Per capita GDP was almost 2.5 times higher in the former EU15 countries than in the new EU (NEU12) group. In 2000, 56% more fertilizer (FER) N+P was applied in the EU15 than in the NEU12, indicating differences in the intensity of plant nutrition. The highest fertilizer NP rates were applied in the Netherlands, Germany and Belgium-Luxembourg.

The numbers in Fig. 1, represent the EU27 countries, as follows: 1 – Austria, 2 – Belgium and Luxembourg, 3 – Denmark, 4 – Finland, 5 – France, 6 – Germany, 7 – Greece, 8 – Ireland, 9 – Italy, 11 – Netherlands, 12 – Portugal, 13 – Spain, 14 – Sweden, 15 – United Kingdom, 16 – Bulgaria, 17 – Cyprus, 18 – Czech Republic, 19 – Estonia, 20 – Hungary, 21 – Latvia, 22 – Lithuania, 23 – Malta, 24 – Poland, 25 – Romania, 26 – Slovakia, 27 – Slovenia.

Almost twice as much NP was produced from farmyard manure (FYM) in the EU15 than in the NEU12, with the highest figures for the Netherlands (196 kg ha^{-1}) and Belgium-Luxembourg (181 kg ha^{-1}). This is the result of the unhealthily high Livestock Unit (LU) number per agricultural area. The amount of fertilizer plus farmyard manure NP was 70% higher in the EU15 than in the NEU12, with levels of over 300 kg ha^{-1} in two countries (the Netherlands: 364 kg ha^{-1} and Belgium-Luxemburg: 302 kg ha^{-1}), and around 200 kg NP per hectare in three other countries (Germany: 195 kg ha^{-1}; Ireland: 193 kg ha^{-1}, and Denmark: 190 kg ha^{-1}) (FAO 2005). In addition, higher per capita GDP and greater population density were also associated with a higher livestock density per unit area, further increasing the NP

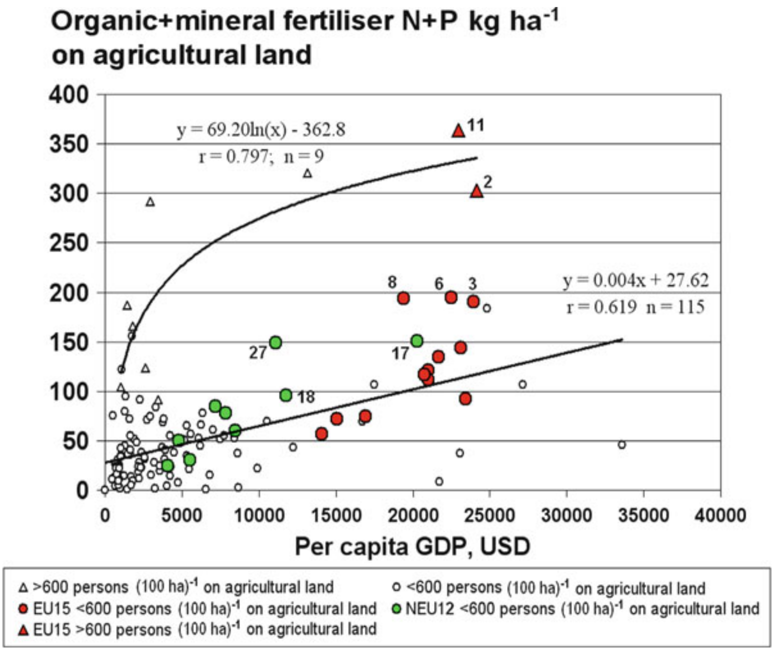


Fig. 2 Correlation between the national per capita income and the application of organic and mineral fertiliser NP in the countries of the world, as well as in the EU15 and NEU12 countries, as a function of population density in 2000. EU15: former western European countries, NEU12: new central-eastern European countries

load to the agricultural area (Figs. 1, 2, and 3). The average number of livestock per 100 ha of agricultural land was almost twice as high in the EU15 as in the NEU12.

The numbers in Fig. 2, represent the EU27 countries, as follows: 1 – Austria, 2 – Belgium and Luxembourg, 3 – Denmark, 4 – Finland, 5 – France, 6 – Germany, 7 – Greece, 8 – Ireland, 9 – Italy, 11 – Netherlands, 12 – Portugal, 13 – Spain, 14 – Sweden, 15 – United Kingdom, 16 – Bulgaria, 17 – Cyprus, 18 – Czech Republic, 19 – Estonia, 20 – Hungary, 21 – Latvia, 22 – Lithuania, 23 – Malta, 24 – Poland, 25 – Romania, 26 – Slovakia, 27 – Slovenia.

The numbers in Fig. 3, represent the EU27 countries, as follows: 1 – Austria, 2 – Belgium and Luxembourg, 3 – Denmark, 4 – Finland, 5 – France, 6 – Germany, 7 – Greece, 8 – Ireland, 9 – Italy, 11 – Netherlands, 12 – Portugal, 13 – Spain, 14 – Sweden, 15 – United Kingdom, 16 – Bulgaria, 17 – Cyprus, 18 – Czech Republic, 19 – Estonia, 20 – Hungary, 21 – Latvia, 22 – Lithuania, 23 – Malta, 24 – Poland, 25 – Romania, 26 – Slovakia, 27 – Slovenia. The highest livestock densities per 100 ha were reported in the Netherlands (268 heads) and in Belgium & Luxembourg (248 heads). The livestock density was extremely high compared with the population density in Belgium & Luxembourg and the Netherlands.

When these two factors were compared for all the countries in the world, it was again these two countries that deviated to the greatest extent from the general trend. Denmark and Ireland also had above-average livestock densities compared with the

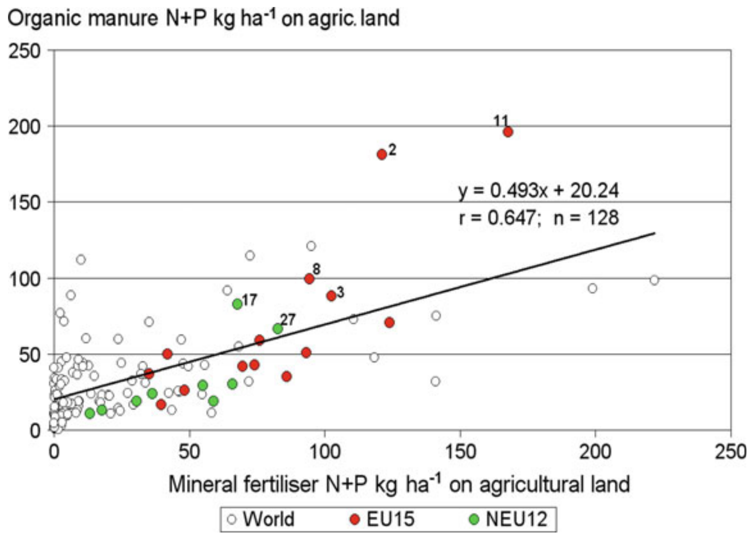


Fig. 3 Correlation between the NP quantities applied as mineral fertiliser and produced as farmyard manure in the countries of the world, as well as in the EU15 and NEU12 countries, in 2000. EU15: former western European countries, NEU12: new central-eastern European countries

population density. Among the NEU12 countries, only Slovenia and Cyprus, the agricultural area of which was only just over 100,000 ha, had a livestock density slightly greater than the average.

3.2 *Phosphorus Balance of Central and Eastern European Countries Between 1960 and 2000*

The intensive use of phosphorus fertiliser began several decades later in Central and Eastern Europe than it did in Western Europe. In most cases this is why the phosphorus balances for these countries were far lower in the 1960s than in the 1980s. The only exception was Slovenia, where the application of phosphorus continued to be as intensive as in Western European countries even after 1990. In Central and Eastern Europe, with the exception of Czechoslovakia, Latvia and Estonia, phosphorus balances in the 1960s were below 11 kg ha^{-1} P and were sometimes negative. In the 1980s, due to the intensive application of fertilisers, the phosphorus balances were positive throughout the region, with values ranging from 4 to 31 kg ha^{-1} P. As a consequence of the rapid decline in P fertiliser use since 1990, the P balances have reached an all-time low, ranging from −7 to +7 kg ha^{-1} P. This can be partly attributed to the fact that the substantial residual P effects still make it possible for the crops to extract large quantities of P, resulting in relatively high yields. The only exception is again Slovenia, with a positive balance of 20 kg ha^{-1} P (Csathó et al. 2007). The reasons for these low P balances can be the economic difficulties of the NEU12 (CEE) countries and their farmers, as well as the lower amount of subsidies received by the NEU12 countries, than by the EU15 countries, according to the Copenhagen Treaty.

Table 1 NP balances in the EU15 countries, Norway and Switzerland, and in the NEU12 countries of Central and Eastern Europe in 1991 (Csathó et al. 2007)

Country	N balance, kg ha^{-1} N	P balance, kg ha^{-1} P
Netherlands	262	40
Belgium	205	34
Luxemburg	*132*	*25*
Germany	129	*21*
Denmark	*129*	*8*
Ireland	76	10
France	*75*	*29*
Finland	72	20
Sweden[a]	66	6
United Kingdom	*64*	*6*
Greece	*58*	*14*
Austria	49	5
Portugal[a]	43	*4*
Italy	39	*13*
Spain	*25*	*12*
Switzerland	80	12
Norway	69	13
Czech Republic	40	2
Slovakia	38	6
Poland	18	5
Hungary	–20	–9

Numbers in italics were taken from Brouwer et al. (1995), while the other data were reported by Steén (1997), OECD (2001, 2008), Klir (2005), Torma (2005), Kopinski (2005) and Csathó and Radimszky (2005b)

[a]Data for 1994/1995

3.3 NP Balances Based on Environment Protection Considerations in the Early 1990s

N and P balances in 1991 for the EU15 countries, Switzerland, Norway and some of the Central and Eastern European NEU12 countries are presented in Table 1.

Nitrogen balances were in excess of 200 kg ha^{-1} in the Netherlands and Belgium, above 100 kg ha^{-1} in Luxemburg, Germany and Denmark, above 75 kg ha^{-1} in Switzerland, Ireland and France, over 50 kg ha^{-1} in Finland, Norway, Sweden, the United Kingdom and Greece, around 50 kg ha^{-1} in Austria, and 40 kg ha^{-1} or less in Portugal, Italy, the Czech Republic, Slovakia, Spain, the Netherlands and Hungary. In 1990/1991 high yields were obtained in Hungary, combined with the most negative NP balance of the century, a situation made possible by the high first-year residual NP effects.

Phosphorus balances followed much the same pattern as the N balances: the greatest phosphorus surpluses were recorded in the Netherlands and Belgium (34–40 kg ha^{-1} P), while the P balances in France, Luxemburg, Germany and Finland

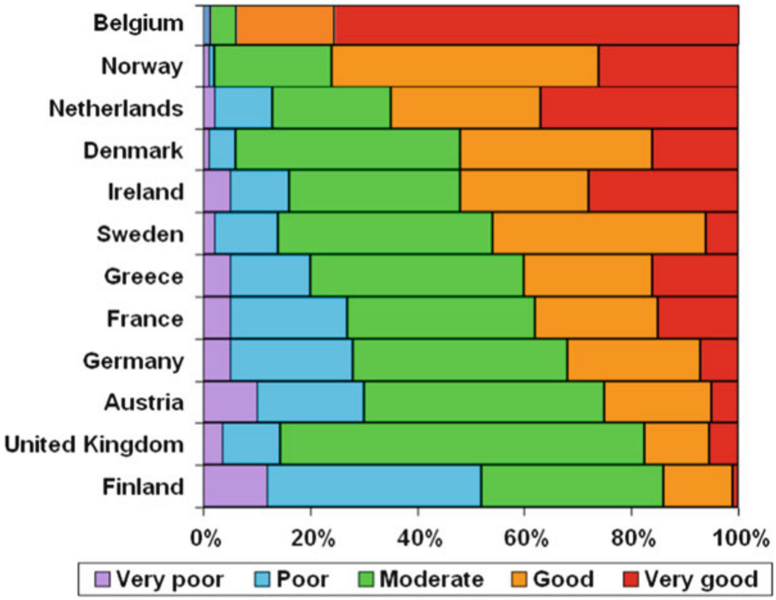


Fig. 4 Phosphorus supplies in the soils of Western European countries in 1991 (Steén 1997); Belgium: (Bodemkundige Dienst van België. 2006)

ranged from 22 to 31 kg ha^{-1} P. In the remaining countries the phosphorus balance was below 13 kg ha^{-1} P, with values below 7 kg ha^{-1} P in the NEU12 countries and in the United Kingdom, Sweden, Austria and Portugal. As the result of legislation aimed at environment protection, the use of N fertiliser has declined by around 10% and that of P fertiliser by around 40% since 1988. Despite the lower NP fertiliser rates, the NP balances have continued to be positive in most of the EU15 countries. The dramatic reduction in NP fertiliser in the NEU12 countries, on the other hand, was caused by the collapse of the economy.

3.4 Soil P Supplies in the EU15 Countries

The distribution of soil P supply categories in 11 Western European countries in the early 1990s is illustrated in Fig. 4 (Steén 1997). The fact that fertilisation has led to positive P balances and to the accumulation of P in the soil is also clear from the levels of soil P supplies in certain countries.

The soil P supplies in Western Europe were still relatively poor at the end of the 1800s, when mineral P fertilisation has first begun. Half a century or more of soil-enriching P fertilisation, however, led to an increase of 30–50% in the P content compared to the 1920s.

Due to the more intensive application of P fertiliser, the P-supplying capacity of the soil is much greater in Western Europe than in the central and eastern parts of the continent. The proportion of land well or very well supplied with P was around 95% (!) in Belgium (The Flamand part), around 75% in Norway, 65% in the Netherlands, 50% in Denmark, Ireland and Sweden, 40% in Greece and France, 30% in Germany, 25% in Austria, 20% in the United Kingdom and 15% in Finland (Steén 1997). Comparing the P status data to the P balance data, the opinion of the authors is, that the P supply data of the Netherlands is highly underestimated. According to the opinion of the authors, soil P soil P saturation in the Netherlands is even higher than in Belgium. For example, the official lower limit of good P supply for grassland in the Netherlands is 300 mg kg^{-1} AL-P_2O_5, (ammonium-lactate-soluble P, Egner et al. 1960) (Handboek melkveehouderij 1997), while above 100 mg kg^{-1} AL -P_2O_5, no responses of less P-demanding crops like grass to P fertilisation is expected according to the results of field trials for acid sandy loam – loam soils (Csathó 2003a, b) (Fig. 4).

According to estimations made by the European Soil Bureau, the NP content of the soil was unfavourably high on 17 million hectares of Western Europe, i.e. on 12% of the agricultural land, representing a serious environmental threat to surface and subsurface waters.

3.5 Soil P Supplies in the NEU12 Countries

Figure 5 illustrates the P status of the soil in Central and Eastern European countries. As in the case of the Western European countries, the countries were ranked according to the proportion of land with good or very good supplies of phosphorus.

In the early 1990s the proportion of land well or very well supplied with phosphorus was far smaller (by 10–25%) in Central and Eastern Europe than in Western Europe. This proportion was around 50% in Slovenia and Hungary, 40% in the Czech Republic, Poland and Slovakia, 30% in Latvia and Bulgaria, 25% in Austria, Albania, Estonia and Romania, 15% in Lithuania and Serbia and 10% in Ukraine (Csathó et al. 2007).

An estimation of the soil P supplies in 2005 is complicated by the fact that an evaluation similar to that published in 1991 is not available for the Western European countries. In addition to the compulsory annual preparation of NP balances by OECD countries, there is an urgent need that the every-5-years changes in the groundwater nitrate-N contents and soil P supplies in these countries to be published.

3.6 Correlations Between P-supplying Capacity and P Balances

One fundamental characteristic of fertiliser recommendations aimed at environmental sustainability is (or should be) that on areas poorly supplied with a given nutrient a quantity larger than that taken up by the crop is applied, slightly more than crop

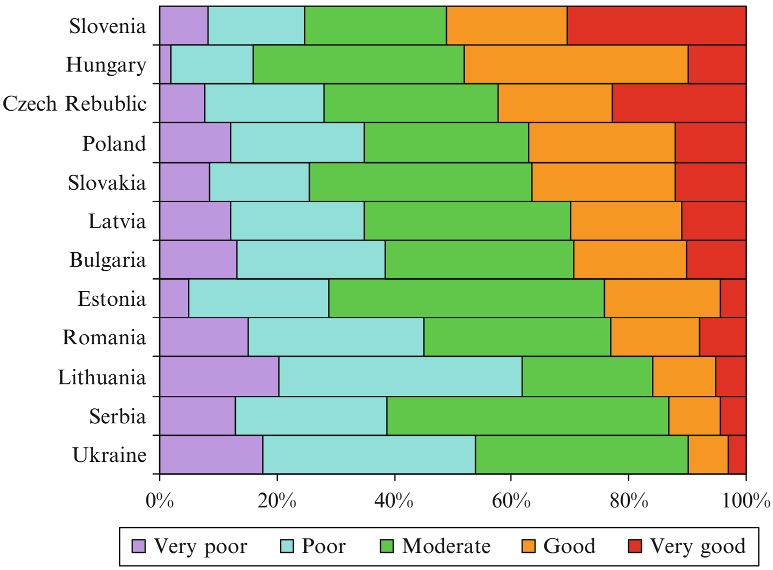
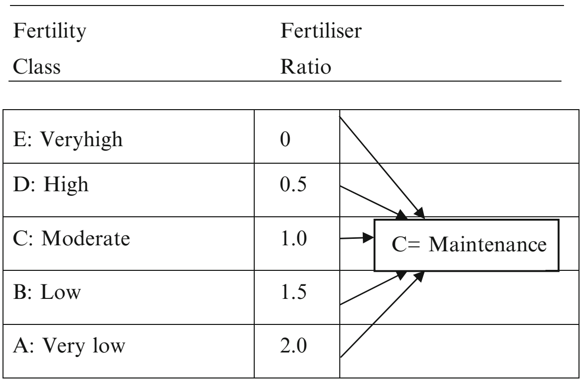


Fig. 5 Phosphorus supplies of soils in Central and Eastern European countries in the early 1990s (Csathó et al. 2007)

Fig. 6 Phosphorus fertiliser recommendation for fields in Germany based on soil fertility class soil test phosphorus (*STP*) based on Vetter and Fruchtenicht (1974), cit: Tunney et al. (1997)



uptake on soil with moderate supplies, an amount equal to or slightly less than crop requirements on soils with good supplies, little or none on soils with very good supplies, and no P fertiliser on soils with an excessive supply level (Fig. 6).

The P recommendations, normally shown as kg P ha^{-1} $year^{-1}$, are usually based on soil test phosphorus (STP) values and the following is an example of a typical fertiliser strategy (Tunney et al. 1997) (i) no P fertiliser required for optimum production for a number of years when STP is high, (ii) maintenance P (replacing removals) required when STP is moderate, (iii) build-up of P recommended when STP is low. An example of an approach used in Germany to recommend fertiliser

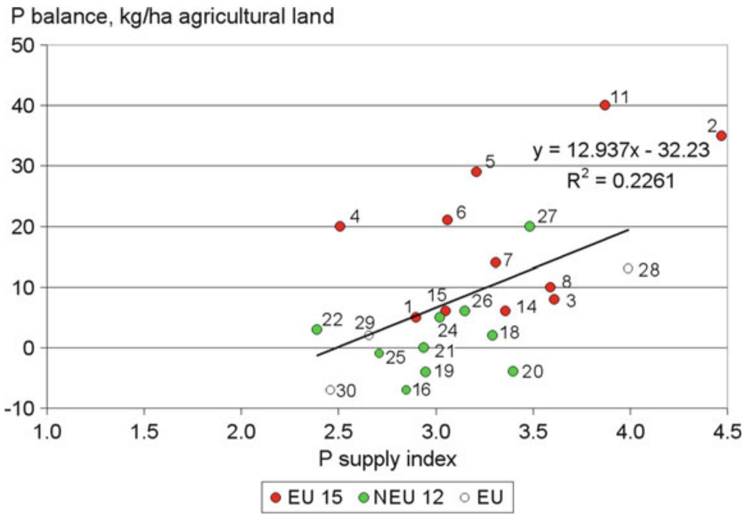


Fig. 7 Correlation between the soil P supply index and the P balance in the countries of Europe in the early 1990s (The numbers in Fig. 7, represent the EU27 countries, as follows: *1* – Austria, *2* – Belgium, *3* – Denmark, *4* – Finland, *5* – France, *6* – Germany, *7* – Greece, *8* – Ireland, *9* – Italy, *10* – Luxembourg, *11* – Netherlands, *12* – Portugal, *13* – Spain, *14* – Sweden, *15* – United Kingdom, *16* – Bulgaria, *17* – Cyprus, *18* – Czech Republic, *19* – Estonia, *20* – Hungary, *21* – Latvia, *22* – Lithuania, *23* – Malta, *24* – Poland, *25* – Romania, *26* – Slovakia, *27* – Slovenia; as well as some non-EU countries: *28* – Norway, *29* – Serbia and Montenegro, *30* – Ukraine)

application at field level is illustrated in Fig. 6 (Vetter and Fruchtenicht 1974). It is based on STP level and shows, for example, that at fertility class A (very low fertility), two times the maintenance P fertiliser dressing is recommended and at fertility class D, only 0.5 times the maintenance level is recommended. At fertility class E (very high fertility) fertiliser P is not recommended (Fig. 6).

If this logic is followed, in the EU27 countries of Western Europe, where the soils were far better supplied with phosphorus in the early 1990s, far lower rates of (N) P should be applied and far lower (N) P balances are justified both from the agronomic and environment protection points of view than in the countries of Central and Eastern Europe, where P supplies were far poorer in the early 1990s.

Let us see how far this theory is put into practice. Figure 7 illustrates the correlation between the P supply index, indicative of the P status of the soil, and the P balance. In order to calculate the P supply index, a value of 1 was applied for areas very poorly supplied with phosphorus, 2 for poorly supplied areas, 3 for moderately well supplied areas, 4 for well supplied areas and 5 for very well supplied areas. This was then multiplied by the percent of land belonging to the given supply category, i.e. by 0.1 for 10% of the land, by 0.2 for 20%, etc. The figures obtained for each category were then summed to give the P supply index of the country.

A country very poorly supplied with phosphorus over 100% of its area would thus have a P supply index of 1.0, while the other extreme would be a country with very good supplies over 100% of its area, having a P supply index of 5.0. The introduction of a sixth category for excessive supplies of P would also be justified, but the necessary data are not available at present.

In Fig. 7, the data of Brouwer et al. (1995) and the OECD (2001, 2008) were used for P balance estimations for the EU15 countries and Norway in the early 1990s, while the following data were used for the CEE countries: Bulgaria: Nikolova (2005); Czech Republic: Klir (2005); Estonia: Astover and Roostalu (2002); Hungary: Csathó and Radimszky (2005a); Latvia: Karklins (1998); Lithuania: Lazauskas (2005); Poland: Kopiński (2005); Romania: Csathó and Radimszky (2005b); Slovakia: Torma (2001, 2005); Slovenia: Csathó and Radimszky (2005a); Serbia and Montenegro: Manojlović (2005); Ukraine: Lisovoj and Nikitjuk (2004).

In the case of soil P status, the data of Steén (1997) were used for the EU15 countries and Norway in the early 1990s, and the following data for the CEE countries: Bulgaria: Nikolov (1998); Czech Republic: Čermák and Budňáková (2003); Estonia: Järvan et al. (1996); Hungary: Csathó (2005); Latvia: Karklins (1998); Lithuania: Mazvila et al. (1996); Poland: Obojski and Straczynski (1995); Romania: Hera et al. (1998); Slovakia: UKSUP (2000); Slovenia: Leskošek (1998); Serbia and Montenegro: Bogdanović et al. (1993); Ukraine: Nosko et al. (1994).

If P fertilisation were carried out in a manner acceptable from the agronomic and environment protection points of view, a negative correlation would have been plotted in Fig. 7., with P balances declining as the P supplies improved. By contrast, the opposite was observed in Europe in the early 1990s: the P balances in Central and Eastern Europe, where the P supply index was lowest, were the smallest, and in some cases negative (between −5 and −10 kg ha^{-1} P), while Western European countries, which had the highest P supply indexes, had the most positive P balances, with surpluses of 18–40 kg ha^{-1} P each year. This unfavourable situation (i.e. the polarization between the Western and Eastern part of the EU) has even accelerated and has become much worse since the introduction of the Nitrates Directive, as is clear from the cumulative nitrogen and phosphorus balances of European countries over the last 15 years.

3.7 Cumulative N and P Balances in the European Union

The cumulative N balances of certain European countries, many of them EU member countries, are presented in Fig. 8. for the period 1991–2005, i.e., the yearly N balances of this period were summed up.

The Netherlands and Belgium lead the field for N balances. During the 15 years that have elapsed since the Nitrates Directive was introduced the total N surplus was 2,800 kg ha^{-1} in Belgium and 3,500 kg ha^{-1} in the Netherlands, and was also well above 2,000 kg ha^{-1} in Denmark. So much for the effectiveness of the Nitrates Directive!

The cumulative N balance was also above average in Germany, Norway and Ireland, while the countries of Central and Eastern Europe came last, as expected (Fig. 8).

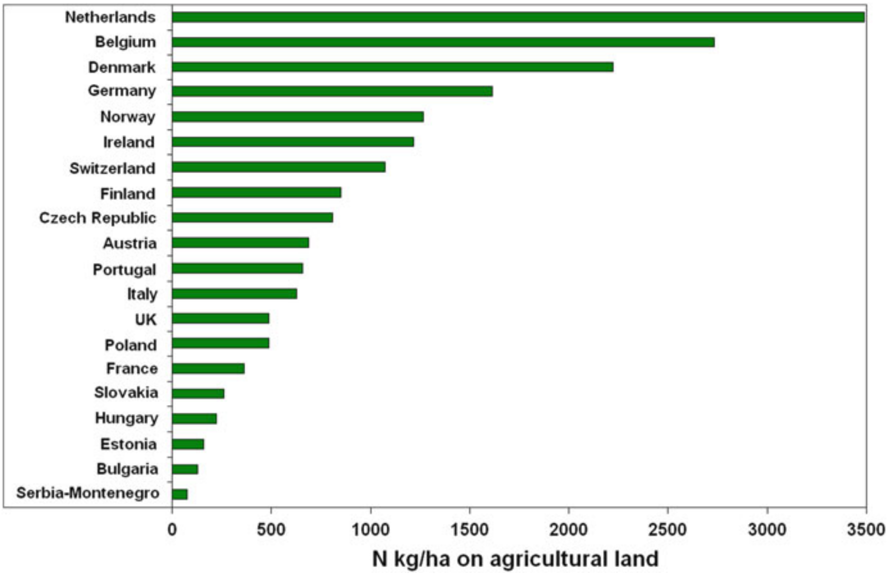


Fig. 8 Estimated cumulative N balance of European countries, 1991–2005 (Csathó and Radimszky 2007, 2009)

For strengthening the trends in cumulated N balances surpluses in the EU27 countries, the ground water quality data of the EU countries are shown in Fig. 9 (Csathó and Radimszky 2007, 2009).

It is important to note that the same sequence of countries is observed both in the 15-year cumulated N balances, and in the percentage of ground water samples above the maximum permissible limit value for ground water nitrate-N, i.e. 50 mg kg^{-1}.

The cumulated P balances are estimated for the period of 1991–2005 in Fig. 10 (Csathó and Radimszky 2007, 2009). For countries where data were only available until 2002 or 2003, NP balances for the missing years were taken as being equal to the last recorded year. The P surplus accumulated over this 15-year period was more than 400 kg ha^{-1} P in the Netherlands and 300 kg ha^{-1} P in Belgium (Fig. 10).

The highest P surpluses (from the environmental point of view), were recorded also in these Benelux countries in the early 1990s (Fig. 11) (Stanners and Bourdeau 1995). A World Bank map on pig density in Western Europe shows the same pattern and feature, indicating, that highest P surpluses were found at the areas with the highest livestock densities (Fig. 12) (World Bank 2005).

Not to mention, that the situation has become even more threatening since 1991, indicating the definite inefficiency of the Nitrates Directive, implemented the same year, i.e. in 1991, aiming to regulate both N and P regime in the EU countries. Slovenia, Norway, Denmark and Finland also registered above-average increases in P over the last 15 years, and the Central and Eastern European countries were again at the bottom of the list.

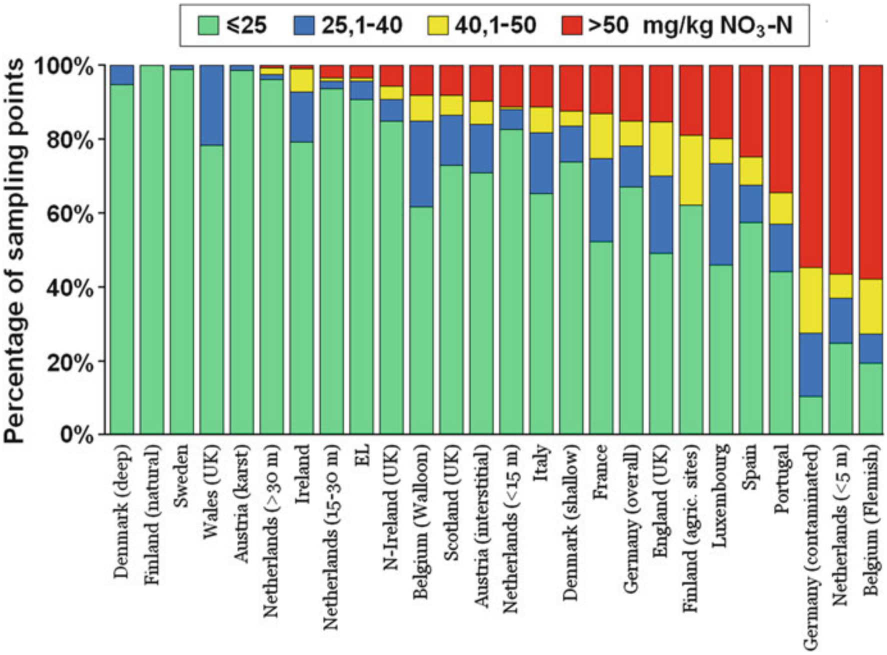


Fig. 9 Ground water nitrates contamination of some EU 15 countries in the mid 2000s (Hamell 2007)

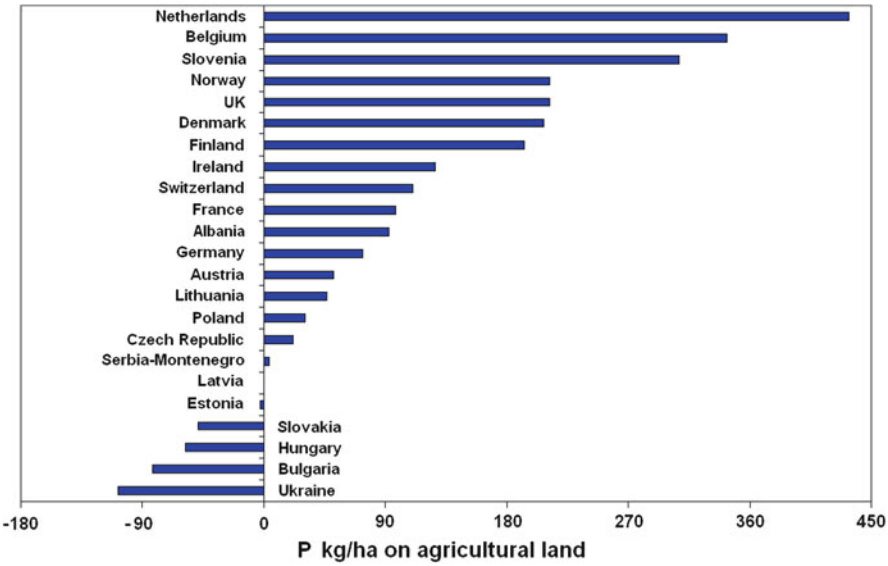


Fig. 10 Estimated cumulative P balance of European countries, 1991–2005 (Csathó and Radimszky 2007, 2009)

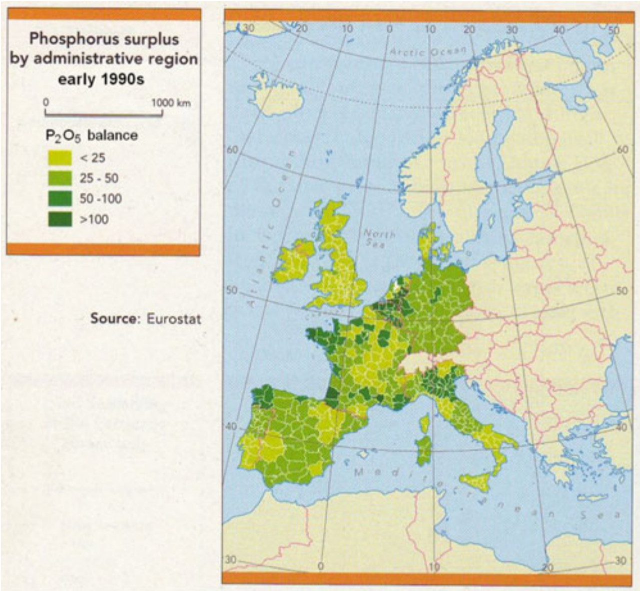


Fig. 11 Phosphorus balances in the EU12 countries, in the early 1990s, in NUTS 2 levels (Stanners and Bourdeau 1995)

Fig. 12 Pig population density in Western Europe (World Bank 2005)

4 Insights, Discussion and Suggestions

In a perfectly correct and justifiable manner, the European Union made investments in environment protection a strict condition for the accession of the Central European countries to the EU. One essential obligation was the satisfactory disposal of sewage, as a water protection measure. The steps taken by the EU to protect surface waters have thus led to a dramatic reduction in point-source pollution caused by the (N) P contained in sewage.

The EU is consistently strict in curbing the comparably low point-source NP pollution caused by agriculture, forcing the farmers in the whole EU, include in the NEU12 countries, to build their slurry and manure storing facilities for the period their distribution to agricultural field is prohibited.

The EU should be just as consistently strict in curbing the by magnitudes higher diffuse NP pollution caused by agriculture, especially of those countries with the highest livestock densities. In the United States, for example, in many states effective legislation has been passed to reduce P loads of agricultural origin, despite the fact that the situation is far less serious than in many European countries (Sharpley et al. 1994; Gartley and Sims 1994). The directives passed by the EU should also be compulsory, not simply recommended.

According to principles of sustainable crop nutrition, the amount supplied by previous farmyard manure and/or slurry application (i.e., in the previous 3–4 years), should be taken into account as mineral fertiliser NP demand reducing factors. For the effective preservation and rehabilitation of the environment from agricultural NP loads, it seems that this principle should be built in the EU agro-environmental legislation, i.e. into **the EU Nitrates Directive**:

(a) On nitrate-sensitive areas, while retaining the maximum permitted application of 170 kg ha^{-1} N of organic origin, the rate at which farmyard manure is utilized by the crops should also be considered, calculating with 50% in the first year, 30% in the second and 20% in the third on sandy or sandy loam soils, and 40% in the first year, 30% in the second, 20% in the third and 10% in the fourth on loam, clay loam and clay soils. If organic manure is applied every year, the total quantity of organic manure that will exert its effect in the given year should not exceed the 170 kg ha^{-1} limit on nitrate-sensitive areas.

(b) Irrespective of nitrate sensitivity, regulations should be passed making it compulsory for fertiliser recommendation systems in EU countries to reduce the recommended mineral fertiliser N rates by the quantity of N applied in the form of farmyard manure, expressed in fertiliser N equivalency, and taking into account the rate at which farmyard manure is utilised by the crop, within the 3–4-year period (see previous paragraph). The fertiliser N equivalency of FYM nitrogen can be considered as 50% on average, varying according to the livestock species and the technology (Kemppainen 1989). The results of long-term field trials, set up on the basis of mineral and organic NP equivalency, it turned out, that, as compared to the nitrogen in mineral fertiliser, the efficiency of total N in solid cow and pig manure ranges from 25% to 70% (Sluijsmans and Kolenbrander 1977; Anonymous 1982; Sarkadi 1993; Árendás 1999), that in solid poultry manure from 60% to 85% (Anonymous 1980, 1982; Beauchamp 1983), that in cow slurry from 30% to 70% (Kemppainen 1989; Anonymous 1980, 1982; Laine 1967; Amberger 1982), that in pig slurry from 65% to 75% (Sluijsmans and Kolenbrander 1977; Anonymous 1982; Amberger 1982; Sutton et al. 1982), that in poultry slurry from 65% to 70% (Anonymous 1980, 1982; Amberger 1982), and that in liquid manure from 75% to 80% (Sluijsmans and Kolenbrander 1977).

(c) Only fertiliser recommendation systems that have been tested under field conditions for a number of years and that meet strict environment protection and economic criteria should be authorized for use in practice. The application of a total nitrogen quantity equivalent to more than 200 kg ha^{-1} mineral fertiliser (applied as farmyard manure + mineral fertiliser) usually cannot be justified from the agronomic point of view and should be officially banned in the interests of environment protection in most cases.

(d) In each EU27 country, annual and cumulative nitrogen balances should be prepared following the OECD environment protection approach for every year of the twentieth century.

As an excess of P rather than N causes eutrophication in the majority of EU countries, according to the authors, a **Phosphates Directive** should be urgently compiled, incorporating the following principles:

(a) When distinguishing soil P supply categories the P fertiliser responses of the crops should be taken into consideration. The upper limit of good P supplies, and thus the lower limit of very good supplies, should not be more than 1.5 times the lower limit of good P supplies. In the same way, the upper limit of very good P supplies, and thus the lower limit of excessive supplies, should not be more than 1.5 times the lower limit of very good P supplies (Table 2). According to the suggestion of Kamprath (2005), soil P limit values of the same soil P test method should somehow differ according to the soil properties as well.

(b) Irrespective of phosphate sensitivity, regulations should be passed making it compulsory for fertiliser recommendation systems in EU countries to reduce the recommended mineral fertiliser P rates by the quantity of P applied in the form of farmyard manure, expressed in fertiliser P equivalency, and taking into account the rate at which farmyard manure is utilized by the crop within the 3–4-year period. In field experiments, the phosphorus in manure has often been observed to be just as effective as that in mineral fertilizer (Kemppainen 1989; Amberger 1982; Asmus et al. 1971; Sharma et al. 1980; Tunney 1980; Smith and van Dijk 1987). In the literature, the phosphorus in manure is also generally considered to be as effective as that in mineral fertilizer (Anonymous 1980; Valmari 1933; Rieder 1983)

(c) Only fertiliser recommendation systems that have been tested under field conditions for a number of years and that meet strict environment protection and economic criteria should be authorized for use in practice. The application of a total phosphorus quantity of more than 50 kg P ha^{-1} (applied as farmyard manure + mineral fertiliser) cannot be justified from the agronomic point of view and should be officially banned in the interests of environmental protection.

(d) The concept of excessive P supplies should be compulsorily introduced in all EU countries. The application of phosphorus in either organic or mineral form should be **prohibited** on soils with excessive P supplies (Table 2).

Table 2 Lower limits for good soil supplies, and suggested lower limits for very good and excessive P supplies for the main soil P test values used in EU countries

Method	Lower limit for good soil P supply	Suggested lower limit For very good soil P supply	 For excessive soil P supply	References for good soil P supply
H_2O	10	15	23	Jungk et al. (1993)
Olsen	20	30	45	Johnston et al. (1986)
Bray-1	22	33	50	McCallister et al. (1987)
Mehlich-3	27	40	60	McCollum (1991)
Mehlich-3 (for org. soils)	30	45	68	Kamprath (2005)
Mehlich-3 (for sandy soils)	40	60	90	Kamprath (2005)
AL (for acid soils)	44	66	99	Csathó (2002, 2003a, b)
CAL	47	70	105	Spiegel (2007)
DL	60	90	135	Baumgärtel (1989)
AL (for calcareous soils)	66	99	149	Csathó (2002, 2003a, b)
Mehlich-3 (for sandy loam soils)	80	120	180	Kamprath (2005)
Mehlich-3 (for clay soils)	300	450	675	Kamprath (2005)

(e) The use of P fertilisers should be banned above this level, at least on environmentally sensitive areas, but preferably throughout the country, and this principle should be introduced in the whole of the EU.
(f) In each EU27 country, annual and cumulative phosphorus balances should be prepared following the OECD environment protection approach for every year of the twentieth century in order to obtain a picture of the dynamics and extent of either soil P enrichment or depletion.
(g) In addition to the annual publication of OECD P balances, it should be compulsory to prepare an every-5 year evaluation of the P supply levels of all agriculturally cultivated land for submission to the OECD, the EEA, EUROSTAT, etc.
(h) The benefit from all these changes should go to the local communities.

5 Changes in the Livestock Densities in the EU Countries, and Their Correlation to the Cumulative NP Balances

One of the major problems of agricultural diffuse NP loads to the environment is livestock density exceeding 100 LU/100 ha agricultural land in certain countries or regions in the EU (Fig. 13).

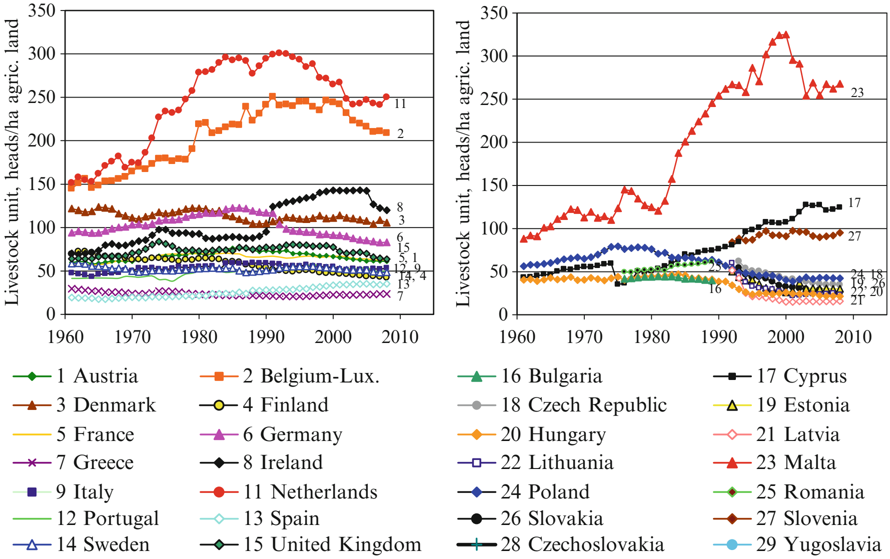


Fig. 13 Changes in livestock density in the former EU15 countries, as well as in the new EU12 countries, 1960–2008 (FAO 2005; EUROSTAT 2005)

If we take into consideration, that the three leading new EU12 countries, respecting livestock density, i.e., Malta, Cyprus and Slovenia, occupy only 1.1% of agricultural land of the new EU12 countries, we can recognize how dramatic is the difference in livestock density between the western and eastern part of EU.

Within the EU countries, there is a strong positive correlation between cumulative NP balances and livestock densities, expressed in livestock units (Fig. 14).

6 Conclusions and Recommendations

Based on the results found in investigating the NP turnover of the EU 27 countries since 1991, it seems to be obvious, that in the present situation, when livestock densities are marked–driven (regulated by free moving of capital), EU agro-environmental, social, and rural development policies are not effective.

It is suggested that legislation in the European Union should be consistent against both point source, and diffuse NP loads to the environment, derived from agricultural production.

It seems that only through a major restructuring the livestock distribution in the EU, and only trough a major restructuring of the export-import policy of agricultural goods, and the price policy of the agricultural goods within the EU, the aims of the various directives, strategies, and policies, and the new SPS system can and will be fulfilled.

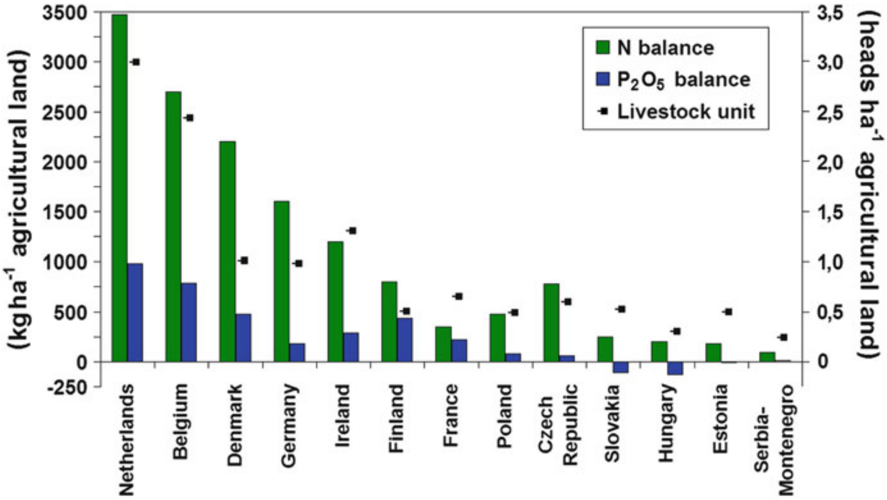


Fig. 14 Estimated cumulative NP balances between 1991 and 2005 as well as livestock density of several European countries (Csathó and Radimszky 2009)

For effective agro-environmental policy in the future, it seems that, based on NUTS-2 levels, EU should pay 0.75 livestock unit per hectares agricultural land subsidies for every EU countries/NUTS-2 levels as an average, regardless the existing livestock densities. This way the EU would be able to work for establishing sustainable livestock densities in each EU country. For turning towards effective environmental protection policy in the EU, it seems to be, that a paradigm shift would be needed, from the market driven economy, into an economy, in which the effective environmental protection, agronomic, social, and rural development policies should enjoy priorities over market based interests.

Based on the principle of subsidiarity it seems that this problem can be solved only in highest EU level, through the EU legislation and EU administration.

The benefit from the changes should go towards the local farmers, farmer associations, and the local communities.

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Tomato Production for Human Health, Not Only for Food

Reza Ghorbani, Vahid Poozesh, and Surur Khorramdel

Abstract The concept of growing crops for health rather than only for food or fiber is becoming a major issue. Since standards of living have improved, food availability and connection between plant production practices and human health are launching new issues of dietary supplements, functional foods and plant-produced recombinant proteins. Consumption of fruits and vegetables is also beneficial to human health since fruits reduce the risk of developing cancer and cardio-vascular diseases. Although tomato have for many years been bred and grown for food, the development and production of health-beneficial tomatoes is of research interest. However the effect of production management practices, processing and storage conditions on quality and health aspect of tomato is not well-known.

Tomato, *Lycopersicum esculentum* L., is one of the world's major vegetables, with an excellent source of health-promoting compounds such as various nutrients, secondary metabolites, ß-carotene, lycopene, vitamins C and E, flavonoids and various phenolic compounds. Dietary intake of tomato and tomato products containing lycopene have been shown to be associated with decreasing risk of cardiovascular diseases and certain types of cancer. Maximizing tomato fruit quality, nutritional contents and mentioned phytonutrient in tomato can be affected by (i) environmental factors such as radiation, temperature, humidity, atmospheric CO_2, air pollutants, soil properties, water quality, mineral nutrition, salinity, mechanical and pest injuries; (ii) agricultural practices and cropping system, and (iii) genetics and seed genotype. The nutrition quality and human health related properties of tomato fruits, especially carotenoids, flavonoids, phenols and antioxidant compounds, are strongly

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affected by light, temperature, air CO_2 content, air pollutants, water rate and availability, irrigation regim and system, salinity and other quality aspects of water, soil structure, soil physical and chemical characteristics, mineral and organic fertilizers and soil organic matter. Those quality values of tomato fruits are developing during ripening stages and thus ripening is a very important stage. Appropriate processing approach and post-harvest storage conditions can also give tomato a higher quality value. In most cases, organic production and low input systems produced tastier and more flavoured fruits, containing higher lycopene, organic acids, phenolic and ascorbic acids, secondary metabolites, vitamin C and E compared to conventional tomato.

Keywords Antioxidants • Human health • Lycopene • *Lycopersicum esculentum* • Phytonutrients • Secondary metabolites

1 Introduction

Rapid changes in diets and lifestyles that have occurred with industrialization, urbanization, economic development and globalization, have accelerated over the past decade. This had a significant impact on the health and nutritional status of human populations, particularly in developing countries and in countries in transition. While standards of living have improved, food availability has expanded and became more diversified. Rediscovery of the connection between plants and health is responsible for launching a new generation of botanical therapeutics that include plant-derived pharmaceuticals, multicomponent botanical drugs, dietary supplements, functional foods and plant-produced recombinant proteins (Raskin et al. 2002). The consumption of fruits and vegetables is beneficial to human health, since they reduce the risk of developing serious diseases such as cancer and cardio-vascular disease (Dumas et al. 2003). A healthy diet is an important factor in preventing chronic diseases and improving energy balance and weight management (Dorais et al. 2008).

Consumer's interest in the quality of vegetable products has increased in recent years worldwide. There are studies have documented methods for achieving a high-quality vegetable product. The quality of the harvest fruit is of major concern to growers because fruit is regarded according to external attractiveness (e.g., colour, size, shape and skin defects) or internal characteristics such as taste and texture (Fleisher et al. 2006; Shi et al. 2002). Fruits and vegetables are rich in dietary vitamins, minerals and fiber and are the primary source of flavonoids in the diet (Mitchell et al. 2007). The factors which strongly influence the quality of tomato fruits are climate, soil, and crop management (Dadomo et al. 1994). Good quality does not always require higher growing costs, because a lower input is often better.

Tomato (*Lycopersicum esculentum* L.) is one of the most popular and extensively consumed vegetable crops worldwide. It is one of the most extensively marketed vegetable foods, with a worldwide production of 126 million Tm in 2005. Tomato fruits constitute an excellent source of health-promoting compounds due to the balanced mixture of minerals and antioxidants including vitamins C and E, lycopene, ß-carotene, lutein and flavonoids such as quercetin (Beecher 1998; Dorais et al. 2008). In particular, the consumption of tomatoes and its products have been associated with a lower risk of developing digestive tract, prostate cancer (Giovannucci et al. 1995; Shi and Le Maguer 2000), chronic degenerative diseases such as certain types of cancer (Giovannucci 1999) and cardiovascular diseases (Pandey et al. 1995; Agarwa and Rao 2000). Antioxidant components of tomatoes reported to be influenced by different factors such as cultivar, growing conditions, season, harvesting stage and ripening on-and off-vine (Abushita et al. 1997; Davies and Hobson 1981; Giovanelli et al. 1999; Toor et al. 2005, 2006b).

Objective of the present study was to update the knowledge available and to review the recent literatures of the main factors that can improve the nutritional quality and quantity of tomato and consequently their beneficial roles in human diet. The effects of environmental factors and agricultural practices on the beneficial components of tomato fruit such as nutrient qualities, lycopene, vitamin C, vitamin E and the main phenolic antioxidant compounds were studied.

2 Tomato Quality and Human Health

In addition to tomato quantity which is more important for producers, the quality of tomato fruits, nutrient composition, soundness, taste, size, dry matter content, colour, viscosity, etc are also important for many producers and consumers (Dumas et al. 2006). Tomato has several components that contributing to human health (Huyskens-Keil and Schreiner 2004; Tonucci et al. 1995). Two main carotenoids are present in tomato: lycopene, which is the major carotenoid compound (90–180%) giving the red colour to the fruit (Nguyen and Schwartz 1999), and ß-carotene, which is 7–10% of the total carotenoid content (Gould 1974). Moreover, carotenoids are a major class of compounds providing precursors to essential vitamins and antioxidants (Dorais et al. 2008). The content of carotenoids in tomatoes is important, not only due to the colour they impart, but also due to their acknowledged health benefits. Lycopene is a hydrocarbon carotenoid, $C_{40}H_{56}$, with molecular weight of 537. In nature, it is most abundantly found as the red pigment of watermelon and tomato. It is a natural antioxidant due to its ability to act as a free radical scavenger. It has the highest singlet oxygen quenching rate of all carotenoids in biological systems (Di Mascio et al. 1989; Tinker et al. 1994). The amount of this carotenoid in raw tomatoes depends on the variety, stage of maturity and the environmental conditions during cultivation (Shi 2000). Therefore, considerable work has been conducted to increase their levels in tomatoes through breeding programmes or ripening intervention technologies during post-harvest storage (Liu et al. 2009; Rosati et al. 2000).

Tomato fruits contain phenolic compounds, which also exhibit a strong antioxidant activity (Shahidi and Wanasundara 1992). Since the taste, colour and nutrient qualities of tomatoes can also depend on their antioxidant contents, further insights into the factors likely to affect their composition should help to define the quality of tomatoes more clearly (Dumas et al. 2003; Gitenay et al. 2007). Antioxidants are believed to be important in the prevention of disease such as cancer and cardiovascular disease. Lycopene is one of the main antioxidants to be found in fresh tomatoes and processed tomato products (Dumas et al. 2003). Lycopene content also accounts for the redness of the fruits, which is one of the main qualities for which industry and consumers now look. Other carotenes (such as ß-carotene), vitamin C, vitamin E and various Phenolic compounds are also thought be health-promoting factors with antioxidant properties (Dumas et al. 2003).

Antioxidant and free radical-scavenging properties of polyphenol compounds in several plant extracts reported, suggesting possible protective roles of polyphenol compounds in reducing risk of cardiovascular diseases in humans (Velioglu et al. 1998). Moreover, tomato contains flavonoids, in particular rutin and naringenin. Some papers pointed out those tomato flavonoids, due to their high antioxidant power and to the significant biological activities, can have a substantial role in the health benefits attributed to the tomato consumption (Bourne and Rice-Evans 1999; Hertog et al. 1993). High intake of tomato juice prevents low density lipoproteins (LDL) oxidation and thiobarbituric reactive species (TBARS) formation in healthy men (Bub et al. 2000; Gitenay et al. 2007). Studies showed that lycopene exhibits antioxidant activities (Di Mascio et al. 1989), suppresses cell proliferation (Levy et al. 1995) and interferes with the growth of cancer cells (Clinton et al. 1996; Giovannucci et al. 1995). The beneficial effects of tomato consumption are generally attributed to carotenoids, which are able to reduce the risk of certain types of cancer, cardiovascular disease, arteriosclerosis, cataract formation and age-related macular degeneration (Clinton 1998; Dorais et al. 2008; Hadley et al. 2002; Heber and Lu 2002; Giovannucci et al. 1995; Giovannucci and Clinton 1998; Sandstrom et al. 1994; Weisburger 1998). Several epidemiological studies have reported that the dietary intake of carotenoids reduces the incidence of degenerative diseases, including heart disease and cancer. Lycopene, through tomato sauce consumption, reduces leukocyte and prostate tissue oxidative DNA damage and decreases prostate specific antigen (PSA) level in prostate cancer patients (Chen et al. 2001; Gitenay et al. 2007).

In conclusion, nutrient qualities, antioxidant contents, taste and colour of tomato fruits can depend on the contents of their lycopene, ß-carotene, vitamin C, vitamin E, flavonoids and various phenolic compounds. These tomato compounds have antioxidant activities, reduce risk of cardiovascular diseases, arteriosclerosis, cataract formation, leukocyte, prostate cancer; suppress cell proliferation and interfere with the growth of cancer cell.

3 Tomato Quality, Environmental Factors and Agricultural Practices

For field tomato crops, changes in nutritional value are often described in terms of variation in geographic location or season, which include interactions among several factors, making interpretation difficult. For example, higher altitudes reduce temperature but increase visible and UV light, which may increase the level of certain phytonutrients such as carotenoids since their major function is to absorb light during photosynthesis and to protect cells against excessive light. On the other hand, carotenoids in the fruit of protected tomato crops were found to be higher at the end of the harvest period than at the first harvest in May (Auerswald et al. 1996). This could be partly due to differences in light but also to the poorer plant water status in older plants. Therefore, a better understanding of the interaction among environmental factors, agronomic practices and cultivar is required. The two best-known environmental factors influencing the quality value of tomato are light and temperature.

3.1 Light

In tomato plants, dry matter production and quality of fruits are influenced directly by photosynthetic activity of leaves. Light has the most profound effect on the fruit sugar concentration. Generally, more sunlight reaching the fruit results in higher sugar content. As a consequence, greenhouse tomatoes grown during the winter months contain substantially less sugar than field-grown tomatoes in the summer (Mikkelsen 2005). Also, phytonutrients of tomato such as vitamin C, carotenoids and phenols are strongly affected by the intensity, duration and quality of radiation. For example, several studies showed that antioxidants such as vitamin C, lycopene, ß-carotene and phenols increased with light intensity (Amiot et al. 2007; Ju et al. 1999; Lee and Kader 2000; McCollum 1954; Merzlyak et al. 2002). Although light is not essential for the synthesis of ascorbic acid, the amount and intensity of light during the growing season influences its content in the fruit because ascorbic acid is synthesized from sugars supplied through photosynthesis (Lee and Kader 2000). In fact, positive correlations were observed between fruit sugar content and vitamin C and lycopene content (Gautier et al. 2005). Similarly, even though the formation of carotenoids in ripening tomato fruit does not require induction by light, but light plays a fundamental role in determining the content of carotenoids. On the other hand, the biosynthesis of anthocyanins in maturing fruit is a light-dependent process (Lancaster 1992) requiring a photomorphogenic signal mediated by photoreceptors. The involvement of a UV-B photoreceptor, phytochromes or cryptochromes has been suggested (Adamse et al. 1989; Giliberto et al. 2005; Kerckhoffs et al. 1992; Mol et al. 1996; Ninu et al. 1999). Sufficient energy of light is also important to promote photosynthetic production of carbohydrates, which are the substrates for flavonoid biosynthesis via the shikimic acid and phenylpropanoid pathways. Formation of flavonol glycosides such as kaempferol and quercetin also requires light, but not all phenolic synthesis is responsive to light (Dorais et al. 2008).

Tomato is a climacteric fruit and continues to ripen after harvest. During ripening, the green pigment chlorophyll degrades and carotenoids are synthesized. Light duration also affects phytonutrient levels. Even though light is not required for the ripening of tomato picked at the breaker stage, fruit exposed to an 8 h photoperiod failed to develop lycopene levels as high as those in 24 h exposed fruit (Cox et al. 2003).

Carotenoids, particularly lycopene and ß-carotene, represent the primary components of ripe fruit pigmentation in tomato pericarp and are responsible for the characteristic colour of ripe tomatoes, conferring deep red and orange colours, respectively. These carotenoids largely influence the quality perception of fresh tomatoes (Liu et al. 2009). Alba et al. (2000) reported that red light treatments (six 40W Gro-lux lamps) increased lycopene accumulation 2.3-fold in tomatoes and that red light-induced lycopene accumulation was reversible by far-red light treatment. Red light treatment increased the carotenoid content and red color of tomatoes, with varying effects on tomato firmness (Lee et al. 1997). Schofield and Paliyath (2005) and Liu et al. (2009) showed that the lycopene contents of the tomatoes were increased greatly by red light treatment, compared to those of control tomatoes. Sun light had the least impact on tomato lycopene content but red light stimulates carotenoid accumulation in tomato, while far-red light stops the production of carotenoids such as lycopene, probably from fruit-localized phytochromes (Alba et al. 2000; Thomas and Jen 1975).

In contrast, under excessive solar radiation or UV radiation of only a few hours, photo-oxidative damage or photoinhibition may occur and reduce lycopene synthesis as well as vitamin C content of tomato fruit (Adegoroye and Jolliffe 1987; Prohens et al. 2004). Torres et al. (2006) observed, either with or without UV radiation, that tomato fruit exposed for 5 h to high solar irradiance had 30% less ascorbic acid and 20% less dehydroascorbic acid in the fruit exocarp, suggesting a partial degradation of the entire ascorbate pool. They also observed a decrease in total carotenoids after 5 h of exposure, with a significant interaction between duration of exposure and intensity of UV radiation. Moreover, UV light seems to have a physiological effect on tomatoes, to our knowledge there are no reports on the effect of UV light treatment on the concentration of the major carotenoids in tomatoes (Liu et al. 2009). The UV-C treatment also increased the lycopene content of tomatoes during storage. Liu et al. (2009) demonstrated that the sun light treated tomatoes had a 1.5-fold increase in lycopene content at day 21 of storage, when compared to that of untreated control tomatoes. This indicates that light (especially at UV-C wavelengths) might be a specific regulator of carotenoid synthesis and accumulation in tomatoes during postharvest storage (Liu et al. 2009). Even though the production of flavonoids and other phenylpropanoids may be stimulated to protect plant tissues from UV damage (Dixon and Palva 1995; Ubi 2004), natural UV radiation does not always affect flavonoid accumulation. Torres et al. (2006) found that tomato exocarp had no detectable changes in concentrations of flavonoids (quercetin, kaempferol, or naringenin enantiomers) as the duration of exposure increased.

Therefore, The quality of tomato fruits especially carotenoids, phenols and antioxidant compounds rates are strongly affected by various aspects of light such as intensity, duration, UV radiation and quality of radiations. Thus tomato quality differs in different climatic conditions and cropping systems such as protected production system or field production. However, the effects of light also depends on field conditions e.g. crop and weed densities, crop residues and mulches, plant population and shading screens that influence light interception and consequently fruit phytochemical content and its quality value related to human nutrition.

Interference of weeds with light in an organic tomato field

3.2 Temperature

Temperature has a direct influence on plant metabolism which has effect on tomato fruit development and its nutritional value (Dorais et al. 2001a; Heuvelink and Dorais 2005).

Fruit temperature affects final fruit composition (Gautier et al. 2008). Air temperature is known to influence tomato production scheduling and, during commercial production, the timing, magnitude and duration of temperature changes can be significant (Fleisher et al. 2006). Tomato plants have, within certain limits, the ability to integrate temperature (Adams et al. 2001). Plants exposed to a fluctuating temperature regime often suffer no overall loss of yield when compared with those grown in a constant regime having the same mean temperature (DeKoning 1990; Hurd and Graves 1984; Khayat et al. 1985). However, fluctuations in temperature may affect the pattern of crop yield as the rate of developmental events such as fruit maturation is determined largely by temperature (Hurd and Graves 1985). DeKoning (1994) indicated that the sensitivity of fruits to temperature interacted with their stage of development, with fruits being less sensitive to temperature in the middle stages of their development. Furthermore, temperature extremes can inhibit the ripening process (Lurie et al. 1996). Temperature affects not only the time of fruit ripening but also the rate of fruit growth. Pearce et al. (1993) found that in the short term the expansion of tomato fruits was closely related to temperature and did not appear to be limited by assimilate supply. Elevating the temperature often increases the fruit growth rate, but it has a greater effect in hastening maturity and, as a result, the final mean weight of tomato fruits is reduced (Hurd and Graves 1985). Adams et al. (2001) suggested that fluctuations in weekly fruit yields may well result from fluctuations in temperature due to the increased sensitivity of mature green fruits to temperature. Low temperatures reduced absolute volume growth rates and delayed the time at which the absolute growth rate became maximal. Temperature also affected the shoot dry matter content and partitioning (Adams et al. 2001).

In the literature available, the main information about the effects of temperature on the antioxidant content of tomato fruit is basically related to the caretonoids (Dumas et al. 2003). Tomatoes exposed to direct sunlight in the field often develop a poor colour, mainly because the fruit exposed to high temperatures have low lycopene content (McCollum 1954). The rate of lycopene synthesis and other carotene content drastically (not that of ß-carotene) reduced at 30°C in fresh tomatoes (Baqar and Lee 1978; Grierson and Kader 1986). In the fruit pericarp sections stored at various temperatures (Hamauzu et al. 1998) the biosynthesis and accumulation rates of phytoene and lycopene were first, whereas those of ß-carotene were low at 20°C. At 30°C, the rates for both lycopene and ß-carotene were higher and the rate for phytoene was low (Dumas et al. 2003). Gautier et al. (2005) reported decreases in sugar and lycopene content in cherry tomato when fruit temperatures were increased by approximately 1°C following fruit-set through harvest under high fruit load.

Tomato fruits are rich in polyphenols, which is the largest part of phenolic compounds like flavonoids and phenylpropanoids. At 35°C compared to 25°C the phenol level was doubled (Helyes et al. 2006). George et al. (2004) measured huge variance among polyphenol (104 – 400 mg·kg^{-1}) content of different tomato varieties. Temperature had a significant influence on the biosynthesis of lycopene and ß-carotene during ripening (Krumbein et al. 2006). They showed that a temperature above 20°C seems to be optimal for lycopene production in studied cultivars, whereas the lycopene content diminished with decreasing temperature to 15°C. Temperatures below 12°C strongly inhibit lycopene biosynthesis and temperatures above 32°C stop this process (Dumas et al. 2003). Fleisher et al. (2006) resulted that colour indices, soluble solids contents (SSD), acidity and viscosity at each ripening stage were significantly affected by high temperature treatments. The results indicate that short-term temperature perturbations following first fruit-set can influence the rates at which change occurred in the external appearance of fruit (colour) and in their internal characteristics. As carbon skeleton availability is required for the biosynthesis of certain phytonutrient compounds such as flavonoids and ascorbic acid, an increase in sugars through reduced respiration under lower temperatures may result in a higher level of phytochemicals. Consequently, ascorbic acid generally declines with increasing temperature, while temperature regulation of caretonoids is crop specific.

The marked effect of temperature upon the production of lycopene was first discovered by Duggar (1913). This remarkable contribution showed conclusively that a temperature of 30–37°C clearly inhibited the development of lycopene both in detached fruit and in fruit growing on the vine. The factors for reddening were not destroyed by the high temperature, for upon return to a temperature of 20°C. Lycopene formation occurs only at temperatures above 10°C and below 37°C. The optimum temperature depends on the genotype and interactions with environmental and cultural factors (Dorais et al. 2001a). On the other hand, Krumbein et al. (2006) recently observed an increase in the lycopene concentration of cherry and round type tomatoes when the temperature during the fruit ripening stage increased from 15°C to 20.3°C in fall and from 18°C to 22°C in spring. In agreement with Robertson et al. (1995) who found a maximum plateau of lycopene concentration between 18 and 26°C in cell suspension cultures. Krumbein et al. (2006) suggested that the optimal temperature for lycopene biosynthesis ranges between 20°C and 24°C. Also, Krumbein et al. (2006) indicated that temperature has a significant influence on the biosynthesis of lycopene and ß-carotene during ripening. They found that a temperature above 20°C seems to be optimal for lycopene production in the investigated cultivars, whereas a decrease to 15°C diminished the lycopene content. Generally, temperatures below 10°C or higher than 30°C inhibit the development of lycopene (Koskitalo and Ormrod 1972; Tomes 1963). Hence, cool night temperatures for field tomato crops reduce fruit carotenoids. In contrast to lycopene, ß-carotene of tomato is only slightly affected by high temperature, probably due to the conversion of lycopene into ß-carotene under high temperature conditions. Lycopene formation proceeded rapidly. For tomato, lycopene synthesis is highest when the temperature ranges between 12 and 21°C.

Gautier et al. (2008) showed that sugars and acids (linked to fruit gustative quality) were not considerably modified, but secondary metabolites with antioxidant properties were very sensitive to temperature. They demonstrated that increasing the temperature from 21°C to 26°C reduced total carotene content without affecting lycopene content. A further temperature increase from 27°C to 32°C reduced ascorbate, lycopene and its precursor's content, but enhanced rutin, caffeic acid derivates and glucoside contents. The effects of the temperature on the synthesis of other antioxidants have not yet been properly assessed (Dumas et al. 2003). Dorais (2007) found that the use of a low temperature pulse (12°C compared to 15°C, over a 2–4 h period) at the end of the photoperiod for a same 24 h average temperature (18.5°C) decreased the lycopene content of the fruit and their antioxidant activity. Consequently, the widespread use of a prenight low temperature by greenhouse growers to control plant balance may affect the health qualities of fruit at harvest. At 35°C, the rates for ß-carotene were high, but lower than at 30°C and the levels of phytoene and lycopene accumulated were both very low. It was postulated that high temperatures (35°C) specifically inhibit the accumulation of lycopene because they stimulate the conversion of lycopene into ß-carotene. Formation of lycopene depends on the temperature range and seems to occur between 12 and 32°C (Leoni 1992). However, the majority of studies on the influence of temperature on fruit quality parameters have focused on post-harvest fruit ripening (e.g., Dalaa et al. 1968;

Lurie et al. 1996). The production of lycopene is inhibited by excessive sunlight and the best conditions are sufficiently dense foliage to protect the fruit from direct exposure to the sun (Leoni 1992).

In conclusion, various aspects of temperature such as temperature regim, timing, duration, fluctuations and extremes have strong effects on production scheduling, tomato growth and development, shoot dry matter weight, carbohydrate partitioning, fruit ripening, yield, fruit colour, caretonoids, lycopene, phenolic compounds and other secondary metabolites, acidity, ascorbic acid and fruit viscosity.

3.3 Atmospheric CO_2

Atmospheric carbon dioxide (CO_2) has increased about 35% since 1800 (from 280 to 380 part per million [ppm]), and computer models predict that it will reach to much higher (IPCC 2001). The beneficial effects of elevated CO2 concentrations on biomass production of horticulture crops such as tomato are well known (Dorais et al. 2001a; Nederhoff 1994; Heuvelink and Dorais 2005). This rise in CO_2 could potentially be mitigated by plants, in which photosynthesis converts atmospheric CO_2 into carbohydrates and other organic compounds. The extent of this mitigation remains uncertain, however, due to the complex relationship between carbon and nitrogen metabolism in plants (Finzi et al. 2007; Johnson 2006; Reich et al. 2006). The enhancement of growth and yields by increasing the level of CO_2 in the atmosphere has been reported for many plant species (Kimball 1983). Atmospheric CO_2 enrichment is known to significantly enhance the growth and development of nearly all plants, implying a potential for elevated levels of CO_2 to alter the concentrations of plant constituents related to animal and human health (Idso and Idso 2001). Atmospheric CO_2 enrichment additionally appears to reduce oxidative stresses in plants and it has been shown to increase the concentration of vitamin C in certain fruits and vegetables. Significant yield increases for most plant species are observed in with CO_2 enrichment (Idso and Idso 2001). Yelle et al. (1989) showed that tomatoes accumulated starch and sugars when exposed to high CO_2 concentration.

In many crops depend on nitrate rate as their primary nitrogen source, with increasing atmospheric CO_2 concentrations and diminishing nitrate assimilation, organic nitrogen, including protein depleted and food quality suffered (Taub et al. 2008). Wheat, rice and potato provide 21%, 14% and 2%, respectively of protein in the human diet. At elevated carbon dioxide and standard fertilizer levels, wheat had 10% less grain protein (Fangmeier et al. 1999; Kimball et al. 2001). Similarly, water and assimilate influx to the fruit i.e. between the fluxes of the phloem and xylem saps and of the fruit transpiration will suffer (Guichard et al. 2001). In contrast, they showed that acids and products of the secondary metabolites that are synthesized during the maturation stages could not be linked to the water and carbon fluxes between the plant and the fruit. Based upon data, it has been determined that when the 75% increase in the CO_2 concentration doubles fruit production, it increases the vitamin C concentration of the juice of the fruit 7%. This nutritional enhancement is even greater in years when fruit production is more than doubled, due to the CO_2-enriched fruit being slightly smaller than the ambient-treatment fruit in such circumstances, which increases the vitamin C concentration of the juice of the CO_2–enriched fruit (Idso and Idso 2001). In the case of ascorbate or vitamin C, Barbale (1970) and Madsen (1971) observed CO_2-inuced increases in the concentration of this important phytochemical in both the leaves and fruit of tomato plants; Kimball and Mitchell (1981) also found that atmospheric CO_2 enrichment stimulated the production of vitamin A in tomato plants.

Clearly, there are many good reasons and experimental evidences to justify the hypothesis that increase air CO_2 content and promote the production of phytochemicals beneficial to human health (Idso and Idso 2001). It is likely, therefore that the ongoing rise in air CO_2 content will continue to increase food production around the world, while maintaining the nutritive quality of that food will be enhanced.

3.4 Air Pollutants

One of the major environmental concerns recent years is the excessive pollution of air. Air pollution is the introduction of chemicals, particular mater or biological materials that cause harm or discomfort to humans and other living organisms or damage the natural environments. The pollution has attained such unacceptable levels that vast forest areas have been damaged, agricultural production lowered and the health of the whole population endangered (Upadhyay and Kobayashi 2007). Air pollutants such as dust, ozone, sulphur dioxide, nitrous oxide, nitrite-N and ammonia decreased ascorbic acid, carotenoids and Bcomplex vitamins in many fruits mainly due to their oxidative damage to fruit DNA, proteins, synthesizing enzymes and membranes (Lester 2006). One of the physiological processes that can alter or reduce the nutritional quality and the antioxidant activity of plant products is oxidative stress (Rosales et al. 2006). Ozone can alter secondary metabolites such as flavonoids or other phenolic compounds, through changes in the activity of Phenylalanine Ammonia-lyase (PAL) and thus the status and productivity of the whole phenylpropanoid pathway (Manning and Tiedemann 1995). Carbon allocation in plants may also be affected by O_3 via effects on photosynthesis and modification of the canopy structure, and hence the environment around the fruit, which may indirectly affect their nutritional value.

Air pollutants had effects on carbon allocations, ascorbic acid and caretonoids phenolic compounds in tomato; however, there are only limited references available. Effect of air contaminants produced by volatilization of pesticides under elevated temperature on health-promoting compounds is also another aspect that has not been extensively investigated in tomato fruit.

3.5 Water and Salinity

Water deficit and poor water quality are the main factors limiting worldwide crop productivity and food quality in terms of nutritional value and food safety (Dorais et al. 2008). Changes in soil-water relations can affect the quality and the yield of crop harvests depending upon irrigation frequency and availability of soil water to the plants (Mitchell et al. 1991). The amount of water applied is dependent on irrigation schule, soil properties and evapotranspiration rates which are in turn influenced by crop environment and stage of growth. Irrigation schedule can impact positively or negatively on the growth and yield of tomato (Lecoeur and Sinclair 1996; Locascio et al. 1981; Obreza et al. 1996) depending on the amount of water applied. Therefore, it is important to determine optimal irrigation regimes that promotes yield and quality of tomato for specific localities, which are essential for successful marketing of tomato (Phill and Lambeth 1981).

Irrigating a tomato field in a semi-arid conditions of Iran

Nutritional quality of tomatoes may be affected by the amount of water applied, regardless of fertilizer management, and their irrigation system. For example, heavy rainfall may reduce the oxygen concentration in the soil, and indirectly affect the nutritional value of fruit. Depending on the production system, irrigation water is generally provided by surface and subsurface irrigation, sprinkler irrigation or micro-irrigation (Locascio 2005). Given the scarcity of high quality water in many parts of the world, deficit irrigation can constitute a sustainable tool for water conservation and reduction of leaching into ground water, as well as a plant management tool to improve the nutritional value of tomato fruit. Depending on cultivar, low soil water tension generally decreased the vitamin C content of the fruit (Rudich et al. 1977). For example, drip irrigation increased the tomato ascorbic acid content compared to surface irrigation due to a reduced amount of water available to the fruit (Mahajan and Singh 2006).

Analysis of cherry tomato produced under the influence of moderate salt stress showed increases in the lipophilic antioxidative ability and the amount of carotenoid, whereas the level of glycoalkaloid decreased (Leonardi et al. 2000). Tomato fruit is an organ with slow transpiration, and more than 85% of the water is supplied via the phloem. Water stress induced by high salinity mainly restricts the amount of water supplied to the fruit by the phloem, whereas the concentration of the phloem sap is increased (Ho et al. 1987). Under water stress conditions, increase in abscisic acid may influence ethylene production, which has an effect on the concentration of carotenoids. Salinization is generally accompanied by a decrease in yield, the use of salinized water increased healthpromoting molecules in tomato and its nutritional value (Dorais et al. 2001b). Because high salinity in the root zone impairs water uptake, the increase in health-promoting molecules may have been related to a water stress and a concentration effect. Moderate stress, however, may activate physiological antioxidant responses (Gomez et al. 1999; Smirnoff 1995) and thereby improve carotenoid levels and antioxidant activity in tomato fruit. More specifically, lycopene concentration may increase with moderate salinity due to an up-regulation of gene encoding enzymes involved in the key steps of lycopene biosynthesis, while inhibition may result under higher salinity, resulting in reduced lycopene content. However, the nutritional quality threshold varies depending on cultivar and growing conditions as well as on targeted phytonutrients. For example, under moderate salinity where greenhouse crop fruit yield was not reduced, adding NaCl to the nutrient solution to improve flavour did not affect phytonutrients such as antioxidant vitamins (ascorbic acid, a-tocopherol), carotenoids (lycopene and lutein), or flavonoids (quercetin) (Shi et al. 2002). An increase in salinity by 45% with NaCl or NaCl/KCl (1:1) did not change lycopene content, but it decreased ß-carotene and vitamin C content and increased lutein concentration by 79% (Dorais et al. 2000). With different tomato cultivars and growing conditions, however, Wu et al. (2004) observed a 34–85% increase in lycopene content on a fresh weight basis when salinity was increased from 2.4 to 4.5 $mS \cdot cm^{-1}$. De Pascale et al. (2001) observed that the optimum total carotenoids and lycopene content were reached when salinity was 4.0–4.4 $mS \cdot cm^{-1}$ (0.25% NaCl), while ascorbic acid content increased with salinity up to 15.7 $mS \cdot cm^{-1}$. Carotene did not change with salinity. Similar results for ß-carotene were found by other authors (Petersen et al. 1998; Krauss et al. 2006).

Salinity in non-tolerant cultivars may reduce leaf area of tomato plants, modifying the light and temperature conditions of the fruit, and thereby indirectly influencing the phytonutrient content. This genotype-dependent plant response may partly explain different results and thresholds reported in the literature. Salinity also changed mineral uptake profiles (Ehret and Plant 1999). For example, increasing water salinity from 0.5 to 15.7 $mS \cdot cm^{-1}$ with NaCl decreased P, K, Mg and Zn fruit concentrations due to ion competition with Na and Cl (De Pascale et al. 2001), which is undesirable. On the other hand, salinity decreased fruit nitrate content, which is desirable for food processing and human health (De Pascale et al. 2001).

In summary, water rate and availability, irrigation regim and system, salinity and other quality aspects of water are important studied water related factors that could change tomato fruit yield, quality, nutritional value, caretonoids, lycopene, ascorbic acid contents and lipophilic antioxidative ability.

3.6 Soil Conditions

Soil is the fundamental medium for crop growth in all production systems. The success of any system depends to a large extent on the soil characteristics such as nutrient supply and structural characteristics that affect rooting. Soil conditions influence crop growth indirectly by affecting weed growth, pests and diseases as well as directly by supplying water and nutrients (Ghorbani et al. 2008b). A good soil structure is very important in having a successful tomato crop. It not only affects crop productivity, it also influences the quality of fruit tomato. When a soil and consequently plant is not healthy, it won't be resistant to disease and pests. Tomatoes prefer a soil that is deep, loose, rich and with plenty of organic matter with a pH level of 6.5 to 7.0.

The effect of minerals on phytonutrients and nutritional value of tomato depends on the specific mineral, the mineral form, the plant genotype, and any possible interactions with environmental conditions and agronomic practices. In general, even though moderate application of N increases yield, N fertilizers decrease the concentration of vitamin C and carotenoids, while K fertilization has the opposite effect. Secondary plant metabolites which lack N in their structure such as lycopene, ß-carotene, phenolics and flavonols are favoured under N-limiting conditions although photosynthetic activity is not simultaneously reduced, whereas nitrogen-containing compounds are favoured when N is readily available and not limiting to growth. Phosphorous may increase the level of some phytochemicals like ascorbic acid, anthocyanins, flavonoids and lycopene, although interactions with climatic factors and growing season may occur (Bruulsema et al. 2004; Lester 2006), while boron availability affects phenolic content (McClure 1975). According to Mozafar (1994), ascorbic acid increases with increasing levels of P, K, Mn, B, Mo, Cu, Co and Zn, while ß-carotene increases with increasing levels of K, Mg, Mn, B, Cu and Zn, and B-complex vitamins increase with increasing levels of N, P and B (Lester 2006). Thus, good nutrition is vital for maintaining health and preventing disease (Hamouz et al. 2005).

Several studies demonstrated direct and indirect effects of plant nutrition on tomatoes. The enhanced nutrition treatment was found to have a significant positive effect on tomato quality, color and acceptability (Kimball and Mitchell 1981). Lowering nitrogen supply had a low impact on fruit commercial yield (−7.5%), but it reduced plant vegetative growth and increased fruit dry matter content, improving consequently fruit quality. Fruit quality was improved due to lower acid (10–16%) and increased soluble sugar content (5–17%). The content of some phenolic compounds (rutin, a caffeic glycoside and a caffeic acid derivate) and total ascorbic acid tended to be higher in fruit with the lowest nitrogen supply. It was concluded that primary and secondary metabolites could be affected as a result of a specific response to low nitrogen, combined with a lower degree of vegetative development, increasing fruit irradiance and therefore modifying fruit composition (Bénard et al. 2009). Nitrogen fertilizer has generally been thought to increase the carotene concentration in plants (Mozafar 1993) but few specific data are available in the literature in this point. A number of studies carried out during the last 50 years or so have consistently shown that increasing the N rates tends to decrease the vitamin C content of the fruit. Mineral nutrition had first been thought to have no effect on the ascorbic acid content in several varieties (Hamner et al. 1945). However, heavy N application might cause some vitamin C decrease, probably for indirect reasons, since N supply might enhance the foliage and hence the shading of the fruit on plants unevenly illuminated by direct sunshine (Dumas et al. 2003). In another study (Montagu and Goh 1990) where various forms of nitrogen at four rates were applied to tomatoes in pots, the fruit vitamin C content decreased almost linearly from about 320 mg·kg^{-1} fm to about 230–250 mg·kg^{-1} fm when the N applied was increased from 0 to 600 kg·ha^{-1}. Therefore, supplementary N, especially at high rates, generally tends to decrease the tomato fruit vitamin C content, possibly due to the increased shading caused by the greater development of plant foliage due to high N availability. The present tendency to reduce the N supply in agriculture as far as possible for food quality and environmental reasons and to reduce the production costs may, therefore, contribute to maintaining a high vitamin C content in tomatoes. It has been reported in several papers that the vitamin C content of tomatoes could increase with the supply of combined fertilizers.

Potassium by influencing the free acid content and P due to its buffering capacity directly affects tomato quality. It was observed that potassium (K) had a significant effect on lycopene and other carotenoids (Dumas et al. 2003). Lacatus et al. (1994) showed that K and P nutrition had a positive effects on fruit sugar and acid content. Of the nutrition factors, the soil K content most affects the total acid content in the fruit. Davies and Winsor (1967) found a positive logarithmic correlation between the K level in the soil and the acid content of the fruit. Increasing the phosphorus (P) supply from 0 to 100 mg·l^{-1} nutrient solution under hydroponic growth conditions greatly improved the colour of fruit and increased the lycopene content (Saito and Kano 1970). Wright and Harris (1985) reported that increased N and K fertilization had a detrimental effect on tomato flavor, as scored by a taste panel (although increased acidity and soluble solid content resulted from increasing fertilization). The application of N fertilizer did not have any effect upon tomato yield, whereas application of K fertilizer did increase the yield. Application of K fertilizer was often associated with increased sugar concentration (Liu et al. 2008). Hartz et al. (2001) suggested that current soil K recommendations be adjusted upwards for maximum fruit yield and that optimizing fruit color uniformity may require a greater soil K supply than needed for maximum fruit yield. K can improve the quality of tomato by influencing carotenoids synthesis. K can improve the quality of tomato by influencing carotenoid synthesis. An early study demonstrated that total carotenoid content of tomatoes generally increased with increasing amounts of K in nutrient solution. Studies of fruit pigmentation at various stages of ripening showed that the chlorophylls generally decreased as the total carotenoids increase during ripening. At any stage of ripening, the carotenoids content of K-deficient fruit was lower than that of normal fruit (Trudel and Ozbun 1970, 1971). Lycopene content of tomato increased linearly with increasing potassium level in the nutrient solution (Serio et al. 2007). Also, the lycopene content rose sharply with increasing K fertilization which was increased by as much as 65%. The authors concluded that lycopene is the pigment most sensitive to K deficiency and that since K is as essential co-factor in protein synthesis its deficiency could lead to reduced rates of enzymatic reactions involved in carotenoid and precursor synthesis (Ramirez et al. 2009).

Therefore, soil structure, soil physical and chemical characteristics, mineral and organic fertilizers and soil organic matter influenced mainly tomato yield, secondary plant metabolites, lycopene, caretonoid, phenolics, flavonols, vitamin C, and vitamin B complex.

3.7 Chemical Pesticides, Growth and Development Regulators

In the last few decades, there has been an emphasis on reducing pesticide use, with some insecticide that represent the greatest risk to human and environmental health losing their registration and being withdrawn from use (Pierzynski et al. 2005). Tomato plants are infected by several soil-borne pathogens such as *Rhizoctonia solani*, *Pyrenochaeta lycopersiand* and *Fusarium oxysporum* f. sp. lycopersici. Their control accomplished through using chemicals such as fumigation of soils with Methyl Bromide (MeBr). This chemical contaminates the environment, affects the ozone layer, destroys the soil microflora and must be applied very season because of its null residual activity and the rapid re-colonisation of soils by the phytopathogens. Evaluation of fruit yield and quality showed that MeBr alone was not better than the other treatments when total yield or first fruit quality were evaluated.

Pest pressures, by inducing defence reactions in the plant, may stimulate the production of antioxidant compounds, especially phenolics. Synthetic pesticides either stimulate or inhibit production of phytonutrients, but little is known about the effects on the composition of the edible part (Brándt and Mølgaard 2001). It has been suggested that an increase in peroxidase activity observed after herbicide treatment may contribute to resistant to herbicides by playing a role in oxidative stress tolerance, in addition to detoxifying herbicides by catalysing their conjugation with glutathione. The effect of different herbicides on phenylalanine ammonia-lyase activity and therefore on phenolic biosynthesis has also been reported (Tomas-Barberan and Espin 2001). Moreover, applications of pesticides for pest control leads to fruit pesticide residues that may exceed the maximal level (Chavarri et al. 2004; Tsakiris et al. 2004). Soils also often have pesticide residues that can be translocated to the fruit (Gonzalez et al. 2005). Despite increasing concerns about fruit and vegetable pesticide residues by consumers, little is known about their direct effects on disease-preventing molecules in plants.

Phytohormones such as auxins, gibberellins, cytokinins and abscisic acid have been implicated in anthocyanin biosynthesis and accumulation in several plant species (Sheoran et al. 2006). Although growth regulator application may not be allowed in some countries, some reports mentioned that they can improve the health quality of tomato. For example, foliar application at the three-leaf stage of 30 lM 2-(3,4-dichlorophenoxy)triethylamine (DCPTA) increased the fruit lycopene content by 28% (Hsu and Yokohama 1991). Similarly, pre-germination seed treatment with up to 30 lM of DCPTA for 6 h increased the content of lycopene from 58 to 118 lg per g fw and of ß-carotene from 2.2 to 5.7 lg per g fw in greenhouse-grown tomato (Keithly et al. 1990).

On full-sized green tomato fruits (cv Moneymaker) at room temperature, the ethephon treatment enhanced the ripening of the fruit and ethephon combined with 2-(3,4-dichlorophenoxy)triethylamine (CPTA) resulted in faster and greater lycopene accumulation (Rabinowitch and Rudish, 1972). At 32°C, only CPTA and the combined ethephon and CPTA treatment resulted in an accumulation of red colour. Normal red fruit treated in an aqueous containing CPTA (430 $mg \cdot l^{-1}$) and 1% Tween 80 as a surfactant, generally showed an increase in the rates of phytoene, phytofluene, ß-carotene, lycopene and γ-carotene syntheis at 21°C (Chang et al. 1977). At 32°C, the rate of lycopene synthesis was mulch lower and was, therefore, not stimulated by the CPTA treatment. The ability of CPTA to bring about carotenogenesis was tested in tomato cell suspension cultures (Fosket and Radin 1983). Untreated dark-grown cultured tomato cells (from callus tissues) contain low levels of carotenoids. DCPTA was applied to tomatoes as a pre-germination seed treatment at five rates, 0, 3, 15, 30, 150 $\mu M \cdot l^{-1}$ (0, 1, 5, 10 and 50 $mg \cdot kg^{-1}$), for 6 h at 24°C with Tween 80 (0.1%, w/v) (Keithly et al. 1990). The lycopene and ß-carotene contents increased from 58 to 118 $mg \cdot kg^{-1}$ and 2.2 to 5.7 $mg \cdot kg^{-1}$ fm, respectively, when the DCPTA was increased from 0 to 50 $mg \cdot kg^{-1}$.

In field-grown tomatoes, gibberllic acid and cycocel (2-chloroethyl trimethylammonium 3-chloride) increased the ß-carotene content of the fruit (Graham and Ballesteros 1980). Gibberellic acid and cycocel also increased fruit ß-carotene. In field-grown tomato, a 25% increase in the ascorbic acid content of the fruit was noted after applying alar solution (1,500 and 3,000 $mg \cdot kg^{-1}$). Gibberellic acid, cycocel and phosphon also increased the ascorbic acid content of the fruit (Dumas et al. 2003).

3.8 Tomato Seed Genotype (Cultivar)

Identification of genotypes with high yield and high quality value, represent a useful approach to select tomato cultivars with better health-promoting properties. Breeding programs aim to accumulate the genes that increase the lycopene content and to eliminate those genes that decrease the lycopene content, while preserving the other quality characteristics (Dumas et al. 2003). Based on such data and on a literature survey on tomato composition, an index called index of antioxidant nutritional quality (IQUAN), was proposed by Frusciante et al. (2007) as a tool to address the breeding programs in selecting tomato genotype with antioxidant nutritional qualities.

The antioxidant composition as well as total antioxidant capacity has been studied with the aim to produce cultivars having high antioxidants content (Frusciante et al. 2007). The antioxidant capacity of several tomato varieties has been also tested. It has been established that the antioxidant activity of tomato extract varies with the tomato variety and the assay method used. Individual compounds found to be significantly related to antioxidant capacity are lycopene and ferulic acids

(Martinez-Valverde et al. 2002) and variation of carotenoids have been found ranging from 18.5 to 60.7 mg·kg^{-1} fm. Data from southern Italy gave 86.0 mg·kg^{-1} fm as the mean lycopene content of 24 tomato varieties in 1998 and 87.0 mg·kg^{-1} fm as that of 29 varieties in 1999. The value ranged from 34 to 150 mg·kg^{-1} in 1998 and 45 to 163 mg·kg^{-1} in 1999, i.e. about 1–4-fold (Dumas et al. 2003). Guil-Guerrero and Rebolloso-Fuentes (2009) demonstrated that colored varieties seem to be good sources of antioxidant, in good agreement with the carotenoid content found in mature stages. Moreover, the antioxidative capacity of the tomato extracts showed that the antioxidant activity of the extracts of some varieties was comparable with those of the commercial antioxidants used for similar purposes. Among the different tomato cultivars, cherry tomatoes are well known, for their good taste and flavor, and although the yield of cherry tomato is only half that compared to standard large tomatoes, it is worth cultivating this new variety, especially in organic system, due to their higher nutrient value (Hallmann 2003; Hobson and Kiby 1985).

Since many epidemiological studies approved that dietary intake of carotenoids reduces the incidence of degenerative diseases, including heart disease and cancer, considerable work conducted in order to increase carotenoid contents of tomatoes through breeding programmes or ripening intervention technologies during post-harvest storage (Liu et al. 2008; Rosati et al. 2000). Changes in the antioxidant contents at seven stages during vine and post-harvest ripening have been assessed in two genotypes (Normal red and Crimson) of tomato cv Moneymarker grown in a greenhouse by Giovanelli et al. (1999) and the results showed that at the end of the experiments, lycopene and ß-carotene concentrations (roughly 12.5–30 mg·kg^{-1} and 12 mg·kg^{-1} fm, respectively) in post-harvest-ripened tomatoes were almost twice as high as the values reached in vine-ripened tomatoes (roughly 75–80 mg·kg^{-1} and 5–7 mg·kg^{-1} fm, respectively) with the same colour (a*/b*) index.

Tomato cherry cultivar of Koralik contained significantly more nutrients than the other tomato cultivars. Organic cherry and standard tomatoes can be recommended as part of a healthy diet including plant products which have been shown to be of value in cancer prevention (Hallmann and Rembiałkowska 2007). Lycopene content of three different varieties (Daaniela F1, Delfine F_1 and cherry tomato), was compared and the highest concentration of lycopene was detected in cherry tomato (77.4 mg·kg^{-1} f.w.) while Daniela F_1 and Delfine F_1 with 59.2 and 69.6 mg·kg^{-1}, respectively, were significantly lower. This agrees with Sass-Kiss et al. (2005) who found that, fresh market varieties grown in greenhouse contained less lycopene then processing varieties grown in the field. In another study conducted by Kuti and Konuru (2005) among 40 tomato varieties, greenhouse-grown cluster and round tomato types contained more lycopene (30.3 mg·kg^{-1}) than field-grown tomato (25.2 mg·kg^{-1}), whereas cherry types had a higher content in field-grown (91.9 mg·kg^{-1}) than in greenhouse- grown (56.1 mg·kg^{-1}). The ascorbic acid content of surface-irrigated tomato grown in a greenhouse was found to be 66% higher than in those grown with surface irrigation outdoors (Mahajan and Singh 2006).

The choice of variety significantly influenced the content of bioactive compounds, particularly ascorbic acid and total phenolic (Juroszek et al. 2009). Chassy et al. (2006) demonstrated that Burbank tomatoes generally had higher levels of quercetin, kaempferol, total phenolics and ascorbic acid as compared to Ropreco tomatoes. The cultivation of long life cultivars, as e.g., Vanessa should be favored. The cultivar Vanessa is characterized by a relative high firmness of the fruit flesh and peel, but by a lower intensity of the descriptive sensory flavour attributes sweet, fruity, intensive and tomato-like compared to conventional round tomatoes and Cherry tomatoes (Auerswald et al. 1997). However, there are older references that stated the variation in the tomato fruit vitamin C content due to the variety is fairly small in comparison with those resulting from the growth conditions (Hamner et al. 1945). In tomato fruit, the total phenols present in the epidermal tissue, the placental tissue, the radial and inner walls of the pericarp and the outer wall of the pericarp did not vary significantly among three cultivars tested, Patroit, Floridade and Walter (Senter et al. 1988).

In conclusion, producing tomato cultivar with genes of higher antioxidant nutritional qualities, higher lycopene contents, ascorbic acid and total phenilic, vitamin C which are human health promoting factors in tomato, are well documented; however, it should be noted that breeding method is very important for many consumers around the world. In some agricultural systems such as organic and biodynamic systems, genetically modified seeds are not allowed to use, but seeds that are improved through natural selection and acceptable classic methods of breeding are permitted.

4 Tomato Fruit Quality and Ripeness Stage at Harvesting Time

The stage of fruit development at harvest is one of the major factors determining the quality of fruit because there is an important change in the profile of antioxidants during ripening. Growth and storage of metabolites in tomato plant occur simultaneously and may hence compete for assimilates (Kosegarten and Mengel 1998). Growth limiting factors may increase the translocation rate of assimilates into tomato fruits and hence promote storage processes during fruit ripening improving fruit quality (Veit-Köhler et al. 2001). The development of red color in tomato fruit during ripening is mainly due to the synthesis of various carotenoid pigments, particularly lycopene (Mikkelsen 2005). While ripening, the concentration of sugar, carotenes, ascorbate, rutin and caffeic acid increased whereas those in titratable acidity, chlorophylls chlorogenic acid contents decreased (Gauiter et al. 2008). Fruit ripened on the plant generally had higher phytonutrient content than table-ripened fruit. Tomato fruit harvested as green or at the breaker stage and ripened to table-ripeness, contained less ascorbic acid than fruit ripened on the vine (Betancourt et al. 1977; Kader et al. 1977). During ripening, the green pigment chlorophyll degrades and carotenoids are synthesized. Carotenoids, particularly lycopene and ß-carotene, represent the primary components of ripe fruit pigmentation in tomato pericarp and are responsible for the characteristics colour of ripe tomatoes, conferring deep red and orange colours, respectively. These carotenoids largely influence the quality perception of fresh tomatoes (Liu et al. 2009). However, Dumas et al. (2003) reported that ascorbic acid was or was not affected by the ripening stage at harvest, depending on the cultivars that was studied. Tomato plants (cv Fireball) grown in a growth chamber (16 h light period at 24°C and 8 h dark period at 18°C, relative humidity 65%), the total carotenoids in the fruit increased constantly during the ripening process from 0.1 to 70 mg·kg^{-1} fm (Trudel and Ozbun 1970). In field tomato, the fruit ß-carotene content increased regularly during ripening, whereas lycopene content increased sharply between pink and red fruit stages (Cabibel and Ferry 1980). In cherry tomato, lycopene increased during ripening by 20-fold and ß-carotene by 3-fold. Lycopene content is a good index to the level of maturation (Cabibel and Ferry 1980). Considering the seven stages of I (mature green), II (green yellow), III (yellow orange), IV (orange-yellow), V (orange-red), VI (red) and VII (deep red) (Venter 1977), lycopene values as percentages of the total carotenoids were 12, 55, 72, 82, 90 and 95% at I, II, III, IV, V, VI and VII, respectively. Thus, lycopene content changed significantly during maturation and accumulated mainly in the deep red stage (Helyes et al. 2006). In all the parts of the tomato, the total phenols tend to increase from green to mid-ripe stages (Senter et al. 1988). Changes in the phenol contents in the pulp and pericarp of the cvs Ailsa Craig and Pik-Red have been reported to depend on the stage of development (Buta and Spaulding 1997). Variation in the total phenol content at seven stages during vine and post-harvest ripening in two genotypes (Normal red and Crimson) of cv Moneymarker have been assessed by Giovanelli et al. (1999) and they found that the total phenolic compound content was higher in postharvest-ripened samples (about 100–200 mg·kg^{-1} fm; the mean various content was 92.5%) than in vine-ripened fruit (about 70–110 mg·kg^{-1} fm). There were no significant differences in the phenol levels between the two genotypes. Polyphenol content changed little during fruit ripening. They also studied vitamin C content at seven stages during the vine and post-harvest ripening of tomatoes cv Moneymarker and found that ascorbic acid content decreased from about 200 to 150 mg·kg^{-1} fm then increased to about 200 mg·kg^{-1} fm. In another study, vine-ripened tomato, ascorbic acid increased from about 200 to 250 mg·kg^{-1} fm and then decreased to roughly 150–200 mg·kg^{-1} fm. However, the total ascorbate contents have been found to be relatively constant in fruit at all stages (Grantz et al. 1995). In plum tomatoes (cv Heinz 9478), ascorbic acid content of whole fresh fruit increased from the mature-light pink stage (175 mg·kg^{-1} fm) to the mature pink (209 mg·kg^{-1} fm) and mature-red stage (256 mg·kg^{-1} fm) (Shi et al. 1999).

Tomato fruit harvested at full ripeness had higher levels of carotenoids and antioxidant activity in the water-insoluble fraction, whereas the main phenolic content and the antioxidant activity of the water-soluble fraction decrease at later stages of ripeness. Lycopene content of four tomato cultivars increased from less than 0.10 lg per g fw in green fruit to about 50 lg as fruit matured to the redripe stage and to 70 lg when the fruit became overripe, softened, and began to decay (Thompson et al.

2000). It has been observed that ß-carotene synthesis stopped after the colour of the tomato had changed from orange to red (Koskitalo and Ormrod 1972).

Conflicting data concerning the accumulation rate of ß-carotene during ripening could be attributed to different growing conditions and cultivars. Fruit bruising at the breaker stage can decrease (−37%) the total carotenoids present in the locular of the fruit when it reaches the ripe stage (Moretti et al. 1998). Phytoene and phytofluene content is linearly correlated with the ripening index and formed 6.8% of the total carotenoids at the red stage. Although fruit of full ripeness exhibited the highest level of α- and ß-carotene, chlorogenic acid (a main phenol compound) declined during ripening. On the other hand, proteins (1.0–1.3 g/100 g), fats (0.1–0.2 g/100 g), fibre (1.4–1.7 g/100 g), and ash (0.6–0.7 g/100 g) did not vary during tomato ripening (Raffo et al. 2002).

Bertin et al. (2002) showed that in July, the ripening stage of tomato did not clearly affect fruit sugar content. On the contrary, in September, a slight peak in sugar content was observed at the turning stage, depending on air vapour pressure deficit and plant fruit load. Changes in acid content during ripening are well documented in the literature. Total acidity increases during fruit development, reaches a peak at the breaker stage and then decreases (Stevens 1972). After the breaker stage, malic acid decreases more rapidly than citric acid, so that the ratio also drops (Sakiyama and Stevens 1976). Davies and Maw (1972) reported that this is due to more active turnover of malic than citric acid in red fruits. The breaker stage is defined as incipient colour (Sakiyama and Stevens 1976) or the first occurrence of pink colouration (Kader et al. 1977). Bertin et al. (2002) demonstrated also that the sugar/acid ratio was better correlated with the acid content than with the sugar content in July, and equally well correlated with both components in September.

In summary, tomato quality and especially human health related characteristics of tomato fruits are influenced by several compounds and substances many of which develop during ripening stages. For example, there are references reporting that during ripening stage of tomato fruits, concentration of carotenoids particularly lycopene and β-carotene, phenol content, ascorbic acid, caffeic acid and total acidity increased. Development of those compounds and many others, occurring during the ripening stage are essential for the typical tomato nutritions and aroma. Appropriate post- harvest storage conditions can also give tomatoes a higher quality value.

5 Tomato Quality and Cropping Systems

In recent years, there has been growing interest among farmers, researchers, governmental agencies and environmental conservation groups in investigating and adopting alternative crop production practices that are less chemical-intensive, less dependent on nonrenewable fossil fuels and that function to conserve soil and water resources. This interest has resulted in part from studies documenting negative impacts of conventional agriculture on long-term profitability and resource stewardship, including declines in soil organic matter levels due to intensive tillage, surface water quality degradation due to reduced water infiltration rates and reduced soil tilth (National Research Council 1989). Over the last decades, alternative farming strategies have been increasingly investigated for opportunities to sustain and improve the soil resource base while meeting the needs and concerns of farmers (Drinkwater et al. 1995; Ghorbani et al. 2010; Mitchell et al. 1998).

Fundamental differences between organic and conventional production systems, particularly in soil fertility management, may affect the nutritive composition of plants, including secondary plant metabolites (Ghorbani et al. 2008b). Organic systems emphasize the accumulation of soil organic matter and fertility over times through the use of cover crops, manures, composts and rely on the activity of a diverse soil ecosystem to make N and other nutrients available to plants (Mitchell et al. 2007). Organic horticulture is generally accepted as friendly to the environment, good for crop quality and also for the consumer's health. Recent research data has shown that organic crops under organic farming practices contained more bioactive substances such as flavones, vitamin C, carotenoids; they also contain less pesticides residues, nitrates and nitrites (Hallmann and Rembiałkowska 2007). Consumers often regard organically produced food to be tastier and healthier than conventional products (Ekelund and Tjärnemo 2004).

Reviews studies comparing the nutritional quality of conventionally and organically produced vegetables demonstrate inconsistent differences with the exception of higher levels of ascorbic acid (vitamin C) and less nitrate in organic products (Bourn and Prescott 2002). There are references that compared the levels of secondary plant metabolites (e.g., antioxidants) in conventional and organically grown foods. Hakkinen and Torronen (2000) compared the phenolic content in three cultivars of strawberries grown organically and conventionally. They reported that only one cultivar grown under organic conditions showed higher levels of phenolic than inorganically grown counterpart, whereas the other two cultivars showed no significant differences in their phenolic contents. Hallmann and Rembiałkowska (2007) demonstrated that conventional tomatoes were richer in lycopene and organic acids. Heeb et al. (2005a) demonstrated that significantly higher scores were achieved for sweetness, acidity, flavour and acceptance for the tomatoes grown with the organic or the ammonium-dominated treatments compared with the tomatoes grown with the nitrate dominated nutrient solution. It is suggested that ammonium is an equivalent nitrogen source for tomato plants compared with nitrate and that, when tomato plants are supplied with reduced nitrogen forms such as ammonium or organic nitrogen, an improved tomato fruit taste can be observed. The nutritional quality of organically grown plants has been compared mainly in terms of macronutrients, vitamins and minerals. The mean total phenolic and ascorbic acid content of tomatoes grown organically was higher than the tomatoes grown using mineral fertilization. (Toor and Savage 2006; Toor et al. 2006a). Ghorbani et al. (2008a) reported that application of poultry manure in an ecological system showed lower disease incidence, as shown by 80% healthy tomato, compared with the other fertilizer.

Many studies around the world reported that organic plants contain more bioactive substances. Guil-Guerrero and Rebolloso-Fuentes (2009) showed that tomatoes grown on organic substrates contained significantly more Ca and vitamin C and less

Fe than did fruit grown on hydroponic media. Another study demonstrated that organic tomatoes contained more dry matter, total and reducing sugars, vitamin C, ß-carotene and flavonoids in comparison to the conventional ones (Hallmann and Rembiałkowska 2007). In a greenhouse experiment, organic fertilizers released nutrients more slowly than mineral fertilizers, resulting in decreased S and P concentrations in the leaves, which limited grown and yield in the organic N treatments. Analysis of tomato fruits and plants as well as taste-test gave no conclusive answer on the relationship between sugar or acid contents in the fruits, macronutrient content of plant leaves and fruits and perceived taste (Heeb et al. 2005a). Organic fertilizers release nutrients not as fast as mineral fertilizers and therefore, plants supplied with organic fertilizers often grow more slowly compared to plants fertilized with readily available mineral nutrients. This might reduce their water content leading to a higher concentration of plant compounds, e.g., sugars and acids (Hobson 1988; Guichard et al. 2001). In a tomato experiment using organic or mineral fertilizers with different ammonium-to-nitrate ratios, it was shown that the taste of organic or ammonium-fertilized tomatoes was better compared to the nitrate-fertilized ones (Heeb et al. 2005b). At moderate total N supply, high ammonium-to-nitrate ratios did not decrease yield or fruit quality (Heeb et al. 2005a, b). Different nitrogen forms in organic or mineral fertilizers affect yield, quality and taste of tomatoes (Heeb et al. 2005a, b). Plants can take up N either as ions (NH_4^+ or NO_3^-), or as organic N (Gagnon and Berrouard 1994; Sandoval-Villa et al. 2001). In organic tomato production, N is supplied as organic fertilizer, e.g., animal manure, composts or plant residues. This organic material is mineralized by microorganisms and small molecules of organic N (e.g., amino acids) and NH_4^+ are released. Finally, NH_4^+ can be nitrified to NO_3^- (Heeb et al. 2005a, b). In this study ammonium was a very effective source of nitrogen for tomato plants when applied in an NO_3^-: NH_4^+ ratio of 1:4 provided that the total nitrogen supply was lowers than 750 mg N plant^{-1} week^{-1}. Gao et al. (1996) observed that application of high NH_4^+ and low NO_3^- levels increased the reduced nitrogen forms in the plants and that this treatment resulted in improved fruit quality. In an organic production system for tomatoes, it was observed that the soil solution of the organic system contained higher NH_4^+ and chloride levels compared to systems using inorganic fertilizer (G redal 1998). Studies on the benefit of NH_4^+ for plant growth have led to contradictory results. The addition of low levels of NH_4^+ to a NO_3^- based system can have positive effects on growth (Gill and Reisenauer 1993) and on taste (Siddiqi et al. 2002). On the other hand, NH_4^+ nutrition, especially at high levels, can result in plant growth problems, generally referred to as NH_4^+ toxicity (Glass et al. 1997; Zhu et al. 2000). The occurrence of blossom-end-rot (BER) was one major problem that has been observed in tomato production when NH_4^+ was used as N source (Hao and Papadopoulos 2000; Hohjo 2001). These experiments suggested that plants may save energy by taking up reduced nitrogen. It is then possible that the energy saved may be used for increased production of secondary metabolites. This could result in an improved fruit quality and taste (Heeb et al. 2005b). There is a scarcity of data on the effect of the form of N on the production of secondary metabolites in plants (Brándt and Mølgaard 2001).

According to the 'C/N balance theory', when N is readily available, plants will primarily make compounds with high N content (e.g., protein for growth). When N availability is limited, metabolism changes more towards carbon-containing compounds such as starch, cellulose and non-N containing secondary metabolites such as phenolics and terpenoids (Haukioja et al. 1998). The relative differences in the release of nutrients from various fertilizers could lead to different C/N ratios in plants and this in turn could lead to a difference in the production of secondary metabolites (Brandt and Molgaard 2001). Compared to their conventionally-grown counterparts, organic products are lower in waste content, reserving higher nutrient density; richer in iron, magnesium, vitamin C and antioxidant; more balanced with essential amino acid. Organic produce has consistently been rated to have better flavor and texture than non-organic produce. Moreover, organic foods have enhanced nutritional quality; for example increased amounts of vitamin C in organic foods increase the effect of vitamin E, folic acid and iron in our bodies. Aggregation of farms by type (organic vs conventional) across two years resulted in no significant differences between organic and conventional farming systems for all tomato parameters measured, including quality (pH, soluble solids, acidity and colour), content of bioactive compounds with antioxidant activity (ß-carotene, lycopene, ascorbic acid and total phenolics), and antioxidant activity (Juroszek et al. 2009). Toor et al. (2006a) showed that the nutrient source plays a major role in determining the levels of titratable acidity and antioxidant components in tomato. Also, fertilizers sources can have a significant effect on the macronutrient concentration, taste and antioxidant components of tomatoes. They suggested that the titratable acidity of tomatoes can be significantly improved with the use of organic and fertilizers and may help to improve the taste of tomatoes. Researches should continue to explore the role of organic foods in promoting human health and safety and make use of new holistic research methods.

In organic systems using mulches are recommended. Mulch materials in tomato crops may have an indirect influence on fruit phytonutrients via their effect on weed control, reduction of nutrient losses, and improvement of the soil hydrothermal regimes, and light quality that is reflected to the plants. Similarly, covering materials for greenhouses generally block most of the UV radiation and may reduce or/and modify the spectral quality received by plants, affecting tomato health-components (see section on light). Protected cultivation and greenhouse technology which are largely spread around the world (greater than 450 000 ha, around 13% of the total tomato production, Dorais et al. 2001a) are the best alternative for using land and other resources more efficiently. Wang et al., (2008) suggested that either production of cover crops, especially sunn hemp, or the application of compost at high rates can improve winter fresh market tomato yields and quality and advance organic farming. Moreover, greenhouses provide a controlled environment that offers a great opportunity to improve the concentration of phytonutrients in tomato. Brandt et al. (2003) significantly higher lycopene content was observed in tomato harvested in glasshouse grown (83.0 $mg \cdot kg^{-1}$ f.w.) than in field- grown (59.2 $mg \cdot kg^{-1}$ f.w.), at different harvesting times.

In conclusion, based on the present data, production system can change the quality of tomato fruits. In addition to sweetness, taste, flavour and storability, contents of lycopene, organic acids, phenolic and ascorbic acids, secondary metabolites, vitamin c and E in tomato produced in organic farming and low input production systems in most cases were higher than tomato of conventional production systems. However, knowledge about the nutritive value and antioxidant status of organic tomato is still leaking.

Application of mushroom-bed residues as a mulch in an ecological tomato farm in Iran

6 Tomato Processing, Packaging and Storage

Although tomatoes are commonly consumed in fresh, over 80% of the tomato consumption comes from proceed products such as tomato juices (Gould 1992). There are various methods of processing, but those that preserve antioxidant capacity of the foods such as high pressure processing which can be achieved without heating are useful for preserving antioxidant capacity (Cheftel 1992; Farr 1990). Different processing forms of tomato including pulp, purée, sauce, juice, paste and peeled whole tomato (Hayes et al. 1998; Slimestad and Verheul 2005) which are important sources of carotenes, organic acids and phenolics for human (Giovanelli and Paradiso 2002; Loiudice et al. 1995; Scalbert and Williams 2000) could be done in many ways. The quality and the chemical composition of tomato may changes during processing. Consumers are demanding high quality and convenient products with natural flavour and taste and greatly appreciate the fresh appearance of minimally processed food (Oey et al. 2008).

The effects of tomato processing on lycopene, ascorbic acid and phenolics have been studied by several authors (Dewanto et al. 2002; Gahler et al. 2003; Re et al. 2002; Sahlin et al. 2004; Toor and Savage 2006; Toor et al. 2006a). In order to extend the shelf life of these products they are usually processed thermally using methods such as hot water immersion, however these treatments can cause a reduction in antioxidant capacity (Dewanto et al. 2002). Mikkelsen (2005) showed that packing commonly expose tomatoes to supplemental ethylene gas (a natural hormone produced by many types of fruit) in order to accelerate the ripening process. Patras et al. (2009) showed that redness and colour intensity of purée were better preserved by high pressure processing than conventional thermal treatment. Also, antioxidant activity, ascorbic acid and carotenoids after exposure to high pressure treatment (400–600 MPa) were well retained. From a nutritional prospective, high pressure processing is an excellent food processing technology which has the potential to retain compounds with health properties in foods. Therefore, high pressure processed foods could be solid at a premium over their thermally processed counterparts as they will have retained their fresh like properties (Patras et al. 2009). Thermal processing is the most common method for extending the shelf-life of tomato juices, by inactivating microorganisms and enzymes. However, heat treatment can reduce the sensory and nutritional qualities of juices (Braddock 1999). Therefore, consumers demands for healthy and nutritious food products with a fresh-like appearance has raised the awareness of the food industry for the development of milder preservation technologies to replace the existing pasteurization methods (Linnemann et al. 1998). High intensity pulsed electric fields (HIPEF) processing of liquid foods is being investigated to avoid the negative effects of heat pasteurization (Deliza et al. 2003). HIPEF treatment is efficient enough to destroy microorganisms in fruit juices at levels equivalent to heat pasteurization (Yeom et al. 2000). Odriozola-Serrano et al. (2008) showed that HIPEF processing could produce tomato juice with higher nutritional value than conventional thermal processing. Also, storage time shows a significant effect on the studied compounds. Lycopene, vitamin C and antioxidant capacity deplete with time irrespective of the treatment applied, whereas the initial content of total phenolic compounds is kept during storage. The bioavailability of the nutrient content of tomato products depends on the processing that they have undergone and on the duration and conditions of storage (Sánchez et al. 2006). A decrease of ascorbic acid quality during the storage of ripe fruits was established. As a result additional ripening during which a synthesis of ascorbic acid becomes and followed by storage at 1°C, its content was near this of fruits in red-ripe stage at the moments of harvesting (Brashlyanova and Pevicharova 2008). The content of pigment substances indicated a changeability which is associated with the decrease of lycopene content and the increase of ß-carotene one. During the additional ripening under refrigerated conditions the synthesis of ß-carotene was faster than the synthesis of lycopene in respect to tomatoes that had been ripened in the open air (Brashlyanova and Pevicharova 2008).

Ordóñez-Satos et al. (2008) concluded that the lycopene content of bottled tomato pulp remained stable during 180 days' storage; ß-carotene and total phenolics concentrations rose significantly, while the concentrations of malic, ascorbic and citric acids all underwent significant reductions that correlated well with an increase inHMF (5-Hydroxymethyl-2-furfural) concentration.

There are large genotypic variations in tomato quality attributes and it is possible to develop new cultivars which have good eating quality and maintain their firmness when fully ripe so that they can withstand the postharvest handling procedures. Hossain and Gottschalk (2009) resulted that significantly higher losses of colour, ascorbic acid, lycopene and total flavonoids were found for room environment than those of cool chamber. Tomatoes subjected to bruising usually have less "tomato-like" flavor and more off-flavors than those without physical damage. Ethylene treatment results in faster and more uniform ripening of green tomatoes by reducing their 'green-life'. Since ethylene treatment reduces the time between harvest and consumption, it may have positive effects on flavor quality and vitamin C content relative to tomatoes picked green and ripened without ethylene application (Kader 1986).

Therefore, the processing method and storage conditions can reduce tomato quality characteristics such as ascorbic acid, pigment substances, lycopene, and total flavonoids. Using processing methods which retain tomato health related properties e.g. high pressure methods instead of thermal processing should be chosen carefully. However, it should be considered that postharvest losses in quality and quantity are very often related to immaturity at harvest, inadequate initial quality control, incidence and severity of physical damage, exposure to improper temperatures, and delays between harvest, processing and consumption. Shortening the time between harvest and consumption can minimize loss of mentioned nutritional characteristics in tomato.

Harvested organic tomato before storage

7 Conclusion

Based on the reviewed literatures in this paper, the final quality is not depending merely on genotype or breeded seeds. Tomato fruit quality, including appearance (colour, size, shape, freedom from defects and decay), firmness, flavor, and nutritional value is a product of interaction of genotype, environmental factors, agricultural practices, after-harvest processing and storage. Many environmental factors especially light, temperature, atmospheric carbon dioxide, air pollutant, chemical pesticides, water availability, salinity and soil conditions can greatly impact the nutritional quality of tomato fruits. Finding the best combinations of those factors to maximize nutritional quality, often affected quite differently by a particular set of conditions, will be a big challenge. The development of models of tomato nutritional quality may assist in defining the conditions required to maximize all of those specific health attributes. Although the ideal would be a single set of environmental conditions which promote high nutritional quality in all tomatoes, this may not be logistically possible. Having a high degree of control over the environmental factors which is being practical in greenhouses could enhance the quality of greenhouse-grown tomato fruit. However, the positive effects of some environmental conditions on nutritional quality are offset by negative effects on yield. This may mean that health-promoting tomatoes would be produced under unique growing conditions which do not necessarily gain the highest yields, and could then be marketed as a specific health promoting food.

It is necessary to know more about the effects of environmental conditions and production practices on quality characteristics, especially lycopene, pholic compounds and antioxidants contents in tomatoes. Cropping production systems such as organic or ecological farming that involve organic fertilizers such as compost, manure and farm yard, using minimum chemical pesticides, using renewable non-fossil inputs, applying mulches and cover crops all had positive effects on tomato fruit quality and human health related factors. It would be of great interest to have more data to help understanding more clearly how agronomic factors and techniques are liable to affect the canopy characteristics and interfere with the effects of light, temperature, and carbon dioxide which along with the genetic background and production practices, are the main determinants really responsible for the accumulation of these compounds during ripening and storage. Packing tomato for houses commonly expose tomatoes to supplemental ethylene gas (a natural hormone produced by many types of fruit) in order to accelerate the ripening process. Commercial tomatoes are frequently selected for disease and pest resistance or growing season restrictions that are best served by a particular hybrid. Also, cultural practices such as picking fruit before it is vine ripened also can have negative effects on taste and quality.

Therefore, increasing consumer demands for healthy and nutritious tomato products with a fresh-like appearance has raised the awareness of the food industry for the development of environmentally friendly agricultural practices and milder preservation technologies should be applied instead of conventional agricultural methods and existing high demand energy and pasteurization approaches. Although improved quantity and quality has long been a goal of breeding programs, little attention has been paid to tomato nutrition and even some scientists (e.g. Davis et al. 2004) believe in a decline in some aspects of nutritional quality of tomatoes in last decades. Therefore, the goal should be now to produce highly flavorful, nutritious tomatoes with healthy promoting compounds while maintaining the more grower-focused characteristics of high yield, pest and disease resistance, etc.

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Jute Biology, Diversity, Cultivation, Pest Control, Fiber Production and Genetics

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Abstract The genus *Corchorus*, commonly known as jute, includes more than 170 species, all of which are annual fibrous plants. Jute fiber is totally biodegradable and compostable and therefore an extremely attractive renewable resource. While the cultivated species, *C. olitorius* L. and *C. capsularis* L., are economically important for fibre production, the wild species are considered important genetic resources for biotic and abiotic stress tolerance and fine fibre trait. However, there are some constraints in jute cultivation and research. The cultivation requires lot of watering which is often hampered due to late showering and low moisture content in the air. Jute is very prone to disease and pest attack. Although application of pesticides is a popular preventive measure it also raises the issue of biomagnifications of those harmful chemicals by entering the food chain of the ecosystem. In addition, the fibre processing disturbs the environment by causing water pollution during retting. Some other negative issues related to its cultivation are indoor air emissions from the products, and greenhouse gas emission due to using waste jute for energy.

The high cost of production in comparison to synthetic materials leads to unemployment due to closing of jute processing factories which becomes a major concern in terms of socio economic impact of jute cultivation. Apart from these issues related to cultivation, some other constraints also exists in its research. The cell wall of *Corchorus* is composed of high amount of lignin which is a major barrier for cytological and cytogenetical analysis. Due to these problems the wild as well as the

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cultivated species of jute are poorly understood and explored and thus in most of the cases hybridization attempts was not successful till now. However, proper hybridization between wild and cultivated species needs adequate information on morphological, cytological, cytogenetical biochemical and molecular aspects and will result in the emergence of novel plant types with several beneficial characters. With a view to all of these including the economical importance of jute species, an overview is conducted involving nearly all essential aspects to provide updated and adequate information to researchers for effective utilization in human benefit.

This chapter reviews morphological, biochemical, cytological, palynological, anatomical and molecular analysis of genome along with induced mutagenesis, interspecific hybridization, pest management, retting procedures, tissue culture and transgenic development strategies in jute species for their successful exploitation. Cytological and cytogenetical aspects will provide a wealth of information about the chromosomes and their behavior that forms the basis of efficient interspecific hybridization. Information on biochemical parameters is important for providing a knowledge base regarding further research on fibre quality improvement. Although induced mutagenesis is known as an effective tool for creating superior plant types having morphological and biochemical marker traits, adequate reports on jute is meager. This aspect is discussed in detail as one of the major points. Jute cultivation has always suffered from pest attack and various microbial infections. Reports on jute pests and disease and their management will be helpful for taking necessary preventive measures against its damage in field. Moreover, transgenic development and efficient tissue culture method are important for rapid propagation of jute and for introducing desirable traits in short times and for optimum utilization of available resource to achieve a low cost of production and high benefit.

Keywords *Corchorus* • Cytomixis • Hybridization • Jute • Karyotype • Meiosis • Mutagenesis • Pests • Polyploidy • Retting

Abbreviations

2,4-D	2,4-dichlorophenoxyacetic acid
AFLP	amplified fragment length polymorphism
AI	anaphase I
AII	anaphase II
BAP	6-benzylaminopurine
cp DNA	chloroplast DNA
*Eco*RI	*E. coli* RI
H_2SO_4	sulphuric acid
I	univalent
II	bivalent
IAA	indole-3-acetic acid
ISSR	inter simple sequence repeat
MI	metaphase I

MS	Murashige and Skoog medium
mV	milli volt
NaOH	sodium hydroxide
NDGA	nordihydroguiaretic acid
NPK	nitrogen phosphorous potassium
PEG	polyethylene glycol
PMC	pollen mother cell
RAPD	random amplified polymorphic DNA
SDS–PAGE	sodium dodecyl sulfate polyacrylamide gel electrophoresis
SSR	simple sequence repeat

1 Introduction

The species of the genus *Corchorus* (Family: Tiliaceae) are annual plants (Fig. 1) and are found distributed in warm regions throughout the world (Kundu 1951; Purseglove 1968). Although *Corchorus* is considered to be under the family Tiliaceae (Selwin 1981; Tirel et al. 1996; Maity and Datta 2008, 2009a, 2010; Colmenero Robles et al. 2010) for long time, but now a day some reports are coming out regarding its belongingness to the family "Sparmanniaceae" (JCU 2010). On the basis of the two criteria – amount produced (the total production of jute in the world is three million

Fig. 1 Plantation of jute: At maturity in field

tones, roughly around Rs. 24–25,000 Crores) and types of uses (more than 800), jute (*Corchorus* sp.) is considered as the second most important fibre producing plant throughout the world (Samira et al. 2010) and as well as in Indian sub-continent after cotton (Basu et al. 2004). The jute fibre is used mostly for making gunny bags and packaging material for agricultural and other industrial products. While the cultivated species (*C. olitorius* L. and *C. capsularis* L.) are globally important for fibre yield, the wild species are potential donor for abiotic and biotic stress tolerance like fine fibre trait, disease resistance, drought tolerance and proved to be important genetic resources. Interspecific hybridization between wild and cultivated species may lead to conserve the wild germplasms and to create genetic diversity for enrichment of jute trade in future. In this regard, adequate information on morphological, cytological, anatomical, biochemical and molecular aspects helps to ascertain interrelationship between the germplasms for their successful exploitation in interspecific hybridization and crop improvement.

2 Common Names and Synonyms

Jute was previously named 'pat' (Wallace 1909). Saha and Hazra (2008) documented the event of first commercial export of raw jute to England under the name 'pat'. They also mentioned that the first commercial application of the word 'Jute' appeared in the customs returned of the exports for 1828 and has been found to suppress the word 'pat' till now.

3 Species Diversity

'Index Kewensis' includes more than 170 species (Mahapatra and Saha 2008) in *Corchorus* and based on species concentration East and South Africa were considered to be the centre of diversity and place of origin (Edmonds 1990; Kundu 1951; Singh 1976), though both the cultivated species of jute (*C. capsularis* L. and *C. olitorius* L.) are distributed throughout India. The genus *Corchorus* is extremely variable but all species are highly fibrous. Mahapatra et al. (1998) reported 10 species (2 cultivated and 8 wild) from India namely *C. capsularis* L. and *C. olitorius* L, *C. aestuans* L., *C. depressus* Stooks L., *C. fascicularis* Lam., *C. pseudoolitorius* I. and Z., *C. tridens* L., *C. trilocularis* L., *C. urticaefolius* W. and A. and *C. velutinus* Her. *C. capsularis* L. (white jute) and *C. olitorius* L. (tossa jute) yields fibre of commerce from bark of the stem (phloem fibre) and are widely cultivated in India, Bangladesh, Nepal, China, Indonesia, Thailand, Myanmar and in South American countries.

The fibre obtained from the cultivated species is retted in water and termed as jute. Although he wild species of jute though poor fibre yielder, but are genetic resources for abiotic stress tolerance (*C. trilocularis* L.), disease resistance (*C. urticaefolius* W. and A. – showed resistance reaction to all diseases but anthracnose – Palve et al. 2004; *C. pseudoolitorius* I. and Z. and *C. pseudocapsularis* L. – resistant to fungal diseases) and fine fibre quality (*C. tridens* L., *C. trilocularis* L.

and *C. aestuans* L.) parameters (Mahapatra and Saha 2008). *C. trilocularis* L. is the only tolerant genotype to water inundation (Mahapatra and Saha 2008).

Germplasms of wild species of jute are exploited for efficient breeding endeavor with the cultivated members for crop improvement. The germplasms are mostly evaluated for potential donor for desirable trait(s). Although collection and utilization of trait specific germplasms have increased the productivity but with the advent of synthetic material jute faces serious competition in the market.

4 Distribution

Corchorus germplasms occur in diverse ecological conditions and habitats like river banks, dry river bed, low altitude valley within mountain folds, hill cliffs, forest floors with open canopy, marshy lands road side fallow, ditches, cultivable as well as homestead lands. The major jute growing states in India are West Bengal, Bihar, Assam, Uttar Pradesh, Meghalaya and Tripura and the most dominating species in occurrence is *C. aestuans* L. followed by *C. olitorius* L., *C. capsularis* L., *C. tridens* L., *C. trilocularis* L. and *C. fascicularis* Lam. (Mahapatra and Saha 2008). *C. capsularis* L. is frequently distributed in Northern parts of India and gradually become scarce towards West. In contrast, *C. olitorius* L. is more frequent in Western and Northwestern India. *C. tridens* L. and *C. trilocularis* L. are restricted to Central, Western and Southern part of the country whereas *C. fascicularis* Lam. is restricted in Western and peninsular India. *C. urticaefolius* W. and A. is also restricted in Tamil Nadu of Southern India while *C. pseudoolitorius* I. and Z. is distributed in Western boundary of the country. *C. capsularis* L. is considered to be native to South China from where it migrated to India and Bangladesh (Purseglove 1968). However, Kundu (1951) and Mahapatra et al. (1998) believes that this species is not an immigrant to India but had originated in Indo-Myanmar region including South China. In contrast, *C. olitorius* L. is proposed to be native to Sri Lanka, India and Kenya and it is now agreed that the species originated in Africa along with other wild species and migrated to India and China via Egypt and Syria (Edmonds 1990; Kundu 1951; Mahapatra et al. 1998).

The diversity and worldwide distribution of jute has now been well recognized as economic resource providing ample scope to mankind to identify and utilize plants especially for food, fiber and other needs.

5 Plant Descriptions

Maity et al. (2008) selected the plots of the University of Kalyani, West Bengal plains as the experimental field having sandy loamy soil, organic carbon 0.76%, soil pH 6.85. The field has the elevation level of 48 ft above mean sea level and geographic co ordinates of 22° 99′N, 88° 45′E. The authors raised plants of individual species of *Corchorus* during the period of March to September and documented their morphological parameters (Table 1).

Table 1 Morphological characteristics of different species of *Corchorus* (Maity et al. 2008)

Name of the species	Characters					
	Stem		Leaf			
	Nature	Colour	Shape	Serration	Venation	Colour
C. olitorius	Terrete, solid, woody, glabrous	Dull green	Ovate, acute to acuminate	Serrated, rounded at base, basal serration tailed	5–6 veined, unicostate, reticulate	Green
C. capsularis	Terrete, solid, woody, glabrous	Dull green	Ovate, lanceolate, acuminate	Serrate, basal serration tailed. Tails equal or unequal	Basal veins 5, reticulation distinct beneath	Green above, green or dull green beneath
C. aestuans	Terrete, solid, woody, hairy	Purple	Ovate to broadly ovate	Serrate, serration tailed	Basal veins 5, reticulation more beneath	Surface green, often with purple blotches
C. fascicularis	Terrete, solid, woody, glabrous	Dull green	Linear, lanceolate, acuminate	Serrate with basal tailed	5 veined at base, reticulate beneath	Green above, dull green beneath
C. pseudocapsularis	Terrete, solid, soft, hairy	Purple	Ovate, acute	Serrated, obtuse to rounded at base	Basally 5 veined, reticulation distinct at both surface	Dull green
C. pseudoolitorius	3–4 angular, solid, woody, glabrous	Green, rarely purple near the nodal region	Ovate to ovate, lanceolate, acuminate	Serrate with basal tailed, tails unequal	5 veined, glabrous reticulation more distinct beneath	Dull green
C. tridens	Terrete, solid, soft, hairy	Purple	Simple ovate, acute at apex	Serrated, rounded at base	Venation unicostate, pinnate, reticulate, 5–6 pairs of secondaries, lower pair basal	Green
C. trilocularis	Terrete, solid, soft with mucilage	Purple	Ovate, lanceolate, acute	Serrated, rounded at base	Venation brochidobromous, basal paired 2, opposite	Green
C. urticaefolius	Terrete, solid, soft with mucilage	Purple	Ovate, acute at apex	Serrated, rounded at base	Basal vein 3, secondaries 5–7 in pairs, unicostate, reticulate, depressed above and prominent below	Green above but dull green beneath

Name of the species	Characters								
	Bud		Sepal				Petals		
	Colour	Shape	Number	Shape	Colour	Bracts	Number	Shape	Colour
C. olitorius	Yellow	Pyriform	5	Spoon shaped, apiculate apex, glandular	Purple black	2 lateral, linear, glabrous, dull green	5	Spathulate, rounded apex rarely notched, glabrous	Yellow
C. capsularis	Yellow	Rounded	5	Oblong, Spathulate, glabrous	Dull yellow	2, sebulate, purple glabrous	5	Spathulate, apex notched or lobed, glabrous	Yellow
C. aestuans	Yellow	Oblong	5	Oblong, Spathulate, glabrous, cuspidate	Purple	2 lateral, linear, glabrous purple	5	Spathulate, glabrous	Yellow
C. fascicularis	Yellow	Pyriform	5	Oblong, cuspidate, glabrous, recurved in blooming	Dull yellow	2 lateral, sebulate, glabrous purple	5	Broad Spathulate, glabrous	Yellow
C. pseudocapsularis	Deep yellow	Obconical	5	Broad , glabrous within, cuspidate, somewhat fleshy	Purple	2 lateral, acute	5	Spathulate	Yellow
C. pseudoolitorius	Yellow	Pyriform	5	Oblong, Spathulate, glabrous, cuspidate	Green but purple towards apex	lateral, glabrous purple	5	Spathulate, glabrous	Yellow
C. tridens	Yellow	oblong	5	Nevicular with subulate or mucronate apex	Greenish purple	linear, glabrous greenish purple	5	Spathulate, rounded apex, glabrous	Dull yellow
C. trilocularis	Yellow	Pyriform	5	Oblong with Nevicular apical part with extended cuspidate tail	Purple with Purple spot	linear, purple, hairy	5	Spathulate, oblong	Yellowish
C. urticaefolius	Yellow	Pyriform	5	Oblong with apiculate apex and Nevicular above, glabrous	Dull green within and below, purple outside,	Glabrous greenish purple	5	Spathulate to obovate, often retuse at apex, glabrous	Dull yellow

(continued)

Table 1 (continued)

Name of the species	Characters									
	Stamen				Ovary				Fruit	
	No.	Anther shape	Anther colour	Filament	Shape	Colour	Style	Stigma	Shape	Color
C. olitorius	>25	Oblong	Yellow	Slender	Oblong angular	Dull green	Stout cylindrical light green	Bristly	Elongated, Ridged	Deep green
C. capsularis	10	2 celled, Oblong, latrorse	Yellow	Glabrous yellow	Subglobose glabrous	Yellow	Yellow glabrous	Trifid yellow	Globose to subglobose depressed above, glabrous	Dull green
C. aestuans	15	2 celled, Oblong, latrorse	Yellowish	Waxy yellow	Oblong glabrous	Waxy yellow	Glabrous waxy yellow	Inconspicuously 3 lobed	3 armed each bifid and horny	Purple green
C. fascicularis	10	2 celled, Oblong, latrorse	Brownish yellow	Glabrous yellow	Oblong to somewhat angular glabrous	Dull brown	Glabrous	Inconspicuously lobed	Cylindrical, triangular in outline, glabrous	Green with purple shade
C. pseudocapsularis	18	2 celled, ovoid, latrorse	Yellow	Yellow	Oblong	Dull yellow	Dull yellow	Trilobed	Globose to subglobose	Purple green
C. pseudoolitorius	10	2 celled, Oblong, latrorse	Yellow	Glabrous yellow	Oblong angular glabrous	Dull yellow	Glabrous	Inconspicuously 3 lobed, yellow	Cylindrical, 3 lobed, glabrous	Green
C. tridens	15	Ovoid	Dull yellow	Glabrous dull Yellow	Oblong glabrous	Creamy	Glabrous dull yellow	Dull yellow bifid	Capsule, elongated	Green
C. trilocularis	>30	2 celled, ovoid	Yellowish	Glabrous dull Yellow	Oblong glabrous	Dull orange	Dull yellow	Dull orange bifid	Capsule, elongated	Purple green
C. urticaefolius	15	Ovoid	Yellow after anthesis	Glabrous dull yellow	Oblong angular	Dull Yellow to creamy	Glabrous dull yellow	Dull yellow lobed	Capsule, oblong	Purple green

6 Notable Varieties

Rao et al. (1983) reported the variety "TJ 40" from the inter-mutant crossing of *C. olitorius* L. Chowdhury et al. (2004) documented different varieties of *Corchorus* such as *C. olitorius* L. – JRO 3690, pedigree: inter-mutant cross; KOM 62, pedigree: gamma-ray and JRO878; *C. capsularis* L. – JRC 7447, pedigree: X-ray and JRC 212; Hybrid C, pedigree: inter-mutant cross; KC 1, pedigree: gamma-ray and JRC 4444; Bidhan Pat 1, pedigree: gamma-ray and D 154; Bidhan Pat 2, pedigree: variety 'x' mutant cross; Bidhan Pat 3, pedigree: variety 'x' mutant cross having increased variability in fibre yield and yield contributing traits.

7 Cultivation

The jute growing areas of the world are found spread over several degrees north and south of Tropic of cancer and generally between longitudes 86° and 92°E. The crop responds favorably to high relative humidity of 70–74% and annual rainfall of 1,500 mm or more with at least 250 mm of monthly precipitation during each of the months of March, April and May. The requirement in regard to range of mean temperature is 18–33° C (Karmakar et al. 2008).

Maity et al. (2008) successfully raised two cultivated species *C. olitorius* L. (Fig. 2a) and *C. capsularis* L. (Fig. 2b) and seven wild species namely *C. aestuans* L. (Fig. 2c), *C. fascicularis* Lam. (Fig. 2d), *C. pseudocapsularis* L. (Fig. 2e), *C. pseudoolitorius* I. and Z. (Fig. 2f), *C. tridens* L. (Fig. 2g), *C. trilocularis* L. (Fig. 2h) and *C. urticaefolius* W. and A. (Fig. 2i) in the experimental field plots of the University of Kalyani, West Bengal plains having sandy loamy soil, organic carbon 0.76%, soil pH 6.85 with elevation level of 48 ft above mean sea level and geographic co ordinates of 22° 99′ N, 88° 45′ E. The plantation was performed by the authors during the period of March to September.

7.1 Land Preparation

Land preparation is very important for successful cultivation. Cross ploughing for 3–5 times and laddering is necessary to prepare uniform smooth soil to have 20% organic content. Generally seed bed is prepared by repeated drilling ploughing and leveling to produce finely macerated and well aerated and clod free soil. Manuring may be done during ploughing. Mostly cow dung is used, along with NPK in appropriate proportion, according to the soil type. However, when used (fertilizer) it must be applied in three stages; one at land preparation, and two as top dressing at appropriate time. During cultivation, weeding is usually done in addition to thinning.

Fig. 2 Plant types of *Corchorus* sp.: (**a**), *C. olitorius* (**b**), *C. capsularis* (**c**), *C. aestuans* (**d**), *C. fascicularis* (**e**), *C. pseudocapsularis* (**f**), *C. pseudoolitorius* (**g**), *C. tridens* (**h**), *C. trilocularis* (**i**), *C. urticaefolius*

7.2 Plantation

Generally, the species is propagated by seeds either by broadcasting method (10–12 kg/ha) or by line sowing (lower amount of seeds is required) keeping distance between plants (5–10 cm) and rows (20–25 cm).

Lack of proper plantation strategy leads to poor utilization of field and thus responsible for reduced yield of jute. It is therefore very much necessary to choose the right option for plantation among others.

8 Germination

Seed dormancy creates a major difficulty in *Corchorus* cultivation (Schippers 2000). Palit and Bhattacharya (1981) reported faster rate of imbibitions of *C. capsularis* L. seeds than *C. olitorius* L., under different degrees of water stress (either by PEG 6000 solutions or deficit moisture), resulted in the earlier germination of the previous one than the later. The authors also suggested the critical water potential for seed germination for *C. capsularis* L. (−0.5 Mpa) and *C. olitorius* L. (−0.3 Mpa). Under field condition, seed germination and establishment are most obviously affected by soil water deficit resulting in poor crop stand (Palit 1987; Palit and Singh 1991). Patel and Mandal (1983) reported wilting and early flowering tendency of young jute seedlings at low humidity below 19% with soil moisture less than 20%. Michiyama and Yamamoto (1990) observed decreased germination of *Corchorus* seeds due to limited water supply. They also suggested positive impact of temperature (25–30°C) on seed germination.

Datta and Palit (2003) reported increased seed germination with the application of two doses (100 mV and 1,400 mV) of electromotive force. Emongor et al. (2004) evaluated the effects of hot water, sulphuric acid, nitric acid, gibberellic acid and etephon on germination of *Corchorus* seeds (*C. tridens* L.) and concluded that treatment of *Corchorus* seeds with concentrated sulphuric acid (98%) for 10, 20 and 30 min significantly increased the germination compared to other treatments, while exposure of seeds to concentrated sulphuric acid for more than 30 min significantly decreases the germination capacity. Further, the authors also reported that hot water (98.5°C) have a positive role in seed germination but with lesser efficiency.

Figueiredo et al. (1980) reported 30°C and light as the best conditions for germination of jute seeds. However, Chauhan and Johnson (2008) nullified the role of light on germination and documented seed scarification and wide range (25/15, 30/20, and 35/25°C) of alternating temperature as stimulating factors for seed germination in *C. olitorius* L.

Seed germination is one of the crucial aspects in plant breeding. Most of the time plant breeders as well as researchers faces failure in germinating seeds due to various constraints like deep seeding, planting in cold soil, extremes of watering, improper soil preparation, birds or squirrels or insect activity and poor seed quality. Therefore a proper strategy or combination of more is needed to overcome the problem. A future researcher or plant breeder will be able to determine an effective strategy if well aware of solutions obtained by previous researchers on the same aspect in different time.

9 Irrigation

Irrigation is an important tool in jute cultivation but reduction in jute fibre yield, its quality, growth and nutrient removal due to water logging, either by excessive water (high rainfall) or irrigation, has been reported by Ghorai et al. (2005).

Ghorai and Mitra (2008) suggested safe disposal of excess water such rainwater for proper crop management to get better yield and quality.

10 Yield

Ghosh and Basak (1958) were of opinion that use of old jute seeds with poor germination capacity gave poor stand and consequently low yield. But, yield of individual plant which constitute the crop, in an average are comparable to those raised from fresh seeds. Water stagnation in the field has been found to possess a lasting effect on jute yield and the quality (Choudhuri and Basak 1969; Ghosh 1983). However, impaired seedling establishment was found to be the single most important edaphic factor for the year to year fluctuation in jute yield (Ghosh 1983). Seedling vigor as well as plant growth and subsequent yield have a positive correlation with seed size (Bhattacharjee et al. 2000; Ghosh and Sen 1981).

Islam et al. (2001) observed that treating seeds with garlic extract (1:2, weigh by volume, g/ml) and Vitavax 200 (0.04%) increased the yield by 77.50% and 82.50% respectively while reducing several fungal attack. Datta and Palit (2003) have found that an external application of electromotive force (emf) of 800 mV influenced stem growth and fibre yield by affecting photosynthesis and wall thickness. Mitra et al. (2006) reported better root growth (9.7–10.2 mm) in *C. capsularis* L. varieties than *C. olitorius* L. under typical rain fed and moisture stressed upland situation in early stages of growth. Saha (2008) found that seed yield of *Corchorus* was influenced by sowing time, seed rate and sowing method.

C. capsularis L. have been shown to produce an initial higher rate of dry matter production than those of *C. olitorius* L. with the advancement of growth (Gopalkrishnan and Goswami 1970; Palit 1993). Palit (1999) observed that both plant height and diameter have a direct relationship with the yield of *C. olitorius* L. and *C. capsularis* L.

The final goal of any kind of cultivation including jute is getting better yield performance in the field. Low yield is associated with poor germination of seed, impaired seedling establishment, improper sowing time and method, poor photosynthetic activity etc. However, all these constraints have been neutralized successfully in different times by adopting various methods to increase the yield in *Corchorus* species as discussed above.

11 Retting

The process of separation and extraction of fibres from no fibrous tissues and woody part of the stem through dissolution and decompositions of pectines, gums and other mucilaginous substances is called retting (Dasgupta et al. 1976; Majumdar and Day 1977). Ghosh and Dutta (1980) proposed retting as the mechanical extraction, washing, drying followed by marketing of fibres.

Dasgupta et al. (1976) reported the movement of microbes (bacteria) from retting water into plant tissue through the stomata, epidermis and cambium and loosening of fibre strand from woody core by their enzymatic action. Liberation of soluble constituents like sugar, glycoside and nitrogenous compounds from swelled and burst plant surface (immersed in retting tank) due to water absorption was also documented (Ali et al. 1972; Ahmed and Akhter 2001).

11.1 Conventional Method of Retting

Majumdar et al. (2008) suggested conventional process of retting as steeping of defoliated jute bundles in clean or stagnant water according to the availability with proper jak material (usually mud or banana logs) followed by manual extraction of fibre either by "beat – break – jerk" or single plant extraction method after completion of retting within 15–20 days.

11.2 Chemical Retting

Dasgupta et al. (1976) reported that ammonium oxalate (0.5% at 27.77–29.44°C for 4 h at 1:10 liquor ratio) and sodium sulphate of 5 g/l at 22.22–23.89°C for 30 min were found suitable for chemical retting of jute without any adverse effect on fibre quality. Ahmed and Akhter (2001) were of opinion that chemical retting causes dissolution of tissue materials (softening of tissues due to degradation of lignin, hemicelluloses and pectin) with certain chemicals such as boiling with acid (0.5% H_2SO_4) or alkali (1% NaOH) at normal or high or boiling temperature for 6–8 h and the fibres obtained by this method have been found little coarser, rough and stiff.

11.3 Dew Retting

Jute plants are kept in worm and humid atmosphere by simply stretching over green grass for 7–15 days so that plants stalks get a direct exposure to bright sunlight in day time and moisture at night in this process (Majumdar et al. 2008).

11.4 Microbial Retting

In microbial retting pectin and hemicelluloses are decomposed into water soluble compounds by specific enzymes secreted by bacteria or fungi present in water. Among the fungi, *Aspergillus niger* (Kundu and Roy 1962), *Microphomina phaseolina*, *Mucor*, *Chaetomium* sp, *Phoma* sp, *Sporotichum* sp, *Trichoderma* sp, and *Curvularia* sp (Haque et al. 2002) were reported to responsible for retting.

Several aerobic bacteria such as *Bacillus subtilis* (Kundu and Roy 1962), *Micrococcus* sp (Haque et al. 2002) and anaerobic bacteria such as *Clostridium tertium*, *C. aurantibutyricum*, *C. felsineum* have been isolated from retting water and were found effective in retting process(Alam 1970).

12 Disease and Pests

Jute productivity suffers vastly due to the ravages caused by many insect pests and hence the entomology of bust fibre crops requires much attention for economic production. Das et al. (1995), Das and Singh (1976), Lefroy (1907), Singh and Das (1979), Tripathi (1967), and Tripathi and Ghosh (1964) reported *A. sabulifera* as a major pest of crop occurs in all the jute growing sectors of India. Repeated damage by this pest checks crop growth and induces profuse branching with reduction to fibre yield (Tripathi and Bhattachrya 1963). It was documented by Tripathi and Ram (1971) that a third instar larva of *A. sabulifera* was more penetrative in action and the larval period ranged between 9 and 16 days. Another most important pest of jute is stem weevil (*Apium corchori*) exists throughout the cropping season and damages the early sown crops (Dutt 1958). *Corchorus capsularis* L. is more susceptible to stem weevil infestation whereas *C. olitorius* L. suffers little because of its higher tannin content (Tripathi and Ram 1971). Yellow mite (*Polyphagotarsonemus latus*) causes serious damages of jute since the 1940s (Das and Roychaudhuri 1979; Das and Singh 1985; Nair 1986; Pradhan and Saha 1997).

Walker (*Spilosoma obliqua*) was once considered as a sporadic pest on jute (Dutt 1958) is now a major threat to jute crop. Das et al. (1999) reported some major pests of jute like semiloper, *Anomis sabulifera* Guenee, stem weevil, *Apion corchori*, Marshall, yellow mite, *Polyphagotarsonemus latus* (Banks), and indigo caterpillar, *Spodoptera exigus* Hubner. Bihar hairycaterpillar, *Spilosoma obliqua*. A number of minor pests (scale insect – *Pinnaspis* sp, Thrips – *Ayyaria chaetophora*, Karny, Mealy bugs – *Ferrisia virgata*) of jute are also reported by Tripathi and Ram (1971). Gray weevil (*Myllocerus discolor*) was first time recorded as a pest on tossa jute in 1973 by Das and Ghosh. The crop loss due the pest was estimated at upto 50% by Dutt (1958), whereas 81% of the damage was limited to seven fully open leaves from top and upto 95% down to the ninth leaf.

The cultivation of jute is severely affected due to disease and pest attack. This plant type is a host of different pest and disease causing micro organisms and the nature of damage is due to degree and intensity of infections. If the breeder is not familiar with the pest then the nature of damage will also be unknown and no preventive measure can be adopted. For the purpose detail knowledge on different jute pests and disease regarding the cause of infections, nature of infection, life cycle, and previous reports of damage is necessary before formulating any preventive measure.

13 Integrated Pest Management

Das (2000) recommended JRO 524 (Navin) and JRC 212 (Basudev) for cultivation in the yellow mite endemic areas as the least susceptible varieties. Studies on seasonal incidence and population dynamics of major pests of jute revealed that the intensity of damage by stem weevil, gray weevil and yellow mite were more on early sown crops but the reverse was true for semilooper incident (Das 1995). Both tossa and white jute varieties, sown in the late April, had shown remarkably less incidence of stem weevil as compared to those sown in late March or early April (Das and Singh 1985). *Physalis minima* was reported as an alternate host for yellow mite (Das and Roychaudhuri 1979). Das and Singh (1976) observed negative impact on the gut physiology of semilooper larvae due to ingestion of *Bacillus thuringiensis*. Some insecticides like Neem oil at the rate of 4 ml/l (Das 2000), Endosulphun at 0.075%, Cypermethrin at 0.03% (Das et al. 1995) were reported to be effective against jute stem weevil and semilooper. The incidence of stem weevil was observed to be less in jute plants inoculated with rice necrosis mosaic virus (RNMV) at early stage of growth of 20 days after germination irrespective of the fertilizer regims on both tossa (JRO 632) and white (JRO 212) jute varieties (Pradhan and Ghosh 1995).

Although few parasitoids were reported as effective bio control agents on jute pests but the mass culture technology is yet to be perfected and thus insecticidal interference is unavoidable in spite of their negative impact on the ecosystem. Besides the application of insecticides, regular pest surveillance is essential. Advanced integrated pest management strategies on the basis of previous damage reports and response after application of pesticides and other measures are required for achieving further success.

14 Biochemical Studies

Laskar et al. (1987) performed studies on the protein solubility of deoiled jute (*Corchorus olitorius* L.) seed in different concentrations of NaCl at pH 8.0 and reported 16 amino acid of which nine were essential. Gel filtration on sephadex G-200 revealed the presence of four components, and their molecular weight were determined by standard methods. Extractable jute seed protein in salt solution were separated into six fractions electrophoretically (SDS-PAGE) whose molecular weight were found to be 118,000; 103,000; 96,000; 67,500; 48,000 and 15,000 Da.

Maity et al. (2009a) reported distinct polymorphism in electrophoretic banding patterns of seed protein following SDS-PAGE in nine jute species and led to the detection of 52 polypeptide bands (cultivated members: *C. olitorius* L. – 42, *C. capsularis* L. – 40; wild species: *C. aestuans* L. – 28, *C. fascicularis* Lam. – 23, *C. pseudocapsularis* L. – 30, *C. pseudoolitorius* I. and Z. – 34, *C. tridens* L. – 30, *C. trilocularis* L. – 26 and *C. urticaefolius* W. and A. – 35) with molecular weight ranging between 13,000 and 122,500 Da. On the basis of this result the authors obtained hierarchical cluster of the species based on proximity matrix by Unweighted

Pair Group Method with Arithmetic Mean analysis. It revealed three prominent clusters – Cluster1: *C. trilocularis* and *C. urticaefolius*; cluster 2: *C. fascicularis*, *C. tridens* and *C. pseudoolitorius* and cluster 3: *C. olitorius*, *C. capsularis* and *C. aestuans*. The authors were of opinion that clustering of genotype signifies close genetic proximity among species which may be used in the crossing program for generating wider variability for selection and crop improvement as well as for hybrid identification in breeding experiments. Hussain et al. (2002) developed an easier modified Kappa Number Method for the estimation of lignin in different samples of jute. The developed method was reported by the authors to be efficient in comparison with the tedious gravimetric analysis of lignin using corrosive inorganic acid.

Sengupta and Palit (2004) induced a lignin deficient mutant (dlfp) of *C. capsularis* L. (JRC-212) with fibre strength as similar to normal plants. The mutant had no decrease in the amount of alpha cellulose and showed hardly any change of cellulose structure of the fibre. It is not the lignin but the amount of alpha-cellulose present in the fibre was more important in providing mechanical strength to the jute fibre (Palit et al. 2004, 2006; Sengupta and Palit 2004).

Palit and Bhattacharya (1984) categorically showed that jute to be C_3 plant with high rate of photorespiration. *C. capsularis* L. shows greater tolerance to stress than others species of jute by restricting H_2O_2 and thereby inhibiting membrane damage (Roy Chowdhury and Choudhury 1985). The activity of RuBP carboxylase enzyme in jute leaf was about five times higher than its phosphoenol phosphate. Palit and Meshram (2004) reported an exotic genotype (PPO_4) with almost half the amount of leaf chlorophyll had better photosynthetic efficiency.

Over the years, information regarding the key internal factor responsible for fibre strength of jute was unavailable. Therefore improvement of fiber strength has been unsuccessful. However, rigorous research on this aspect has solved the problem. Taxonomic characterization has always been difficult in jute due to poor exploration of wild and to some extent the cultivated species also. However, hierarchical classification in recent time using protein profile has provided an accurate characterization for their classification. The stress tolerance ability of jute has also been increased by manipulating some enzyme activity. All these reports discussed above proved the importance of biochemical studies in *Corchorus*.

15 Cytogenetical Studies

15.1 Karyotype Analysis

Karyomorphological studies in jute species are scarce (Banerjee 1932; Datta 1968; Datta et al. 1966; Paria and Basak 1973; Rao and Datta 1953; Sharma and Roy 1958) due to small sizes of chromosomes in species of *Corchorus* and presence of lignin in cell wall that produces some difficulties in the hydrolysis of materials and improper staining. For that reasons, photoplate evidence of jute mitotic chromosomes are lacking.

Somatic chromosome number in *C. olitorius* L. and *C. capsularis* L. were reported as 2n = 14 and the chromosome length varied from 1.3 to 2.7 µm (Sharma and Roy 1958) and 1.7–3.7 µm (Paria and Basak 1973) in *C. olitorius* L. and *C. capsularis* L. respectively. However, Datta et al. (1975) were of opinion that chromosomes of *C. olitorius* L. are larger (1.95–3.30 µm) than those of *C. capsularis* L. (1.65–3.10 µm). The authors also suggested that *C. capsularis* L. were with 7 median chromosomes and *C. olitorius* L. had 5 median and 2 sub-median chromosomes. Datta et al. (1975) observed that *C. urticaefolius* W. and A. (5 submedian, 2 sub terminal; length: 2.0–3.0 µm) and *C. aestuans* L. (2 median, 3 submedian and 2 sub terminal; length: 1.00–2.5 µm) also had 2n = 14 chromosomes while 3 median and 4 submedian chromosomes were reported in *C. trilocularis* L. (2n = 14) by Datta (1968). From karyotype analysis of some jute species it was indicated that evolution in the genus was not only divaricated but intricate also (Datta et al. 1966, 1975). Akhter et al. (1991) made karyotype analysis in diploid and colchicine induced tetraploids of *C. olitorius* L. and *C. capsularis* L. and suggested that there exist intra-pair chromosomal heteromorphicity in few pairs apart from predicting distinct centromeric and chromosomal formula. Samad et al. (1992) reported homomorphic nature of chromosomes in *C. olitorius* L. Alam and Rahman (2000) observed 14 equal sized metacentric chromosomes in *C. olitorius* L., *C. capsularis* L. and *C. trilocularis* L. with presence of one interstitial CMA-positive band in each of the two chromosomes of *C. capsularis* and also one interstitial DAPI-positive band and suggested common ancestral origin of the species due to the base specific banding similarity of the chromosomes.

Maity and Datta (2009a) performed karyotype analysis in nine species of *Corchorus* and provided first photo plate evidence of 2n = 14 mitotic chromosomes (Fig. 3a) in this regard. The authors documented three (*C. fascicularis* Lam. – $2Am^{sc} + 8Bm + 4Cm$), two (*C. olitorius* L. – $2B_{sm}^{sc} + 6B_m + 6C_m$, *C. capsularis* L. – $2B_m^{sc} + 2B_{sm} + 4B_m + 2C_{sm} + 4C_m$, *C. aestuans* L.–$2B_{sm}^{sc} + 6B_m + 4B_{sm} + 2C_m$; *C. pseudoolitorius* I. and Z. – $2B_m^{sc} + 8B_m + 4C_m$; *C. pseudocapsularis* L. – $4B_m + 2C_{sm}^{sc} + 8C_m$) and one (*C. tridens* L. – $2C_{sm}^{sc} + 12C_m$; *C. trilocularis* L. – $2C_m^{sc} + 12C_m$; *C. urticaefolius* W. and A. – $2C_m^{sc} + 10C_m + 2C_{sm}$) morphologically distinct chromosome types (A = long: ≥3.26 µm; B = medium: 2.26–3.25 µm and C = small: 1.25–2.25 µm) in the genus. Variation in absolute chromosome length was also noted among the species (*C. olitorius* L. –2.10–2.94 µm; *C. capsularis* L. –2.10–3.15 µm; *C. aestuans* L. – 2.03–2.83 µm; *C. fascicularis* Lam. – 1.77–3.50 µm; *C. pseudocapsularis* L.– 1.58–2.74 µm; C. *pseudoolitorius* I. and Z. – 2.00–2.73 µm; *C. tridens* L.– 1.37–2.00 µm; *C. trilocularis* L. – 1.50–2.07 µm and *C. urticaefolius* W. and A. – 1.61–2.25 µm).

15.2 Meiotic Studies

The haploid chromosome number in *C. capsularis* L. and *C. olitorius* L. was first reported to be seven (Banerjee 1932) and later confirmed by Bhaduri and Chakraborti (1948). The haploid chromosome number in *C. tridens* L., *C. trilocularis* L. and

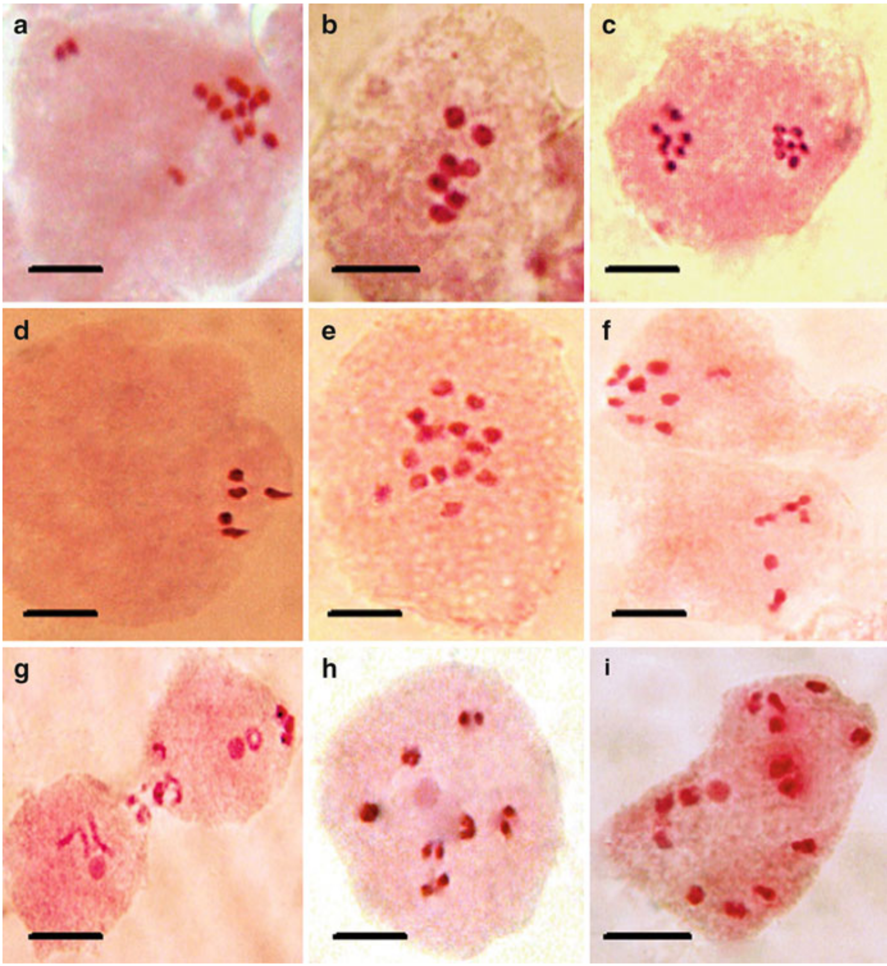

Fig. 3 Cytologiaogical behavior in *Corchorus* sp.: (**a**), Mitotic configuration in *C. olitorius* showing 2n = 14 chromosomes at metaphase (**b**), Meiotic configuration at metaphase I showing normal 7II formation (**c**), 7–7 separation at Anaphase I (**d**), Aneuploidy at metaphase I showing n = 5 chromosome configuration (**e**), Aneuploidy at metaphase I showing 14II (**f**), Two adjacent PMCs with n = 7 at upper and n = 5 at lower (**g**), Cytomictic chromosome behavior at diplotene (**h**), Desynaptic behavior of chromosomes with 3II + 8I (**i**), 2n = 28 chromosomes in amphidiploid at diplotene (Scale Bar = 10 µm)

C. fascicularis Lam. were also observed as seven (Datta 1952, 1953, 1954; Mukherjee 1952; Rao and Datta 1953; Sharma and Datta 1953). Meiotic lability was reported by Datta (1953) in both the cultivated species of jute and later in *C. fascicularis* Lam. by Rao and Datta (1953) along with hypo- and hyperploid pollen mother cells containing 4–12 bivalents, even 14 also observed in *C. olitorius* L. suggesting possibility of the occurrence of polyploids under natural condition. Sharma and Datta (1953) reported a type of *C. capsularis* L. (roundish leaf), with hypo- and hyperploid PMCs containing 6–12 bivalents in addition to the normal number of seven. Presence of secondary association of bivalents in *C. capsularis* L. was also documented (Nandi 1937). Occasional presence of two bivalents in attachment with the nucleolus was observed both in *C. capsularis* L. and *C. olitorius* L. (Datta 1952). Kumar et al. (1981) reported 7 bivalents in two cultivated species of jute where ring bivalents were most frequent and rod present occasionally. In *C. tridens* L. and *C. aestuans* L., 5–9 bivalents and 5–14 bivalents respectively were reported in addition to the normal seven bivalents (Annual Report JARI, 1952–53).

Maity and Datta (2009b) performed mean chromosome association in nine species of jute and suggested that *C. olitorius* L. (mean/cell: 7 II – Fig. 3b), *C. capsularis* L. (mean/cell: 6.98 II + 0.03 I), *C. tridens* L. (6.98 II + 0.03 I), *C. trilocularis* L. (7 II) and *C. urticaefolius* W. and A. (7 II) always form 2n = 14 chromosomes at metaphase I with balanced anaphase I (7/7) segregation (Fig. 3c). The authors also noted numerical variations in chromosome number like n = 1,2,3,4,5 (Fig. 3d),6,9,10 and 14 (Fig. 3e) in addition to n = 7 (normal number – Fig. 3f) in the meiocytes of *C. fascicularis* Lam. (24.42% – MI; 1.79% – AI), *C. aestuans* L. (33.33% – MI; 28.57% – AI), *C. pseudoolitorius* I. and Z. (24.69% – MI; 15.73% – AI) and *C. pseudocapsularis* L. (2.56% – MI; 0.0% – AI) with aneuploidy and polyploidy. Average chromosome association per cell at metaphase I was 0.002 VI + 0.006 IV + 6.98 II + 0.31I in *C. fascicularis* Lam., 6.55 II + 0.60 I, in *C. aestuans* L., 6.60 II in *C. pseudoolitorius* I. and Z. and 7.08 II + 0.21 I in *C. pseudocapsularis* L. Study on meiotic chromosome configurations and chiasma frequency at diplotene in the cultivated species of *Corchorus* revealed ring and rod (*C. olitorius* L.: ring – 2.66 ± 0.37/cell, rod – 4.25 ± 0.35/cell, chiasma: 1.37/bivalent, out of 24 cells analyzed; *C. capsularis* L.: ring – 4.68 ± 0.14/cell, rod: 2.32 ± 0.14/cell, chiasma: 1.67/ bivalent, out of 59 cells analyzed, *C. aestuans* L. : ring – 2.00 ± 0.22 /cell, rod – 4.96 ± 0.20/ cell, chiasma 1.28/ bivalent, 23 cells observed; *C. fascicularis* Lam. : ring – 2.84 ± 0.16/cell, rod – 4.25 ± 0.14/cell, chiasma 1.42/ bivalent, 63 cells estimated; *C. pseudocapsularis* L.: ring – 2.33 ± 0.20/ cell, rod – 4.08 ± 0.21/ cell, chiasma 1.25/ bivalent, 24 cells noted; *C. pseudoolitorius* I. and Z. : ring – 1.44 ± 0.13/ cell, rod – 5.44 ± 0.14/ cell, chiasma 1.20/ bivalent, 27 cells observed; *C tridens* L. : ring – 1.89 ± 0.10/ cell, rod – 5.11 ± 0.10/ cell, chiasma 1.27/ bivalent, 36 cells scored; *C. trilocularis* L. : ring – 2.38 ± 0.19/ cell, rod – 4.60 ± 0.19/ cell, chiasma 1.34/ bivalent, 50 cells studied; *C. urticaefolius* W. and A.: ring – 1.94 ± 0.15/ cell, rod – 5.06 ± 0.15/ cell, chiasma 1.28/ bivalent, 54 cells observed) configurations having nonrandom in distribution of ($p < 0.001$) ring and rod bivalents among the species; with random ($p = 0.50–0.70$) occurrence of chiasmata per cell and per bivalent (Maity and Datta 2009b).

15.3 Cytomixis

Cytomixis, a phenomenon relating to cell to cell migration of nuclear materials through cytoplasmic connections (Gates 1911) was first noted by Kornicke (1901) in pollen mother cells of *Crocus sativus* and since then its occurrence has been reported more commonly during microsporogenesis in countless flowering plants. The phenomenon has also been recorded in root meristems (Brown 1947; Bobak and Herich 1978; Jacob 1941; Sarvella 1958; Tarkowska 1960), leaves and epidermal scales (Tarkowska 1960) and tapetal cells (Cooper 1952; Sapre and Deshpande 1987). In spite of its wide occurrence and reports, the validity and significance of the phenomenon is still ambiguous. Maity and Datta (2009b, 2010) noted cytomixis in both cultivated (Fig. 3g) and wild species of jute leading to aneuploidy in the species and also reported it from all hybrid lines.

15.4 Desynapsis

Maity and Datta (2009c) reported a spontaneous viable desynaptic (medium strong) mutant (monogenic recessive) in *C. fascicularis* Lam. with morphological variations than normal (1 out of 27 plants scored) jute species following male meiotic analysis and demonstrated enhanced univalent frequency per cell – Fig. 3h (4.05, normal – 0.31), reduced number of chiasma (6.67, normal – 7.28) and bivalent (5.12, normal – 6.99) per nucleus, few meiocytes (13.64%, normal – 5.36%) with unequal separation at AI, Cytologically near normal AII (94.83%, normal – 100.00%) cells and high male fertility (81.77%, normal – 92.06%).

15.5 Polyploidy

Maity and Datta (2010) induced an amphidiploid ($2n = 4\times = 28$) with normal pairing (Fig. 3i) behavior (to expand the gene pool for crop improvement) from the seeds of F1 hybrid (*C. trilocularis* L. × *C. capsularis* L.) plants (Fig. 4a) by treating the meristematic tips of young seedlings bearing only two cotyledonary leaves with aqueous solution of colchicine (0.25% and 0.5% treatments for 6 h on 1, and 2 consecutive days; 10 seedlings were treated in each lot for each variety). The amphidiploids (allopolyploid) induced (0.5% colchicine, 6 h, 2 consecutive days) was found to possess general polyploid traits like reduced growth (Fig. 4b), vigor and viability but with enhanced chlorophyll content in leaf and enlarged stomata (Fig. 4c) than F1 (Fig. 4d) but with near normal pairing behavior (12.95 bivalent/cell and 2.10 univalent /cell) and high pollen fertility (82.53%). The pollen (Fig. 4e) size was also enhanced in this allopolyploid in comparison to F1 (Fig. 4f). The plant yielded a total of 32 seeds but seed size increased significantly than F1.

Lignification of somatic cells has been a major constraint of karyotype analysis for a long time in jute. Due to unavailability of karyotype data and poor information on behavior of meiotic chromosomes it was difficult to ascertain the interrelationship among the species of *Corchorus*. It has led to unsuccessful hybridization

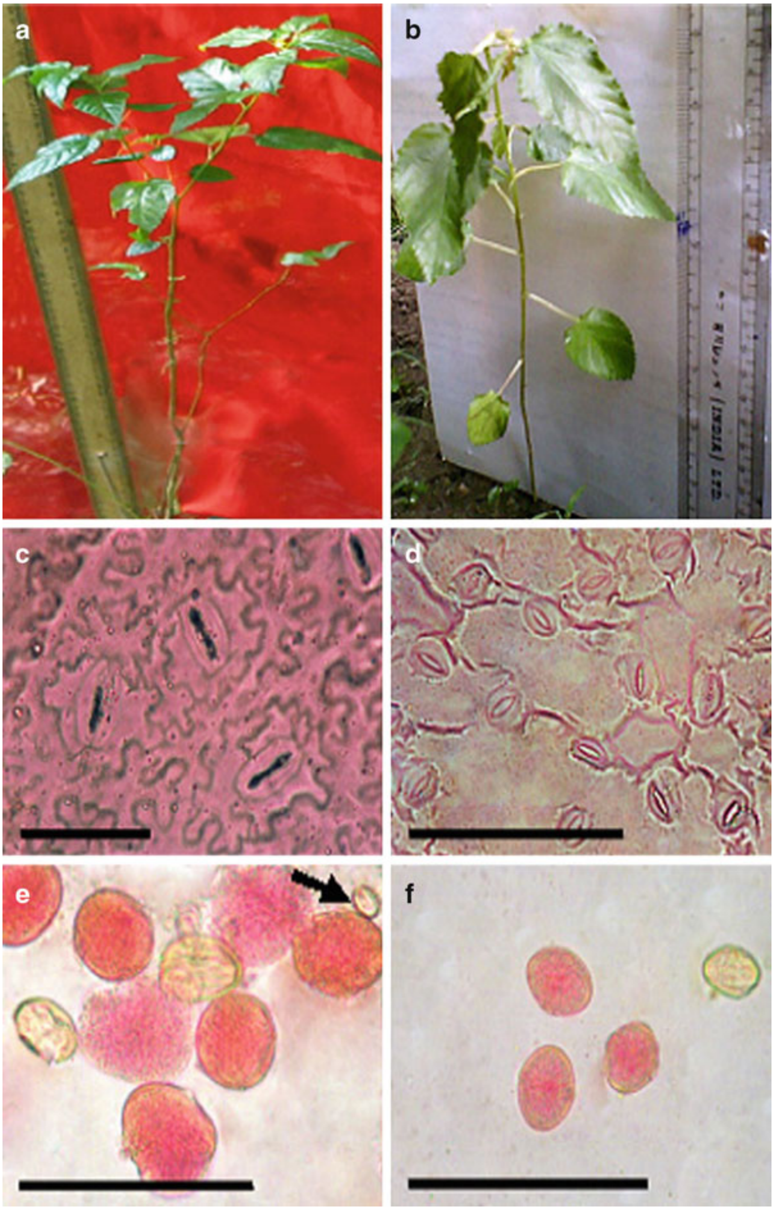

Fig. 4 Morphological and different attributes in *Corchorus* plant types: (**a**), F1 plant (**b**), Amphidiploid plant (**c**), Enlarged stomata in amphidiploid (**d**), Normal sized stomata in F1 (**e**), Enlarged pollen grains in amphidiploid with micropollen formation marked by *arrow* (**f**), Pollen morphology in F1 plant (Scale Bar of Fig. 3c–f is 100 μm)

among species and responsible for limiting the scope of raising a superior hybrid. However, recent reports on all of these aspects will be helpful to the future researchers for creating superior plant types following successful hybridization.

16 Pollen Morphology

Maity et al. (2009b) performed palynological studies of two cultivated (*Corchorus capsularis* L. and *C. olitorius* L.) and seven wild (*C. aestuans* L., *C. fascicularis* Lam., *C. pseudocapsularis* L., *C. pseudoolitorius* I. and Z., *C. tridens* L., *C. trilocularis* L. and *C. urticaefolius* W. and A.) species of jute following acetolysis (Erdtman 1952) and Scanning Electron Microscopic Analysis and revealed subprolate (exception: *C. pseudocapsularis* L. – prolate), tricolporate (excepting: *C. trilocularis* L. had both tricolporate – 90.0% and tetracolporate – 10.0% pollen grains) Nature of pollen grains having medium to relatively longer colpi with normal or incurved margin. The authors also reported variable pollen size with lalongate pore (raised or inconspicuous edges), reticulated exine surface and irregular morphology of walls among the species.

Identification of pollen characters through Scanning Electron Microscopy and acetolysis techniques may be the additional parameters to decipher inter relationship among different species of *Corchorus*.

17 Genetical Studies

17.1 Induced Mutagenesis

The systematic breeding programme in jute has been inadequate (since the early 1940s) due to its lack of genetic variability. To get rid of this constraints, physical mutagens (X-ray, gamma-ray) were applied extensively for obtaining genetic variation in short period of time and various aspects on both basic and applied mutagenesis in jute were documented over time by Basu (1965), Bose and Banerjee (1976), Chattopadhyay et al. (1999), Kundu et al. (1961), Rakshit (1967), Sharma and Ghosh (1961), Shaikh and Miah (1985), Singh et al. (1973), and Thakare et al. (1973). Jacob and Sen (1961) obtained three X-ray induced haploids in *C. olitorius* L. but not exploited further. Thakare et al. (1974) reported four primary trisomics from irradiated population of *C. olitorius* L. Basak et al. (1979) documented haploids in *C. olitorius* L. by crossing mutant strains but the genetic combination was found to possess profound negative effect on fibre yield.

Apart from cytological variation by mutagenesis, plant type induced mutation in *C. olitorius* L. are *crumpled leaf* (40 kR X-ray – tolerance to drought and non-shattering pod; Singh et al. 1973); *tobacco leaf* (50 kR X-ray – increased number of internodes; Singh et al. 1973); *narrow leaf* (60 kR X-ray + 1.0% EMS – small

Fig. 5 Morphological and anatomical attributes in normal and mutant plant types of *Corchorus* sp.: (**a**), Induced chlorophyll deficient mutant plant type *chloroxantha* in *C. olitorius* at left position with the normal plant at the right side (**b**), Stick of *thick stem* mutant plant of *C. olitorius* at the right and normal plant at left position (**c**), Stem anatomy of normal *C. olitorius* plant (**d**), Distinct variation in fibre pyramid size and distribution in the stem anatomical section of *thick stem* mutant plant (Scale Bar of Fig. 4c–d is 500 μm)

narrow deep green leaf; Chattopadhyay et al. 1999); KOM 62 (gamma-ray induced – Chowdhury et al. 2004) and those of *C. capsularis* are *patchy albino leaf* (30 kR X-ray – rectangular fibre wedge, Singh et al. 1973); *ribbon leaf* (male sterile – Rakshit 1967); *soft stem* – (absence of lignified fibres, Chattopadhyay et al. 1999); *unfolded lamina* (50 kR X-ray – no lignification in secondary phloem, Chattopadhyay et al. 1999); *snow white* (snow white fibre – Ahmed et al. 1983); *short petiole* – (efficient solar radiation utiliser – Sinhamahapatra 2005); *narrow erect leaf* (Anonymous 1970); JRC 7447 (X-ray induced – Chowdhury et al. 2004); KC 1 (Gamma-ray induced – Chowdhury et al. 2004); *Bidhan Pat* I (Gamma-ray – Chowdhury et al. 2004) amongst others.

Maity and Datta (2009d) reported eight induced (different doses of gamma-irradiations: 50, 100, 200 and 300 Gyre and EMS: 0.25, 0.50 and 1.00% for 2 and 4 h durations) viable morphological mutants of *C. olitorius* L. including *chloroxantha* (Fig. 5a), *viridis*, *pigmented stem*, *thick stem* I (Fig. 5b) and II, *broad leaf, lax* *branching* and *late flowering* at M_2. Normal and mutants had 2n = 14 chromosomes at metaphase I. Mutation frequency were higher in EMS induced mutants (1.49%) than gamma irradiations (0.52%). The mutant traits were found monogenic recessive to normal. Analysis of stem anatomical features from suitable transverse sections in control (Fig. 5c) and in 3 mutants (*thick stem* I – Fig. 5d and *thick stem* II and *pigmented stem*) revealed that fibre zone, number of fibre pyramid/ section and number of fibre bundles / pyramid enhanced significantly in mutants than control. The authors also reported these mutants as promising plant types (in comparison to the normal untreated plant) on the basis of physiological (*Thick stem* I and *broad leaf* – high photosynthetic efficiency; *thick stem* I and *lax branching* – drought tolerant), biochemical (seed protein content: *Thick stem I* – 18.1% and *broad leaf* 17.2%), yield (*Lax branching* – enhanced fibre yield) parameters and possessed lower amount of lignin content in fibre (3.5–8.5%) than control (11.0%).

Jute mutants are available as marker traits and genetic linkage between two marker genes in *C. capsularis* L. were: (i) bitter leaf taste and branching habit (Ghosh et al. 1948), (ii) branching habit and fasciation of stem (Basak et al. 1971), (iii) blue seed-coat and snow white fibre (Ahmed et al. 1983), (iv) snow white fibre and green stem (Ahmed et al. 1983); (v) leafy stipule and green seed-coat (Basak 1993), (vi) cordate leaf and dwarf stem (Basak 1993) and leaf stipule and non-abscisic leaf petiole (Basak 1993). Maity and Datta (2009d) suggested *viridis*, *chloroxantha* (seedling colour) and *pigmented stem* mutants to be used as genetic markers in efficient breeding programme in tossa jute.

Induced mutagenesis is as an effective tool for creating superior plant types having morphological and biochemical marker traits. The mutants evolved seem to be in the direction of the objective for better exploitation being looked for in the crop. Proper agronomic management of mutants is most desirable for their future exploration in the field of genetics and efficient breeding in the species.

18 Anatomy

18.1 Stem Anatomical Parameters in Relation to Fibre Yield

In jute, fibre bundles form definite layers of concentric arcs in succession in cones or pyramids which lie next to the cambial layer towards the periphery of the stem in the cortical region and the number of layers in each arc varies according to species or varieties in each species (Hazra and Karmakar 2008). The length and breadth, thickness of wall and dimensions of lumen of the fibre cells are different in different axial positions of the plant parts. The degree of variations in each character is different in different jute varieties and strains (Haque 1992; Haque et al. 1976). The genetic relationship between anatomical characters and fibre yield and quality in *white* jute was reported (Chen 1991; Chen et al. 1990). It was reported by Kundu (1954, 1968), Kundu et al. (1959) and Maiti (1997) that fibre yield depends on the anatomical parameters like bark thickness, number of fibre pyramids, number of fibre bundles in a fibre pyramid, fibre bundle compactness, density of fibre bundles per unit area and arcs of non fibrous tissue between the epidermis. Lower value for last parameter as stated above indicate higher yield and higher values for the rest of the parameters indicate higher yield (Islam et al. 1980). Maiti (1997) proposed positive correlation between fibre fitness and area of transverse section of fibre bundle and number of cells per bundles. Majumdar (2002) documented that fibre quality depends on fibre fitness and mean area of fibre bundle minus lumen area, followed by that mean area of fibre bundle and number of cells per fibre bundle.

Maity et al. (2009c) performed transverse section of nine jute species – two cultivated: of *C. olitorius* L. and *C. capsularis* L.; seven wild: *C. aestuans* L., *C. fascicularis* Lam., *C. pseudocapsularis* L., *C. pseudoolitorius* I. and Z., *C. tridens* L., *C. trilocularis* L. and *C. urticaefolius* W. and A. from stem of uniformly matured plant (at fruit ripening stage,175–180 days from sowing) having basal zone: 1.5–2.0 cm. above ground level and upper zone: 15.0–20.0 cm. from apex, following the double staining method of Johansen (1940), considering the following aspects: fibre zone, appearance and shape of phloem fibre, number and area of fibre pyramid, number of bundles per pyramid, diameter of fibre cell, xylem area and Nature of pith and reported distinct variation in the species (*C. oilitorius* L.: discontinuous phloem fibre with disintegrated pith and elongated phloem patches having oblong outline; *C. capsularis* L.: phloem zone one third of the xylem zone, pith disintegrated; *C. fascicularis* Lam.: continuous patches of phloem fiber with linear bundles, phloem zones more or less half of the xylem zone, pith intact; *C. tridens* L.: phloem zone one fourth of the xylem zone with rectangular bundles, pith intact; *C. urticaefolius* W and A.: discontinuous patches of phloem with irregular, polygonal fibrous zone, phloem and xylem zone occupying equal spaces, pith initiate to disintegrate; *C. pseudocapsularis* L.: phloem zone one fourth of the xylem zone with rectangular bundles, pith intact; *C. aestuans* L.: fibrous zone square in outline and patches are pyramidal at base; *C. trilocularis* L.: phloem patches interrupted and elongated oblong in outline; *C. pseudoolitorius* I. and Z.: phloem fiber continuous and pyramidal at base with intact pith).

In jute mutants, variability in the anatomical features effecting fibre development process indicates the possibility of influence of genetic control on fibre production harnessing higher fibre yield. During searching for donors for fibre quality improvement, these anatomical parameters should also be given emphasis along with physical parameters of the fibre. Apart from that inter relationship between different species of Corchorus can also be depicted from anatomical parameters.

19 Interspecific Hybridization

Interspecific hybridization between *C. aestuans* L. and *C. capsularis* L. (Islam and Sattar 1961), *C. trilocularis* L. and *C. capsularis* L. (Arangzeb and Khatun 1980; Faruqi 1962; Maity and Datta 2008), *C. aestuans* L. and *C. olitorius* L. (Haque and

Islam 1970) and *C. trilocularis* L. and *C. capsularis* L. and *C. olitorius* L. (Arangzeb 1994) were attempted with the objective to incorporate fine fibre trait from wild species (donor) to cultivated members of jute. Of practical importance, it was found that *C. trilocularis* L. donated fine fibre trait to *C. capsularis* L. in the elite strain 'Tri Cap' an interspecific hybrid from Bangladesh (Khatun 2007). Datta and Sen (1961) performed crossings between *Corchorus sidoides* F.Muell. (as female parent) × *C. siliquosus* L. (as male parent) and obtained 19.05% pod setting in comparison to 8.7% in reciprocal crossings but in either case crossed pods had nonviable seeds. The authors were of opinion that the species were phylogenetically unrelated and therefore the possibilities of getting viable hybrids were rather impossible. Islam et al. (1973) isolated a spontaneous amphidiploid in the F_3 progeny of the cross, *C. olitorius* L. × *C. depressus* Stooks L. Islam et al. (1981) failed to develop any plantlet in an attempt to produce polyploids through anther culture from a spontaneous amphidiploid of the hybrid *C. olitorius* L. × *C. depressus* Stooks L. Maity and Datta (2008) raised viable F1 hybrids (*C. capsularis* L. – male parent × *C. trilocularis* L. – female parent) plants and cytomorphologically assessed. The cross derivatives of F1 hybrid were examined at diploid (F2 and F3 generations) and tetraploid (amphidiploid) levels by the authors.

Although the wild species of *Corchorus* are poor fibre yielder, but are reported as genetic resources for disease resistance (Palve et al. 2004). Conservation and exploitation by interspecific hybridization between wild and cultivated species is an efficient strategy for creating genetic diversity in jute.

20 Molecular Genetics

20.1 Genetic Diversity

Study of jute at molecular level has been very brief till now (Samira et al. 2010). Molecular study of jute carried out till date includes genetic diversity analysis of jute using different molecular markers e.g. RAPD, AFLP, chloroplast – SSR, SSR, STMS and ISSR (Qi et al. 2003 a, b; Basu et al. 2004; Roy et al. 2006; Akter et al. 2008; Mir et al. 2008) and construction of genomic and cDNA library followed by subsequent sequencing of randomly selected clones (Islam et al. 2005; Wazni et al. 2007). Hossain et al. (2002) investigated the genotype characteristics of cultivars (12 accessions) along with varieties (9 different ones) of both of the jute species, *Corchorus olitorius* and *Corchorus capsularis* by DNA fingerprinting analysis using RAPD and generated species specific RAPD markers that helped to relates molecular marking data with existing genetic classification. Basu et al. (2004) evaluated genetic diversity from 49 genotypes of *C. olitorius* and *C. capsularis* using amplified fragment length polymorphism (AFLP) and simple sequence repeat analysis (SSR) and reported high level of variation between them. Qi et al. (2004) documented the fact that random amplification of polymorphic DNA (RAPD) and inter simple sequence repeat (ISSR) markers, used for genetic diversity analysis of 27 accessions of jute from China, India, Vietnam and Japan, were found to be efficient in revealing inter and intra specific genetic differences and diversity. Mir et al. (2007) assessed the genetic diversity between *C. olitorius* and *C. capsularis* (81 genotypes used) for fibre yield and four other related traits, using SSR marker developed from *C. olitorius*.

In earlier time's only morpho-physiological traits like plant height, harvest index, stomata size, protein profile etc. were considered for genetic diversity analysis in *Corchorus*. But they are limited in number and are often influenced by environment, making them unsuitable for proper assessment of the genetic diversity. This constraint can be overcome by the use of molecular markers as they are unlimited in number and not influenced by the environment. Apart from this genetic diversity analysis by molecular markers are also considered as the most advanced and accurate tool for taxonomic characterization, predicting evolution and performing phylogenetic analysis in all living organisms including jute.

20.2 Gene(s) Identified

The number of genes identified so far in jute is very limited (Samira et al. 2010). Islam et al. (2005) documented sequences of 15 jute genomic and cDNA clones having significant similarity to Arabidopsis genes. Wazni et al. (2007) reported 16 expressed sequence tags (ESTs) showing significant similarity to Arabidopsis. EST's reported from *C. capsularis* were RNA polymerase C1 (rpoC1) gene and putative phosphate transport ATP Binding protein (Ingram et al. 2006), and that from *C. olitorius* was chloroplast 18S ribosomal RNA gene (Stone et al. 2005). Among three genes (caffeoyl-CoA-Omethyltransferase, cinnamyl alcohol dehydrogenase and 4-coumaryl CoA-ligase) involved in lignin biosynthesis pathway, complete cDNA sequences of the first two genes from *C. capsularis* have been deposited in Gene Bank by Basu et al. (2004). Alam et al. (2010) identified a putative leucine-rich repeat receptor-like protein kinase (LRR-RLK) gene together with its 5′ and 3′ untranslated regions of jute (*Corchorus olitorius* L.) and sequenced. The gene (3,371 bp) contains two exons and one intron (coding sequence 2,879 bp long encoding a peptide of 957 amino acids) and expressed in low temperature, high salt concentration, dehydration, abscisic acid treatment, and fungal infection, suggesting the involvement of the gene in multiple stress response pathways in jute (*C. olitorius* L.). The authors were of opinion that LRR-RLK is the only jute gene which has been completely sequenced and characterized till date. Samira et al. (2010) reported the presence of nuclear, chloroplast and mitochondrial genes related to signaling pathway, metabolic and functional processes of jute biology, to determine molecular marker linked to different biotic and abiotic stresses, after performing bioinformatics analyses of two jute Simple Sequence Repeat (SSR) libraries and their analyses also revealed seven CpG islands and one rRNA gene.

21 *In Vitro* Studies

21.1 Tissue Culture

The scope of crop improvement through gene introgression is limited due to presence of a strong sexual incompatibility barrier between the two cultivated species of jute. Protocols have been developed for jute explants and protoplast culture systems to address these issues. Halder and Seraj (1992) obtained friable calli of *Corchorus capsularis* L.var. D-154, var. CVL-1 and *C. olitorius* L.var. 0–4 by sub culturing compact calli through suspension culture (MS + BAP + tyr and MS + BAP + tyr + NDGA hypocotyl segments were used as inoculums) and found greater friability of callus in media containing NDGA. They also observed optimum growth curves for suspension cultures in MS + BAP + tyr + 2, 4-D. Saha and Sen (1992) have successfully performed somatic embryogenesis in protoplast derived calli of *C. capsularis* L. Khatun et al. (2003) established an efficient seed germination system and healthy seedling production in different varieties (O4, O9897, OM1 and O72) of *C. olitorius* L. on agar supported hormone free MS medium and cotton free hormone supported Murashige and Skoog (MS) medium and concluded that the percentage (98%) seed germination on cotton supported medium was higher than the agar supported medium (46%). The authors also observed that plant regeneration from the cotyledonary petioles of the varieties on Murashige and Skoog agar solidified medium supplemented with IAA: 0.5 mg l^{-1} and BAP: 3.0 mg l^{-1} was as good as agar supported seedlings.

A liquid culture protocol was developed to regenerate shoots from cotyledons of germinating seeds of *C. capsularis* L. by Saha et al. (2004). Mir et al. (2008) reported a chloroplast DNA (cp DNA) marker, showing species specific hybridization patterns with *Eco*RI – digested total genomic DNA of *C. capsularis* L. and *C. olitorius* L., and used in the characterization of the somatic hybrid cell lines at their early stages of growth.

Although tissue culture is a popular approach to overcome sexual incompatibility barrier between different species of *Corchorus* either for regeneration in short or performing hybridization between distantly related species, some limitations also exist. In earlier time regeneration of plant from cotyledons without petioles, hypocotyles and root explants was nearly unachievable. This problem was solved by adopting the method of callus culture and also regenerating plant from internodes, zygotic embryo etc. using various combinations of growth regulators in Murashige and Skoog medium.

22 Transgenic Development

Khatun et al. (1993) developed a direct transgenic plant regeneration protocol from *Agrobacterium tumifaciens* infected explants. Biolistic particle delivery system developed by Ghosh et al. (2002) is an efficient protocol for the generation of stable genetic transformants in jute variety JRC 321. Transgenic hairy roots were induced in jute cotyledons and hypocotyles of both *C. capsularis* L. and *C. olitorius* L. using *A. rhizogens* strains and somatic embryos were obtained from these tissues. The bialaphos resistance gene *bar* and *rolC* genes of *A. rhizogens* were used for transformation and transgenic plants obtained showed resistance to bialaphos (Mir et al. 2008).

Conventional breeding approach by various traditional methods has always been the popular choice to breeders for creating high yielding varieties in jute. However, these methods have some limitations like creating sexual hybrids, successful introduction of foreign genes etc. Therefore biotechnological approach is necessary for developing superior plant types with desirable foreign genes. Although information on such kind of research is meager in jute but a future researcher will be benefited with the existing reports discussed above for formulating convenient methods.

23 Market Value

The crop suits well in crop rotation and has high socio-economic (about 2.5 lakh people are employed in the jute industry and 25 lakhs people are engaged in jute based ancillary sector) significance in India and contributes about 40% of the world production of jute fibre earning annually 1,200 crore rupees approximately as foreign exchange by exporting different jute products (Karmakar et al. 2008).

24 Conclusion

The time and effort that has been devoted for the improvement of fibre crops is much less as compared to vegetable and cereals. A detailed report regarding all essential biological aspects will be helpful for widening the genetic base in *Corchorus*. Molecular characterization of *Corchorus* species is essential and together with the other information may provide better precision for exploring the genetic diversity in jute.

Reports on normal and as well as abnormal cytological phenomenon, induced mutagenesis, transgenic development, gene identification, anatomical features were meager in jute over long time. Information on these aspects of both cultivated and wild species provide a certain knowledge base which are essential to formulate an appropriate research strategy to utilize valuable molecular techniques and generate information on genome structure for its best exploitation. A beginning has already been made in all these areas which need to be strengthening further for achieving the desired goal in varietal improvement of jute. In addition, the collection and utilization of jute germplasms have made a significant increase in productivity and have to be assessed further for desirable traits to create market demand. Hence, introduction of trait specific germplasms has become a compulsion. However, strong promotional efforts and price competitiveness has to be adopted also to make it a popular choice for use.

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Decision Support Systems for Agrotechnology Transfer

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Abstract Climate change causing sudden floods or prolonged droughts, and global warming resulting in loss of soil carbon and an increase in temperature are two major recent concerns in agriculture. The goal of maximum possible production to feed the world's booming population is also a priority. Maximizing crop production while mitigating the effects of climate change and global warming can only be achieved if sustainable agriculture is practiced. As agricultural management practices and views of agriculturists changed, the definition of sustainable agriculture also changed. However, conservation of environmental resources along with maximum yield of crops or cropping systems has always been the main aim of sustainable agriculture. Crop forecasting through anticipation of future weather patterns and timely decision of proper agricultural management practices to avoid sudden crop failure is one of the most advanced ways of sustainable agriculture. The suite of crop simulation models in Decision Support Systems for Agrotechnology Transfer (DSSAT) is a very useful tool for sustainable agriculture advancement. DSSAT, which is used to predict the productivity ranges of crops, also has the flexibility to use geographic information system (GIS), decision-making analysis programs and weather generators. DSSAT has been used by many scientists, decision-makers and researchers all over the world for more than two decades and has been modified to meet specific needs and improve the predictability of the crop models under different circumstances.

In this review article, the earlier phase of developments of opinions of using different crop models, details of crop models, functionalities of various programs/data management systems and the idea of evolvement of DSSAT are explained.

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The software package, methodology of functioning of DSSAT and its development stages are described. The article also includes (i) the advantages and scopes of using DSSAT with GIS and weather generator to predict growth, development and yields of various crops, (ii) analysis of interpretations (iii) how DSSAT may help sustain agricultural system both economically and environmentally by simulating crop systems for spatial variability, water stress situation, pest damage, climate change, risk factors and bio-energy production. The article describes researches under various adverse crop growth situations such as decline in ground water level, drought, increased temperature, CO_2 elevation and interprets the results. The results in this article mainly illustrate how researchers could explore (i) the benefits of using DSSAT as an essential software, (ii) its usefulness in modeling details of soil-crop-water system functions and future potentials, and (iii) its performance as an early warning tool for determining suitable management practices to avert crop failure and stabilize the maximum production of cropping systems. The modifications made to improve the capability of the decision-making process and more accurate prediction in various modules of DSSAT and its different versions are also discussed. Researches that illustrate the comparison of DSSAT with other crop simulation models and inter-linkage of other model programs with DSSAT to address various issues of sustainable agriculture are also discussed.

Keywords Sustainable agriculture • Crop simulation models • Climate change • DSSAT • CERES • CROPGRO • SUBSTOR • IBSNAT • ICASA • Management practices • Spatial agriculture • Precision agriculture • Regional agriculture • Weather generator • Crop forecasting • Genetic coefficient • Root length density • Crop water use • Maize • Soybean • Rice • Wheat • Irrigation strategies • N and P application rate

Abbreviations

AEGIS	Agricultural and Environmental Geographical Information System
BMP	Best Management Practice
CERES	Crop Estimation through Resource and Environment Synthesis
CSM	Crop Simulation Model
CTIC-TFI	Conservation Technology Information Center and The Fertilizer Institute
CWP	Crop Water productivity
CWU	Crop Water Usage
DM	Dry Matter
DSSAT	Decision Support Systems for Agrotechnology Transfer
DSS	Decision Support System
E	Evaporation
ET	Evapotranspiration
GC	Genetic Coefficient

GCM	General Circulation Model
GIS	Geographic Information System
HI	Harvest Index
IBSNAT	International Benchmark Sites Network for Agrotechnology Transfer
ICASA	International Consortium for Agricultural Systems Applications
N	Nitrogen
P	Phosphorus
RZWQM	Root Zone Water Quality Model
SARP	Simulation and Systems Analysis for Rice Production
SWB	Soil Water Balance
T	Transpiration
YVC	Yield Variability Coefficient

1 Introduction

Sustainable agriculture is the key to successful agricultural systems which can meet the huge food demand of future population growth and maintain a perfect balance amid environmental, ecological and economical aspects of the society. Since the end of World War II and with advance of the green revolution, agriculture in both developed and developing countries have changed dramatically. Developed countries increased agricultural production, especially of food and fiber crops through mechanization, use of new technologies, application of inorganic fertilizers and other chemicals for crop protection, supporting government policies and less labor intensive agriculture. While in developing countries, production improved with introduction of high yield varieties of food crops and use of chemicals that help increase the yield of crops. However, the sudden increase in production which reduced the risk in agriculture, left severe negative effects to the ecological and social environments.

The overall increase in ground water contamination, erosion of top soil along with reduction in family farming and degradation in the social and economic conditions of the farming communities in developed countries and reduction in biodiversity and economical condition of poor farmers in developing countries are the most prominent consequences. All of these deleterious effects of conventional farming on society can only be corrected by practicing sustainable agriculture, but the precise meaning of sustainable agriculture can be very confusing to the general agriculturists, agronomists and environmentalists at the time when many just started accepting the view of sustainable agriculture.

At first, there were two different kinds of views expressed by groups of Economists and Ecologists. Based on the first point of views, a profitable agricultural system was considered a sustainable system. However, the definition was not simple to understand since a profitable system may not be sustainable over time or in other way, a sustainable system may not be always profitable. Gradually, this definition of sustainable agriculture was changed considering that the profitability could not be an important indicator of economic sustainability and a new definition evolved which considered sustainable system as a resilient, resistant, renewable and regenerative system. This definition was more readily acceptable by both biological and economical scientists and if the ecological health of soil, plants, animals and people of a farming system was found to remain healthy, the system was considered ecologically regenerative and also sustainable in both the terms (Francis et al. 2006).

The definition of sustainable agriculture was modified with time by scientists of different backgrounds, agriculturists, ecologists, environmentalists and economists to combine these different views to give a compact idea of sustainable agriculture. Though some of the critics commented on high production using modern techniques and high yield varieties, some of international and renowned scientists supported that strongly. Therefore, a new definition of sustainable agriculture based on the points of views of environmentalists was evolved. Presently, sustainability is considered as a holistic and complex multi-dimensional concept that includes social, economic and environmental issues and its assessment through implementation in sustainable agricultural systems (Sadok et al. 2008). An agricultural system was considered a sustainable system only when it was stable for a long time and was found to be economically viable, environmentally safe and socially fair (Lichtfouse et al. 2009). It was accepted by most scientists of all dimensions that sustainable agriculture is the only way to feed an increasing population which is estimated to be around 9.4 billion in 2050 (U.S. Bureau Census Report 2010). In words of Sir Norman Borlaug: agricultural researchers and farmers worldwide will face the challenge during the next 25 years of developing and applying technology that can increase the global cereal yields by 50–75% and to do so they need to follow the ways that are economically and environmentally sustainable (Moore 2008).

The important aspects which farmers face while implementing best management practices for farming land/cropping system for sustainable agriculture are financial and technical assistance. Most small and poor farmers do not pay attention to some of the basic steps of sustainable farming such as soil testing, conservation tillage practices, sustainable nutrient management and integrated use of pesticides just because they are unable to afford these practices. Thus greater percentages of large scale and educated farmers are likely to adopt conservation agricultural practices than small scale farmers (CTIC-TFI survey 2008). There are other challenges which need to be met by sustainable agriculture; such as (i) reduction of arable land for agriculture, (ii) increased price of non-renewable resources, (iii) use of crop lands for biofuel production (Gregory and Ingram 2008) and (iv) global climate change (Dordas 2008). Increasing ground water pollution and other contaminants in soil and water environments also need to be addressed through sustainable agriculture. On the other hand, special attention to selection of management practices is essential to improve the soil environmental status and soil organic carbon level for lands where conventional management practices were followed in the past and also while shifting crop lands to biofuel production lands. Therefore, the concept of sustainable agriculture should cover up all the multidimensional concepts and be accepted as a holistic view which can meet all the present and future challenges and act as the management and utilization of agriculture ecosystem in a way that maintains its biological diversity, productivity, regeneration capacity, viability to function (Lewandowski et al. 1999).

One way to attain all of the multidimensional concepts of sustainable agriculture and fruitful applications of sustainable agriculture is to use crop simulation modeling and decision support system. As use of computers all over the world has increased in the advent of the information age, the use of crop simulation models will not only be advantageous for fruitful application of sustainable agriculture, it also will be beneficial in reducing the unnecessary loss of resources and utilizing space, time and technology efficiently. Though crop simulation models will never be a substitute for field experiments and field data will always be necessary to calibrate and run models. However, models can solve many of the problems related to sustainable agriculture as that integrate knowledge from different disciplines and provide researchers with capabilities for conducting computer experiments to supplement actual experiments (Jones 2000).

A crop simulation model is a collection of computer programs which simulate crop growth and yield based on previously established mathematical relationships and input data of soil, weather and crop management practices. To fulfill the objectives of sustainable agriculture rather agro-ecosystems and to handle the complexity of agricultural systems, interdisciplinary assessment and input from a wide variety of disciplines are required. The development of crop simulation models fulfilled this kind of engagement of vast groups of scientists who understand crop production system along with its soil-plant-environmental impact. Thus crop simulation models become indispensable to be considered for sustainable agriculture and as models can assess the impacts of an agronomic system both spatially and temporally, it is also useful to analyze a system's stability in long run.

Decision Support Systems (DSS) are the computer aided algorithms to help decide the options of crops, management practices, economic analysis and risk analysis for a particular cropping system. The interlinking of crop simulation models and DSS has been proved to be the most useful tool in agrotechnology transfer. Decision Support Systems for Agrotechnology Transfer (DSSAT) is one of such computer tool which is a combination of crop simulation models, database management programs and decision support systems. It was developed by scientists from International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) group for the purpose of transferring the most advantageous agro-technologies to the most needed farmers (Tsuji and Balas 1993). One of advantages of using DSSAT in sustainable agriculture is its 'System Approach' which integrated the knowledge of climate, soil and management of crops together. This 'system approach' provides DSSAT a niche in using it for agrotechnology transfer and to deal with production and management of crops as a whole system (Sarkar 2009). An illustration of how DSSAT can be indispensable in various aspects of sustainable agriculture is shown in Fig. 1.

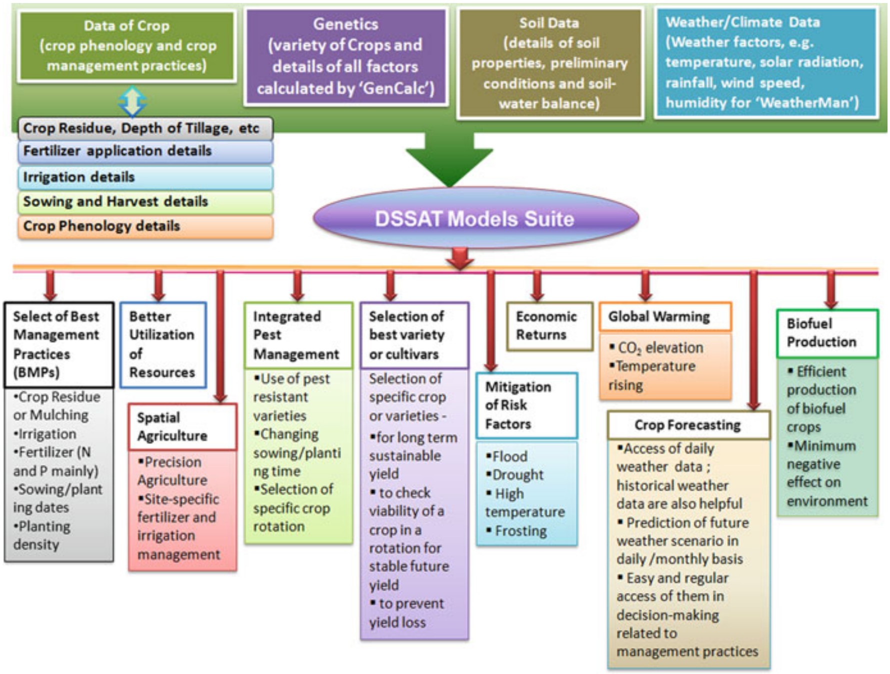

Fig. 1 Application of DSSAT model suite in sustainable agriculture. DSSAT: decision support system for agrotechnology transfer

2 History of Crop Model Development and Role of International Consortium for Agricultural Systems Applications

Various groups of scientists with different goals approached in 1970s and 1980s for developing and using crop simulation models for crop production. The dark age in crop modeling (Acock 1989) was followed by shining periods in 1980s and 1990s due to two projects, IBSNAT (Uehara and Tsuji 1993) and Simulation and Systems Analysis for Rice Production (SARP; Berge 1993). These systems brought the use of crop models back into agrotechnology despite several barriers (Jones 1998) which were mainly (i) the requirement of high quality data for model development and evaluation, (ii) difficulty in obtaining inputs of models, (iii) necessary time and resources for development and validation and (iv) limitations in simulation the actual yield of farmers field. To overcome the barriers, a forum called International Consortium for Agricultural Systems Applications (ICASA) was established (Bouma and Jones 2001). The ICASA started networking among the scientists and developers, to help them seek opportunities to receive funds, arrange meetings to discuss the progress of work, focus on getting good quality data and integrating GIS to DSSAT, locate expertise for modular development and DSSAT's application in precision agriculture, publish new results in the form of papers and arrange meetings and training programmes to teach interested researchers. In addition, ICASA has an important contribution in networking and this helps reduce duplication in research activities related to development of modules and models components.

3 Crop Models and DSSAT

Since 1970s different crop simulation models have been developed and adopted by ICASA. Most of the models were first developed and validated for one or two specific crops and were later modified to simulate a greater number of similar crops. For example, the CERES group of models for cereals and CROPGRO models for beans are two such models. These models evolved to simulate maize, wheat, soybean, peanut and dry beans and modified later for various other crops (Wilkerson et al. 1983; Ritchie and Otter 1985; Jones and Kiniry 1986; Boote et al. 1998; Ritchie et al. 1998; Singh et al. 1998). The features of these models were incorporated in a single structure along with other databases and applications; DSSAT was developed and published as an outcome of IBSNAT project. It continued to grow, develop and be modified under ICASA forum even after the end of IBSNAT project.

DSSAT evolved as a collection of databases, models and different applications which are operated by software to help users select and compare different options and predict the final results. Different input data related to soil, climate, crop experiment and genotypes are stored in databases, which archives and supplies the data to the models for simulating the different kind of experimental situations and assess the risks or simulate yield in a long term basis (Jones et al. 2003a). Though DSSAT was developed with a simple view to spread agrotechnology to the needed farmers, DSSAT was later found helpful in simulating many of other useful aspects of agriculture. It was tested to optimize nitrogen and irrigation strategy (Rinaldi et al. 2007), estimate soil carbon content (Koo et al. 2007), decide cultivar coefficients for better performances of a crop (Anothai et al. 2008a, b), to define viability of crops based on future climate under limited water conditions (Holden et al. 2003) and as a tool for resource management and yield evaluation (Hartkamp et al. 1999; Ma et al. 2006). The linkage of DSSAT with some submodules of other models or programs were also evaluated to study spatial variability and its application in precision farming (DeJonge et al. 2007) and estimate pest damage (Batchelor et al. 1993). The prediction capability of DSSAT models was also evaluated and compared with some other models to check the accuracy in predicting water and N uptake (Ma et al. 2005), explore crop specific plant growth modules for improvement in simulating yield (Saseendran et al. 2007), assess soil water dynamics (Suleiman 2008) and runoff (Sadler et al. 2000).

The goal of developing DSSAT as a computer tool was to help farmers, policy makers and agriculturists of all levels to assess the profits and risks by adopting new and untried cropping systems, management practices, technologies and policies without sacrificing the sustainability of production (Tsuji and Balas 1993). After validation of the models for a specific crop and place, DSSAT was generally found useful for development of a viable and sustainable agricultural industry, economic

Table 1 List of crop simulation models in DSSAT and crops simulated by these models. DSSAT: decision support system for agrotechnology transfer

Crop models	Simulated crops	References
CERES	Maize, Rice, Wheat, sorghum, millet and barley (mainly for cereals)	Ritchie and Otter (1985), Jones and Kiniry (1986), Tsuji et al. (1994), Hoogenboom et al. (1994), and ICASA (1993)
CROPGRO	Soybean, peanut, dry bean (mainly for bean group)	Wilkerson et al. (1983), Boote et al. (1996), Ritchie et al. (1998), Singh et al. (1998), Jagtap and Jones (2002), and ICASA (1993)
SUBSTOR	Potato	ICASA (1993) and IBSNAT (1993)
OILCROP	Sunflower	ICASA (1993)
CROPSIM	Cassava	ICASA (1993)
CANEGRO	Sugarcane	IBSNAT (1993) and Inman-Bamber and Kiker (1997)

analysis and risk assessment of a farming enterprise (Jame and Cutforth 1996). During its development, IBSNAT scientists took it as a challenge to prove DSSAT as valuable tool in predicting the trends of biophysical indicators such as N uptake, N leaching along with soil C levels and crop yields (Bowen et al. 1998). Afterwards when DSSAT was published and its usefulness was realized by the users, scientists/developers tried to improve it so that it could be used as a valuable means to solve current agricultural problems. The portability of DSSAT package and a tool which can analyze most of the commercial crops made DSSAT a useful and popular tool for agriculturists and researchers. Its popularity has been increased in last two decades and it has been used in more than 100 countries to sustain crop productivity at national and global level studies in eastern and central Europe, Asia, Latin America, Pacific and Americas (Ahuja et al. 2002; Jones 2000). After its first release, DSSAT was improved and released in many different versions. The version 2.1 of DSSAT was first released in 1989 with very few crop models such as CERES models for maize and wheat, SOYGRO for Soybean and PNUTGRO for peanut. Later, version 3 and 3.5 were released respectively in 1994 (Tsuji et al. 1994) and 1998 (Hoogenboom et al. 1999). DSSAT version 3.5 included CERES models for maize, wheat, rice, sorghum, millet and barley, SUBSTOR for potato, OILCROP for sunflower, CROPSIM for cassava, CANEGRO (Inman-Bamber and Kiker 1997) for sugarcane and CROPGRO for soybean, peanut, dry bean, chickpea, tomato, Bahia grass and it also had a option for fallow land in a cropping system. After version 3.5, DSSAT was again revised and re-designed by IBSNAT scientists with some modifications of soil model components and it was released as DSSAT-CSM in 2001 (Jones et al. 2001). The recent version 4 is more comprehensive and user-friendly than version 3 and has Microsoft Windows based application programs and provides an immediate concepts of yield gap analysis and an idea about yield limiting conditions under specific soil, weather and management practices to the comparatively new users (Jones et al. 2003b). The version 4 of DSSAT has total 19 crop models for rice, wheat, maize, sorghum, barley, millet, soybean, peanut, dry bean, chickpea, cowpea, velvet bean, faba-bean, pepper, cabbage, tomato, potato and grasses like Bahia and Brachiaria. Even after version 4, IBSNAT scientists worked constantly to improve and develop a more user-friendly, robust and reliable decision support system. This resulted in release of version 4.2 and a much improved recent version 4.5. DSSAT 4.5 has models for three more crops (cotton, sweet corn and green beans) and a new version of genetic coefficient calculator (ICASA 2010). Table 1 shows different groups of models in DSSAT and the crops which can be simulated by them.

4 Description of DSSAT Models Software Package and Its Working Methods

DSSAT is a model suite and collection of programs that incorporates three main elements: (i) various crop simulation models, (ii) data base management system and (iii) other different programs which help in risk assessment, predicting long term yield trend and spatial variability in yield. It produces the answers for 'what if' questions of the researchers and farmers, and simulates the conditions and effects of changes in soil properties, weather, crop phenotype and management practices on growth and yield of a system. In order to get a precise simulated value DSSAT needs sets of essential data, known as Minimum Data Set. Different parameters for minimum data set related to soil, weather and experiment details which are necessary to validate the results and run the crop simulation models, were especially defined by IBSNAT scientists. Once minimum data set is supplied to the input data files, it archives the data in various databases and all databases connect to Data Base Management System. The data base management system produces and stores various chronological data related crop growth and phenology, details of soil environment and weather factors such as rainfall, temperature and solar radiation and degree-days. These data are supplied to the models and other programs/modules when needed (Tsuji and Balas 1993). There are different modules for calculating the growth and yield of crops based on the input data provided to the model and previously established mathematical equations. The different crop modules embedded in DSSAT V. 4 are: land module, management module, soil module which has some other submodules to calculate soil-water balance, soil N content and organic matter content, weather module, soil-plant-atmosphere module which acts for the balance of light and water in soil-plant-atmosphere system along with a newly added module for soil organic carbon, which was taken from the CENTURY model and plant growth modules such as CERES (for six cereals), CROPGRO (for seven different legumes, three vegetables and two grasses) and SUBSTOR (for potato). Other than these modules, some changes which were done in DSSAT V. 4 are addition of the residue layer for top soil and modifications in senescence module for CROPGRO. The major tools incorporated to DSSAT 4 for data management, output and graphical presentation are XBuild, ATCreate, Weatherman, GBuild and SBuild (ICASA DSSAT V. 4 2009). Some additional accessory tools such as ICSim, Stats and EZ Grapher. DSSAT can always be used with other programs and software compiled in DSSAT package based on required output results, including assessment of crop evapotranspiration, effect of increasing CO_2 concentration on crop yield, recommendation of regional crop management, selection of specific management practices using seasonal and sequence analysis and simulation of site-specific crop yield using spatial analysis (Sarkar 2009).

5 Applicability of DSSAT Crop Models for Sustainability of Agricultural Systems

DSSAT crop simulation models have been used for more than two decades in many ways to sustain the agricultural productivity. Some of the research findings to study various important agricultural aspects are discussed under the following headings:

(a) Selection of best suitable management options,
(b) Sustainable crop yield through simulation of crop water use as a major factor
(c) Simulation of root distribution/yield components/biomass of a crop to increase the yield under specific management options
(d) Sustainability of systems of spatial variability concerns and regional prediction
(e) Simulation of pest intervention and genetic parameters for sustainable crop yield
(f) Diagnosis of risk factors and use of crop models as an early warning tool
(g) Simulation of crop based on weather factors for sustainability of a system
(h) Improvements of modules/components in DSSAT models
(i) Climate change and Its effect on future sustainability of an agricultural system
(j) Bio-energy production and use of crop models for sustainable agriculture

The research studies related to applications of various DSSAT models which are discussed in this article to address different sustainability issues are shortlisted in Table 2.

5.1 Selection of Best Suitable Management Options

Once calibration and validation of a model of DSSAT is over and it is confirmed that the model is working satisfactorily, its ability to analyze the various management strategies can be assessed. In IBSNAT Decade, it is mentioned that DSSAT's real power exists on its ability to analyze various management strategies through some comprehensive analyses of crop performances based on data provided for soil types, cultivars, planting dates, planting densities, fertilizer and irrigation strategies, and generated or historical weather data. DSSAT can evaluate the combinations of management practices and help select the less risky and profitable options (Tsuji and Balas 1993). After calibration and validation, sensitivity analysis can be done to assess the performances of some specific parameters related to soils or crops. The most widely accepted model CERES-Maize (Jones and Kiniry 1986) was used in a study to monitor the effect and consequences of drought in Delaware,

Table 2 Resolution of various sustainability issues through use of crop simulation models/programs of DSSAT suite

Sustainability issues and resolve	Approaches to address the issues	Crop models or programs used	References
Negative effects of conventional agricultural practices on soil (erosion, compaction, runoff etc.) and environment by selection of best management practices (BMPs)	Better selection of management practices (MPs) such as row spacing, planting density	Sensitivity Analysis of DSSAT models and CERES-Maize	Quiring (2004a, b)
	Simulation of effect of daily solar radiation and soil factors		Bert et al. (2007)
	Selection MPs such as row spacing, plant population, dates of seedling emergence to mitigate yield losses due to biotic and abiotic stresses	PEANUTGRO; CERES-Maize V.1; CERES-maize; CSM-CERES-Maize	Singh et al. (1994), Piper and Weiss (1990), Pommel et al. (2002), Lizaso et al. (2003), and Soler et al. (2007)
	Assessment of impact of variability in percentages and rates of crop residue incorporation and inorganic N application; impact of some of the soil related factors	Sensitivity Analysis CERES-Maize, CERES-Wheat and CERES-Rice	Jones and Kiniry (1986), Sarkar (2005), Bert et al. (2007), and Rinaldi et al. (2007)
	Selection of optimum and useful application rate of N and P for sustainable crop yield	CERES group mainly CERES-Maize, CERES-Rice and CERES-Wheat; CROPGRO group	Jones and Kiniry (1986), Sarkar and Kar (2006), Daroub et al. (2003), Dzotsi et al. (2010), and Yang et al. (2006)
	Selection of irrigation strategies to get maximum water uptake		Holden et al. (2003) and Timsina et al. (2008)
	Planning of drip irrigation system under semi-arid climate		Dogan et al. (2007)
	Selection of irrigation schedule for economic crop yield		Nangia et al. (2008)

(continued)

Table 2 (continued)

Sustainability issues and resolve	Approaches to address the issues	Crop models or programs used	References
Loss of agricultural resources by achieving economic returns through selection of crop management practices for a cropping system for more than a year	Selection of planting dates for higher yield	Seasonal analysis program of DSSAT models	Lal et al. (1993)
	Cost-benefits of agricultural practices		Rinaldi (2004)
	Selection of hybrids and planting dates based on irrigated or rainfed situations		Soler et al. (2007)
	Selection of best suitable combination of crop residue and N fertilizer rates		Sarkar and Kar (2006)
	Enhancement of productivity in water –limited or non-limited conditions		Bhatia et al. (2008)
Long term sustainability by assessing consequences and effects of a cropping system on soil-crop environment based on future or historical weather scenarios and through selection of a crop rotation with BMPs	To check the stability of a cropping system for 15 weather years under 200 soil scenarios	Sequence analysis of DSSAT	Hartkamp et al. (2004)
	Stability of cropping system in subhumid subtropic weather scenario for 30 generated future weather years		Sarkar and Kar (2008)
	To study the whole-farm systems	Network flow model	Detlefsen and Jensen (2007), Stockle et al. (2003), and Haneveld and Stegeman (2005)
	To find an optimal crop rotation with a given selection of crops for selected land	DSSAT and CropSyst	
Decline in ground water table, loss of irrigation water by prediction of soil-water content and crop water use through parameterization of the soil properties affected by soil water holding capacity, root depth and root density	Simulation of crop water usage for sustainable yield, planning of useful drip irrigation	CROPGRO-Soybean, DSSAT suite	Bhatia et al. (2008) and Dogan et al. (2007)
	Simulation of soil water balance to solve problem of ground water depletion	DSSAT suite	Timsina et al. (2008)
	Sustainable production of good quality potato in future years by studying soil water and rainfall	SUBSTOR-Potato and DSSAT suite	Stastna et al. (2010)

	Assessment of the root proliferation characteristics or root length/density of a crop to judge the sustainability	DSSAT suite, CERES-Wheat, RZWQM along with DSSAT 4.0	Jones et al. (1991), Savin et al. (1994), and Ma et al. (2009)
Impediment due to soil variability in a larger agricultural land under same crop or crop rotation by site-specific agriculture	Site-specific climate data to choose optimum N rate, irrigation strategies	AEGIS/WIN of DSSAT	O'Neal et al. (2000) and Nijbroek et al. (2003)
	Expand of sustainable agriculture to low-lying volcanic land	Spatial analysis of DSSAT	Zehetner et al. (2006)
	Assessment of potential soil organic carbon and N application strategies		Diagana et al. (2007)
Pest Infestation by integrated pest management for sustainability in crop system	Quantification of pest damage and prediction of future sustainable crop yield	CERES-Rice, SOYGRO, PEANUTGRO and 'Structure' and hybrid of CERES-Rice and BLASTSIM	Alocilja and Ritchie (1988), Batchelor et al. (1993), Boote et al. (1993), Teng et al. (1991), Pinnschmidt et al. (1990), and Kroff et al. (1995)
Viability of a variety or type of crops in future for a specific region for long-term sustainability	Adjustment of crops for different environmental factors for sustainable yields by improving the genetic coefficients	DSSAT suite, SUBSTOR-Potato, CERES-Maize	White and Hoogenboom (2003), Travasso et al. (1996); Bannayan et al. (2007), Putto et al. (2008), and Yang et al. (2009)
Sudden yield loss due to draught or flood by crop forecasting and maintaining sustainability in system	Use of predicted weather and crop models as early warning tool to save sudden yield loss	DSSAT suite, CERES-Barley, CERES-Wheat, CERES-Sorghum	Jones et al. (2000), Al-bakri et al. (2010), and MacCarthy et al. (2010)
	Application of future weather scenario generated by weather generators in crop models to check stability of a system	WGEN, SIMMETEO, CLIGEN, GiST	Soltani and Hoogenboom (2003), Zehetner et al. (2006), Sarkar and Kar (2008), Apipattanavis et al. (2010), and Guo et al. (2010)

(continued)

Table 2 (continued)

Sustainability issues and resolve	Approaches to address the issues	Crop models or programs used	References
Impact of climate change by crop prediction using future scenario	Sustainable crop prediction while studying details of climate change factors	DSSAT crop models, weather generators of DSSAT; YIELD	Mahmood (1998), Hammer et al. (2001), and Quiring (2004a, b)
Effects of global warming by well predicted future weather scenario and crop modeling	Sustainable agriculture to reduce the negative effects of global warming	Weather generators and crop models of DSSAT; general circulation models, CLIGEN	Southworth et al. (2000), Zhi-Qing and Da-Wei (2008), Guo et al. (2010), and Liu et al. (2010)
Biofuel production	Economic production of bioenergy without any adverse environmental effects	CERES-Maize, DSSAT	Persson et al. (2009) and Persson et al. (2010)

USA (Quiring 2004a). The sensitivity analysis feature of the model was adopted to assess the impact of variability in row spacing, plant density, planting date, initial soil moisture, air temperature, solar radiation and soil type on growth and yield of maize. The results of the study produced some interesting conclusions: (1) 20% changes in row spacing and planting density only affected 1% in yield prediction, (2) larger changes in air temperature showed quite a change in yield prediction, (3) increase in solar radiation by 25% increased yield by 3% and (4) CERES-Maize was found extremely sensitive to soil type. In another study, sensitivity analysis of CERES-Rice and CERES-Wheat models was used to assess the impact of variability in percentages of crop residue incorporation (percentage of ratio of freshly added organic matter to humified organic matter), rates of crop residue and inorganic N application on summer rainfed rice and irrigated winter wheat under subhumid subtropical climate and red and laterite soil condition of Eastern India (Sarkar 2005). The study produced some acceptable results in changes of yields, harvest indices, biomass and grain N contents of rice and wheat crops which indicated that the models are well sensitive to the experimental management options. Soil factors are also very important while simulating crop yield. Bert et al. (2007) aimed to study the impact of some of the soil related factors through sensitivity analysis of CERES-maize. This group of scientists tried to predict maize yield under uncertainty of soil factors such as N (nitrate and ammonia) content at sowing, soil organic matter content, water storage capacity, soil water content at sowing and soil curve number along with a climate variable: daily solar radiation. They found CERES-Maize was a very sensitive model to various soil factors and the results of the study was helpful to evaluate the robustness of the model's results and help guide the users to interpret the results in decision making.

Various options in DSSAT models give users choices to check the crop performances based on 1 or 2 years of weather data and some specific management practices or decide best management practices (BMPs) for long-term sustainable system based on historical or generated future weather data. The selection of BMPs were done by studying various management options such as, seeding rate (plant population or planting density), application of fertilizers specially rate of nitrogen (N), irrigation application strategies sometimes even at water scarcity conditions, and use of seasonal and sequence analysis program of DSSAT to decide BMPs along with the system's long term stability. Some of the research results are discussed here briefly.

Planting density or plant population has always been critical management options to obtain the optimum and/or expected yield of a crop since it is actively associated with the environmental stresses to a plant, leaf area index and sunlight absorption by leaves which ultimately contributes to the growth and yield of crops. Both the influences of row spacing and plant population on groundnut crop production were tested in a study by scientists of International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). The study was conducted for 3 years in rainy seasons to check the simulated results on phenological development, light interception, canopy growth, dry matter production and pod and seed yields by PEANUTGRO model of DSSAT. The model satisfactorily simulated results on crop growth and yield;

simulated maximum leaf area indices and pod yields under different combinations of treatments of row spacing and plant populations were also found significantly correlated with the observed ones. The model PEANUTGRO was suggested to simulate peanut as influenced by plant population and row spacing satisfactorily (Singh et al. 1994). However, Piper and Weiss (1990) found disparities in predicted (by CERES-Maize V.1) and observed grain yields under high and low plant population while studying the effect of plant population on maize yield losses due to biotic and abiotic stresses. They found over and under predictions of yields at plant population of 6.5 and 5.6 plants m^{-2} respectively. They suggested further researches on redistribution of carbon during vegetative growth after leaf area reduction and prediction of kernel number to address these problems.

Selection of planting date is an important management practice which has direct effect on growth and yield of crops. Planting dates can be adjusted based on the availability of resources for the crop production but sometimes delay in planting dates results in more pest attack or other environmental stresses. CERES-maize model was used to simulate the leaf area index, total biomass, grain number and grain yield of maize under three different dates of seedling emergence (normal, late and delayed) and heterogeneous canopy for 2 years in two same kinds of trial studies in France and Belgium (Pommel et al. 2002). The challenged situations of various dates of emergence and variations in light received by the plants were simulated by the model satisfactorily and the studies suggested possibility of adapting CERES-Maize to study variations in dates of emergence and skip canopy (presence of short sequences of missing plants in rows of maize canopies) of maize crop based on the results from both Belgium and France. Similarly, Lizaso et al. (2003) also suggested more local calibration of CERES-maize to improve the accuracy in predicting photosynthetically active radiation at 'silking' stage and total number of seeds per plant in various treatments of three different row spacing, four plant populations and two rates of N application for three maize hybrids. Later, performance of CSM-CERES-Maize model was checked under both irrigated and rainfed conditions for six planting dates. The model CERES-Maize was found capable of simulating the phenology and yield of maize crop with various planting dates. The results were found helpful to farmers and decision makers in determining the yield of maize crops accurately well before the actual harvesting dates and estimating the grain stocks (Soler et al. 2007).

Selection of optimum and useful application rate of nitrogen (N) has always been critical issue for sustainable cropping system. N, the most important plant nutrient which is applied as inorganic or organic fertilizer, biosolids or as green manure, needs to be estimated in the form of plant uptake as well as leaching loss. Application of slightly lesser than optimum rate definitely results in yield reduction while application of little more can be unsafe and a cause of ground water pollution. DSSAT models have been adapted for various crops to assess the different forms of N and its presence in soils and crops to manage the N and C levels in soils as well as to maintain the efficient applications of N to crops. CERES-Rice and CERES-Wheat models of DSSAT 3.5 effectively assessed rice and wheat plant N uptake and yield of the crops at various application rates of inorganic N in subhumid subtropical climatic condition (Sarkar and Kar 2006). CERES-Maize, the most elaborately used (Jones and Kiniry 1986) model of DSSAT suite was found helpful in simulating N uptake and yield (Asadi and Clemente 2001) as well as estimating N leaching under irrigated cropping system in tropical climate condition (Asadi and Clemente 2003). CERES-Maize was also found useful in temperate climate condition; the model was successful in assessing the N dynamics and yield of maize crops (Huffman et al. 2001). DSSAT models were also found useful in deciding some forage crop rotation strategies with minimum N leaching for different seasons in a year after analyzing different forage systems with 43 years of seasonal weather data on a typical dairy farm (Cabrera et al. 2007). In another study (Rinaldi et al. 2007), CROPGRO of DSSAT model for tomato was found useful in predicting some irrigation and N strategies in Italy. It was suggested from the study that use of comparatively lower amount of water and frequent irrigation with lower rate of N can increase both water and N use efficiency along with reducing crop stress and increasing crop yield.

Phosphorus (P) is the second most major nutrients taken by plant. It always has been a challenge to apply P in soil and keep it in readily available form that can be easily absorbed by plant roots. Though some researchers tried to connect P module with DSSAT and tried to check the performance of various crops, the P module was not fully functional in previous versions of DSSAT. As for example, Daroub et al. (2003) used a P module and linked with CERES and CROPGRO models to simulate maize, wheat, soybean and bean grain yield and P uptake in semiarid conditions of Colombia, Syria and Tanzania. The results of the study showed little response to P fertilization in case of wheat, overestimated P uptake for both soybean and bean but accurately predicted yield and P uptake for maize in acid soil. The authors suggested more future testing to improve the quality of prediction. Recently, Dzotsi et al. (2010) tested the P module in P deficient environment of Ghana. The results were different for different places but were in good agreement with the modeling philosophy of unavailable P in root-free zone that renders P unavailable to plants. The authors suggested the use of the P module (which has been introduced to version 4.5 of DSSAT) in P-deficient soil environment but encouraged the evaluation of the model in wider range of agro-ecological conditions.

To meet the goal of high production for the booming population and also to maintain sustainable production-cost ratio, management of irrigation water is very important. Water is one of the resources used in agriculture which has high demand in various industries and household activities other than agriculture. It is also very essential to solve some serious problems such as water scarcity or ground water pollution while using it efficiently for agriculture. To solve these kinds of water related problems, it is very important to imply some critical decision-making processes related to irrigation strategies which should be based on spatial conditions and sustainable crop production. Many studies were performed on various aspects related to irrigation management to decide the optimum irrigation level along with other crop/soil management practices for sustainable as well as optimum crop production (Holden et al. 2003; Rinaldi et al. 2007). Recently, Bahera and Panda (2009) adopted version 4.0 of DSSAT suite of models and used CERES-Wheat specifically to decide the best level of irrigation among three levels of irrigation along with four fertilizer treatments. They found 40% maximum allowable depletion of available soil water as the most profitable irrigation level for highest water use efficiency of winter wheat crop in subhumid subtropical climate condition. Water management for sustainable agriculture can also be improved by increasing the crop water productivity (CWP). The CWP of a crop always gets reflected by the accuracy in estimation of soil water balance (SWB) in case of crop modeling. In DSSAT, good soil data archival leads to accurate simulation of SWB, soil-plant water deficit and crop yield ultimately. DSSAT evaluates SWB components for a cropped or fallow land as a function of precipitation, irrigation, transpiration, evapotranspiration, run-off and drainage of the soil profile on daily basis (Ritchie 1998). As most of the components of SWB can be estimated easily, the most difficult job of water management is to study the evapotranspiration (ET) and transpiration (T) factors of a crop. DSSAT is very efficient in simulating both evaporation (E) and T, and expresses a little change in water level through changes in yields and harvest index (ratio of economic yield and biomass production, HI). Thus, DSSAT was used to schedule irrigation by studying either SWB components or the yield related factors. For example: DSSAT was used to schedule irrigation and solve the problem of ground water decline by defining SWB components and economic yields (Timsina et al. 2008), plan drip irrigation system under semi-arid climate condition of Turkey based on yields under water-stress situations (Dogan et al. 2007), plan irrigation and understand the reasons of ground water depletion by estimating crop water usage (CWU) and yields under different irrigation levels (Yang et al. 2006) and set irrigation schedule by simulating economic yields, HI and CWU under different water stress level during flowering (Nangia et al. 2008).

Seasonal analysis is a very beneficial program-driver in DSSAT models to check long term and seasonal performance of a crop or cropping systems. It has been used all over the world by various scientists to simulate crop yield under various management options and climatic conditions. Some evidences are discussed in the following section. In a study, the cumulative probability distribution analysis of seasonal analysis program was used to predict the best planting date and the predicted date also resulted to higher yield of dry bean in Puerto Rico. The results of the study showed that DSSAT-BEANGRO V. 1.01 can be a very useful tool in deciding planting dates for several other locations in the Caribbean basin and tropical regions of the world (Lal et al. 1993). Seasonal analysis driver of CERES-Wheat in DSSAT 3.5 version was used to understand cost and benefits of agricultural practices for winter wheat crops in Capitanata Plain in Italy (Rinaldi 2004). The study indicated that the soil available water during sowing time was an important indicator for crop production under rainfed condition. The analysis results with long time weather data was found to help determine the soil moisture levels at various crop stages and time for N application for plant N availability and highest yield.

In a study in subtropical climate condition of Brazil, sustainability of maize crop in autumn-winter season was analyzed using seasonal analysis driver of CSM CERES-Maize model. The results of the study showed the predicted growth and yield of maize with various planting dates under both rainfed and irrigated conditions were accurate match of the observed results for four varieties. The predicted results also showed decrease in yield in case of delayed planting dates in rainfed condition but short season hybrids crops did well both in rainfed and irrigated conditions. Based on results, it was recommended for possible implementation to check the sustainability of maize crop even 45 days prior to harvest. However, the authors suggested more calibration of the model when using new varieties (Soler et al. 2007). In subhumid subtropical climatic region of India, the seasonal analysis was successfully used to select best suitable combination of management options for rice-wheat systems and the model performed well in selecting best suited crop residue and N application rates for long-term rice-wheat system (Sarkar and Kar 2006). Bhatia et al. (2008) also found seasonal analysis driver of CROPGRO-Soybean as a useful tool to enhance the productivity of soybean in central and peninsular India under both water-limited and non-limited conditions.

Another useful module named Sequence Analysis Driver (Thornton et al. 1995) of DSSAT models has been found to be very beneficial in analyzing the consequential effect of a cropping system along with soil and weather scenarios to help understand sequential impact and sustainability of a system in long-term basis. The sequence analysis driver was used by many scientists to judge various effects of management practices and climate concerns and to judge the risks in agriculture. A vast study was undertaken with 12 years of maize-fallow system with 15 consecutive weather years and 200 soil scenarios were run to find out the effect of crop residue retention and its effect on soil and cropping system in Jalisco, Mexico (Hartkamp et al. 2004). The study showed that residue retention in soil increased soil water holding capacity and reduced the runoff during heavy rainfall. Thus, the study demonstrated application of temporal and spatial dimensions of DSSAT model in case of assessing the impact of partial and total retention of crop residues on soil water holding capacity and soil organic C and N retention with hypothesized reduction in runoff from soil. Overall, the study was very beneficial in estimating the impact of crop residue retention in maize-fallow cropping system and its regional effect in terms of social and economic concerns. Another study with both transplanted rice-wheat-fallow and direct seeded rice-wheat-fallow system conducted in subhumid subtropic weather scenario also showed the utility of sequence analysis program (Sarkar and Kar 2008). The study also successfully demonstrated the utility of generated weather data (of 30 years) from SIMMETEO weather generator and its use in selecting specific management options and judging the stability and sustainability under various combination of rate of N application and crop residue incorporation in future. In a different study, a completely different kind of model named network flow model was used by Detlefsen and Jensen (2007) to study the whole-farm systems. Although the approach of developing the model was based on the functionalities of models DSSAT and CropSyst (Stockle et al. 2003), the idea to develop the model was mainly optimized from linear-programming model (Haneveld and Stegeman 2005). The study showed how a network-flow model can also be useful to find an optimal crop rotation with a given selection of crops for selected land which has impacts on crop production.

5.2 Simulation of Crop Water Use for Sustainable Crop Yield

Simulation of crop growth and yield under irrigated, rainfed and water-limited conditions works differently in case of various DSSAT models. These kinds of simulations of crop growth and yield under water-limited conditions are also a challenge. To find out what causes a model to over- or under- predict crop yield in various water availability conditions, few factors related to soil water module should be checked. The factors affecting the soil water module mainly depends on the parameterization of soil properties and soil-crop water balance. Soil-crop water balance which helps predict soil water content and water availability to crops is affected by soil water holding capacity, crop water usage, root depth and root density.

One of the studies with CROPGRO-Soybean was used to simulate soybean yield under both water-limited and non-limiting conditions in 21 locations that represents the major soybean growing areas in India. The model evaluation results showed that the simulated growth and development features of soybean were in good agreement with actual values. Predicted results also showed 28% reductions in yield under water limited conditions than water nonlimiting conditions. However, the actual yields were not matching with the predicted values in some cases. The authors recommended farmers should follow harvesting of excess rainfall water in water-limited areas, alleviation of water logged areas and use of water-resistant varieties in water-logged areas to increase yield (Bhatia et al. 2008). In water-limited condition under semi-arid climate of Turkey, a drip irrigation system was planned and DSSAT model was used to maximize the water use; the model was found successful in planning the sustainable water use (Dogan et al. 2007). Ground water level depletion is a major problem in agriculture in recent age. This problem was solved by analyzing soil water balance factors (Timsina et al. 2008) and estimating crop water productivity (CWP) factor (Yang et al. 2006) of DSSAT. The models were successfully used to plan the irrigation system and increase yield of crops. Crop water stresses at important crop growing stages are very much effective in reducing crop yield; so water stress at those crop growing stages should be avoided. A study with DSSAT model was conducted to avoid water stress during flowering by analyzing CWP factors, to increase harvest index and yield (Nangia et al. 2008).

Potato is a root crop which is highly depended on availability of water for its yield as well as quality. Stastna et al. (2010) adopted SUBSTOR-Potato of DSSAT to assess the yield of early growing potatoes in Czech Republic and found the model capable of simulating the yield accurately for 4 out of 9 weather years; specifically the model underestimated the yield in dry years. The authors suggested evaluation of the model with more historical weather data and modifications in some modules to improve the accuracy of the model while predicting in dry conditions.

5.3 Root Distribution/Yield Components/Biomass to Increase the Yield Under Specific Management Options

Root length and density serves as important parameters which contributes to crop water and nutrient uptake, root-shoot distribution, and ultimately biomass and yield of a crop during simulation by most of the DSSAT submodels (Tsuji and Balas 1993). Root proliferation in soil depends on some chemical/physical properties of soil as well as genetic characteristics of a plant (Jones et al. 1991). Surprisingly, even in most favorable soil-environmental condition sometimes roots do not proliferate and displays inherent root growth habits (Kramer 1983). In terms of modeling, the root growth factor is mainly expressed as root length to weight ratio, which is calculated from growth stage and average depth of the soil layer relative to root system depth based on ideal conditions (Derara et al. 1969; Nielsen and Barber 1978). However, root growth can be much lesser in stress than in ideal condition due to changes in partitioning and requirement of more energy for maintenance of the rooting system (Smucker 1984). Scientists all over the world have tried to simulate the root length and distribution in soil layers to determine the models' capacity to predict soil-water balance and accuracy of the models of DSSAT to predict yield of crops. The enhancement of root length has always been a preferred option for the breeders to increase the water storage of a crop and eventually increase the yields. Savin et al. (1994) studied root length and its density to study the growth of spring wheat. They found that the model CERES-Wheat simulated root length density and soil water content quite well; the model predicted growth and yield of crop accurately but overpredicted the root depth at some stages of the crop. The model also underpredicted root mass which mainly depends on the partitioning of root-shoot criteria in the model. Later, Ma et al. (2009) checked the root growth of six different crops by considering DSSAT4.0 and implementing the features of DSSAT in RZWQM2 in simulating soil hydraulic properties and root growth factors. The results of the study showed right implementation of DSSAT in RZWQM and improvements of the features of both of the models. Other crop growth factors such as yield components, biomass and grain factors were enormously used to evaluate the accuracy of the submodels of DSSAT in CERES (Alves and Nortcliff 2000; Lopez-Cedron et al. 2005; Povilaitis et al. 2008; Ritchie et al. 1998; Shivsharan et al. 2003; Staggenborg and Vanderlip 2005; Timsina and Humphreys 2006; Xiong et al. 2008) and CROPGRO (Bastos et al. 2002; Hartkamp et al. 2002; Meireles et al. 2002; Mercau et al. 2007; Sau et al. 2004). groups respectively for cereals and bean crops. Most of these models have been adapted since last two decades and the models successfully predicted the growth and yield of those crops under different soil and weather conditions.

5.4 Sustainability of Systems of Spatial Variability Concerns and Regional Prediction

Soil environmental conditions are highly variable with space and time, thus sometimes it becomes a challenge to decide on an irrigation strategy or rate of fertilizer/pesticide application for an extended agricultural plot with numerous soil series. In these cases, studies of spatial variability in soil characteristics based on grid system are highly recommended. DSSAT cropping system models have a program called spatial analysis tool, which can be used to deal with this kind of spatial problems and decide management strategies for large agricultural plots for sustainable crop yields. The geostatistical analysis tool within the spatial analysis module is an excellent tool to study the impact of spatial variability. DSSAT also has a facility to study the crop yields of a region through Agricultural and Environmental Geographical Information System (AEGIS) (Beinroth et al. 1998) tool, which interlinks GIS with DSSAT. Some examples of using spatial analysis and AEGIS tools to deal with spatial variability and assess sustainability of a cropping system based on climate and soil data are chronologically discussed below.

The use of the spatial analysis program in DSSAT was found successful in studying green leaf area index of wheat based on spatial variations of soil and climatic data (Barnes et al. 1997), estimating yield components and yield variability of peanut based on soil variability in USA (Engel et al. 1997), characterizing corn yield variability and optimal N prescriptions (Paz et al. 1999), analyzing large-scale estimation of sugarcane growth and yield in Thailand (Promburom et al. 2001) and assessing the effect of site-specific precipitation to estimate the accurate yield and phenological events of crop systems (O'Neal et al. 2002). AEGIS/WIN of DSSAT was found helpful in selecting N rates based on site-specific climate data (O'Neal et al. 2000), selecting N levels through assessment of thematic maps of run-off and N leaching in Brazil (Heinemann et al. 2002), finding combined variability in yield stress (Booltink et al. 2001), determining spatially variable irrigation strategies under weather uncertainty (Nijbroek et al. 2003), expanding irrigation system from other irrigated agricultural land to low lying volcanic landscape and help expand agriculture on such degraded lands in Ecuador (Zehetner et al. 2006), and assessing the potential of soil carbon sequestration, strategies of future N application and residue management in Peanut basin of Senegal (Diagana et al. 2007).

5.5 Simulation of Pest Intervention and Genetic Parameters for Sustainable Crop Yield

There are mainly two kinds of ecophysical models and both can be used to calculate yield loss and crop damage by pests. Both kinds of the models can be used complementary to each other to predict pest damages. In the types of models where dry matter (DM) production is calculated based on photosynthesis and respiration, acquired data related to effect of pest damage on canopy photosynthesis can be easily articulated and yield damage can be calculated. However, for model types where DM is calculated based on radiation use efficiency, it is difficult to calculate the actual pest damage as it requires some field level data on every particular infested situation to quantify actual loss caused by every disease and pests (Kroff et al. 1995). Several approaches were taken to combine the pest damage with the model to predict growth and yield of crops (Alocilja and Ritchie 1988; Batchelor et al. 1993; Boote et al. 1993; Teng et al. 1991). Pinnschmidt et al. (1990) identified 20 different coupling points in CERES of DSSAT to express pest damage through leaf, stem, root, panicle or grain development which led to quantification of pest damage through pest module. However, since the models of DSSAT do not contain any pest module directly, these sometimes fail to accurately predict the crop yield during high pest infestation. For example, Quiring and Legates (2008) found an overestimation of maize yield when disease infestation was quite high.

In the DSSAT model suite, the genetic coefficients of a crop are a reflectance of how crop growth is contributed by various climatic and genetic factors. Thus, these coefficients can be modified to adapt a crop to certain specific weather or soil conditions; such as, climate change factors to have sustainable crop yields based on some specific conditions. According to White and Hoogenboom (2003) these coefficients can be modified to get a reliable description of growth and development of a specific crop cultivar. There are lots of examples where modelers attempted to fine-tune the genetic coefficients (GC) to adapt crop cultivars based on their environmental conditions and management options. Travasso et al. (1996) evaluated the potato model, SUBSTOR-Potato of DSSAT, and included a coefficient for the duration of tuber filling to avoid overestimation of leaf area index (LAI) and tuber yields. Bannayan et al. (2007) suggested an improvement of GCs for quantifying the environmental factors and improvement in predictability of models mainly for rice crop. However, Putto et al. (2008) found GCs useful in evaluating the breeding lines of peanuts for multi-environmental trial in Thailand. Yang et al. (2009) successfully used the CSM-CERES-Maize model to estimate GCs using 53 genotypes for several locations using 10 year data and found that the model could be used in N non-limiting soil conditions.

5.6 Risk Factors and Use of Crop Models as an Early Warning Tool

Suite of crop system models such as DSSAT is useful in assessing future risk factors in a cropping system and anticipating the chances of risks long before the harvest of a crop to gain sustainability in a system. DSSAT has been used in various climatic scenarios to assess the risk factors for crops and find origins of those risk factors as the model suite is very efficient in predicting yields under particular management options. The following illustrations show how climate forecast and use of the model suite have helped researchers find a way to assess the risk factors under different climate scenario and improved sustainability of cropping systems for the long-term.

Jones et al. (2000) evaluated the possible changes in management practices and economic returns of a cropping system under climate variability and determined how decision making based on climate prediction can reduce the unwanted impacts on crop production. The study outcome is mainly related to estimation of potential economic value of climate forecasts from farm scale management of two locations, one in Tifton, Georgia in Southeastern USA and the other in Pampas region of Argentina. The results showed variations in optimal management and expected maize yields under different climate forecasts for both the locations. The authors mentioned the difficulty and challenge of uncertainties associated with climate forecasts and complexities in agricultural systems that must be overcome to fully reap the benefits of using climate forecasting. The authors also suggested the huge potential for adjusting crop management improvement if climate forecasts can be improved. Complexities in agricultural systems could likely be avoided if the technology of using climate forecast in crop production could be afforded in a routinely manner in future agriculture.

In the arid climate condition of Jordan where both land and water resources are limited, a study was conducted with DSSAT to predict the future situation to adapt barley and wheat crop under several climate change scenario. The model-predicted results for both crops were realistic and matched the Department of Statistics data. However, the prediction of yields under long time changes in rainfall and temperature gave different results for barley and wheat crops. With 10–20% decrease or increase in rainfall, yield of wheat varied much more than in barley; increase in air temperature reduced the predicted yield of barley and increased the yield of wheat which showed risks in adapting barley in situation of increased temperature in future (Al-bakri et al. 2010). In another study in the semi-arid region of Ghana where slight changes in climate factors play a great role in terms risk to agricultural production, DSSAT was used to find water and nutrient efficiency based on climate change. This study produced very helpful information for smallholder farming systems especially for those on poor soils. In this study, CERES-Sorghum of DSSAT was adapted to evaluate the N and water use efficiency of sorghum crops. The results showed increased use of mineral N rate improved the water use efficiency as well as reduced the variability in yields. The study was concluded with a suggestion that the use of mineral N along with acceptances of good management practices to retain organic matter in soil will have a greater tendency to sustain the yield and food security in semi-arid region (MacCarthy et al. 2010). DSSAT was also found to give some practical solutions for risks by optimizing the sowing dates (Cabrera et al. 2007), suggesting supplementary irrigation strategies (Meireles et al. 2003) and maximizing resource use efficiency (Simane and Tanner 1998) along with predicting the sustainability in the cropping systems.

5.7 Weather Factors and Crop Simulation for Sustainability of a System

Weather is one of the important factors used in crop simulation models to get simulated precise crop yield; the more accurate the data fed into the model, the more accurate will be the crop yield prediction. Various weather generators can also be used in absence of some of the weather data and eventually to get future prediction; however, hourly and daily weather data always help predict more accurate results. Weather generators in DSSAT models are mainly used to generate daily data or missing or long term historical and future weather data (Hoogenboom 2000). WGEN and SIMMETEO are the two weather generators which are inherent to DSSAT suite of models. Both generators use same kinds of algorithms but the methods of parameter estimation are different. The input data used are daily and monthly weather parameters for WGEN and SIMMETEO, respectively (Soltani and Hoogenboom 2003) but generated data by both are accurate and sufficient to use for selecting best management practices (BMPs) of cropping systems (Soltani and Hoogenboom 2007). A different weather generator named WGENR, which is mainly used to generate solar radiation data, was also calibrated, validated and used by some of the scientists (Hodges et al. 1985; Garcia and Hoogenboom 2005). A study to assess the usability of generated solar radiation data to simulate cotton, maize and peanut crops showed that the generated data did not change the simulated crop yield, above ground biomass and total water use of the following crops from the genuine data under both rainfed and irrigated conditions (Garcia et al. 2008). Some examples of use of weather generators while predicting sustainable crop yield are given below.

WGEN was found to be a capable weather generator, producing 30 year of future weather data based on 30 year of previous weather data of nearby weather stations and the generated weather data was suitable enough to simulate maize yield in rainfed and irrigated maize-fallow cropping system in volcanic land of Ecuador (Zehetner et al. 2006). On the other hand, SIMMETEO was also successfully used as weather generator and the generated data was found suitable to select BMPs for sustainable rice-wheat system in a subhumid subtropical region of India (Sarkar and Kar 2008). A weather generator named SWG (semiparametric weather generator; a hybrid stochastic weather generator), which was developed in comparison to WGEN (a weather generator that comes with DSSAT) was found useful in analyzing seasonal risks factors (Apipattanavis et al. 2010). Baigorria and Jones (2010) recently developed a weather generator, GiST that accounts for spatial correlation of rainfall and the generated output from this was found useable as input in crop and environmental models. The estimated data of daily rainfall by GiST was compared with the observed data and the correlation coefficients were 0.977 and 0.964 for Florida and North Carolina, respectively. While comparing daily rainfall and amount of rainfall data estimated by both WGEN and GiST, it was found that the root mean square error values were lesser in case of GiST than WGEN. Since WGEN does not consider spatial correlations, correlation of estimated and original data of daily rainfall events gave better correlation coefficient value for GiST than WGEN. The study also showed no over dispersion problem on monthly number of rainy days but did show some problems on rainfall amounts.

5.8 Improvements of Modules/Components in DSSAT Models

Various modules and components in DSSAT models that deal with different variables to simulate crop and soil characteristics in predicting growth and yield have been improved by scientists to fine-tune the accuracy of the DSSAT model suite in predicting the effect of climate and soil conditions more precisely. Here are some illustrations of researches related to this topic:

Among CERES models of DSSAT, the CERES-Sorghum model was calibrated and a few components were modified to improve the soil water balance module for dry, high radiation and windy conditions based on the results of experiment conducted in Southern Italy (Castrignano et al. 1997). The modified model simulated the grain yield well but it failed to simulate the daily evapotranspiration correctly. Improvements in simulation of soil evaporation and crop response function to temperature were suggested for further modification to achieve better results. However, Sau et al. (1999) modified the model CROPGRO-Soybean of DSSAT to use it in cool environment of north-west Spain. After making some changes in the parameters such as temperature functions affecting N_2-fixation and photosynthesis and the model was found reliable in predicting biomass at harvest, seed yield and harvest index. CROPGRO-Soybean was also modified by Ruiz-Nogueira et al. (2001) for different parameters such as soil depth, water holding capacity and root elongation to meet the goal to simulate long term crop yield under rainfed and water-stress situations in northwest part of Spain. After calibration, the model was used to choose the best sowing date for maximum yield under water limited conditions and the model was found successful.

An extension of previous model was developed and integrated to DSSAT-CSM for better estimation of soil water content at near surface level (5 cm surface layer) and the estimation gave more accurate results than original DSSAT soil evaporation model (Ritchie et al. 2009).

In order to address various critical crop growth issues, some investigators tried to use two models together which allowed them to make hybridization of models. This provided better sensitivity of a single model to certain crop growth factors, climatic or soil conditions. In one such kind of study, a hybrid of Root Zone Water Quality Model (RZWQM) and DSSAT 4.0 were used to simulate soil moisture, crop yield and above ground biomass successfully for wheat-maize cropping system under water limited condition. The hybrid model was found more sensitive in simulating various irrigation levels during dry growing seasons than wet seasons. Long-term (1961–1999) simulation of same hybrid model showed the available water at root zone was adequate for wheat growth due to moisture accumulation by high rainfall in previous maize growing seasons (Fang et al. 2010).

5.9 *Climate Change and its Effect on Future Sustainability of an Agricultural System*

Agricultural systems and its associated businesses and government systems are diverse and risks or profits of agribusinesses are highly dependent on climate change. Though a number of efforts were made to predict the climate change to improve agriculture and related businesses from last one decade, the prediction of climate change and its variability, and application of skills on the agricultural systems based on climate prediction are sometimes imperfect (Hammer et al. 2001). Climate change specifically the changes in dry and wet spells for uncertain period or temperature change leading to anomalies in soil moisture content results in drastic changes in crop growth and yield patterns. To get an idea of future sustainability, it is very important to have the reasons of past abnormalities in weather which led to failure in crop yield, but it is not always easy to get weather data from previous years. Studies by Quiring (2004a, b) resulted in some interesting facts. His aim was to determine why the drought in fall and winter of 2001 extended until the next spring and summer of 2002 and its effect on agriculture in Southern and Mid-Atlantic region of the USA. The drought was followed by a wet season for the remainder of 2002 and 2003 which resulted in severe crop failure in that region; however, analysis of 800 years of historical weather data cleared the ambiguity and confirmed that it was never an anomaly in weather, and the drought and consequent wet weather was normal climate variability for that region.

Climate change such as the temperature rise always has been a major concern in agriculture. Mahmood (1998) tried to compare one of the DSSAT models CERES-Rice with YIELD to predict yield of 'Boro' (winter) rice in two places of Bangladesh with completely contrasting weather scenario. He found crop simulation models like CERES-Rice can be a good approach to deal with climate change and estimate rice yield in normal or abnormal weather scenarios in Bangladesh, but the complex dataset required by the model was an impediment. Another study considering ten representative areas in the world's most productive agricultural zone of Midwestern Great lake region showed how seasonal rise in temperature led to the variability in maize yield. The increasing temperature gave increase in simulated yield in northern states but decreased yield in southern states. The performance of present hybrid varieties was best in case of long-season followed by mid-season and short-season varieties. The overall study results showed that the tolerance of the present hybrid varieties to high temperature should be increased, or new varieties should be developed to cope up with the climate change and rising temperature due to global warming (Southworth et al. 2000).

Temperature changes along with precipitation and CO_2 concentration in air can also be an interesting combination of climate change factors affecting crop yield. Zhi-Qing and Da-Wei (2008) studied the effect of that kind of combination of climate change factors and its consequences on future food production in three different zones of China. Outputs of three general circulation models (GCMs) were used as baseline weather data and these data along with weather generator WGEN were implemented in the study to produce 0–20% variability regarding changes in precipitation and temperature. These variable weather factors through four crop models: SOYGRO, CERES-Maize, CERES-Wheat and CERES-Rice in DSSAT were used to check the variability in predicted yields of soybean, maize, spring wheat and irrigated rice. The yield variability coefficient (YVC) of rice was found lowest due to sufficient supply of irrigation water in all the three zones. YVCs of four crops were found to vary most in Western Arid Zone (31%) followed by Northern Cold Zone (22%) and Eastern wet Zone (20%). Doubling of CO_2 induced heat injury to the crops, however climate variability also followed by some other weather disasters such as heavy rain, seasonal drought and chilling effect. Overall effects of climate variability were found to be favorable for soybean and rice, but unfavorable for maize and spring wheat. In another study in China, the effects of climate change specifically 2°C and 5°C rise in temperature, precipitation increase and decrease by 15% and 30%, and CO_2 concentration increase to 500 and 700 ppmv on winter wheat and summer maize system were investigated. The weather data was derived from GCM and historical trends (1996–2004) and was used in bio-geo-physically process-based dynamic crop model. The study revealed that the negative effect of increased temperature can be reduced by CO_2 fertilization and mitigated by increased precipitation. The effect of CO_2 fertilization was found better in case of drier than wet conditions (Liu et al. 2010). A different investigation showed an inconsistent impact of increased temperature and CO_2 concentration on wheat-maize system in effect of future climate change factors when studied in North China Plain. In this study, the climate generator CLIGEN along with crop models CERES-Wheat and CERES–Maize predicted that wheat yield would increase but maize would decrease under same kind of climatic conditions. High temperature proved to be intensifying the evapotranspiration other than affecting the crop yield and water use efficiency. Though the simulated results showed a positive impact of CO_2 fertilization on crop yield, results of the study led to uncertainty regarding it and that further research was anticipated (Guo et al. 2010).

5.10 Bio-energy Production and Use of Crop Models for Sustainable Agriculture

Production of biofuel in the form of ethanol from various crops has become a crucial scientific area of research. However, a food crop (e.g. corn) which is grown for some other purposes rather food and exploits the land areas which can be used to grow food crop in the present situation of shrinking agricultural land area also turns out to be questionable. On the other hand, the production of biofuel from food crop also needs some energy for its growth and development which also sets a question of sustainability in the whole agro-ecosystem. Thus, sustainable growth and yield of the crops that can produce ethanol along with profitable production of biofuel become a serious issue at present. Climate and soil conditions are two important factors responsible for variable biofuel production and therefore use of crop models such as DSSAT can be helpful way to analyze the maximum potentiality of the biofuel crops to produce ethanol in a profitable way. Persson et al. (2010) adopted crop simulation model CERES-Maize and used 68 years of weather data to find the net energy yield and potential of biofuel production through prediction of growth and yield of maize crop under different soil and climate conditions. The net energy yield was calculated based on simulated yield and energy requirement for the production. They found ethanol production potential was higher when larger production acreage was taken than smaller one and less weather variability which reduce the potential of ethanol production from maize in south-eastern USA. Other than variations in soil and climate conditions, the factor which affects the productivity of ethanol or yield of the biofuel crops is crop management practices. Research also showed that irrigated maize had a double net energy value than rainfed maize crop when the impact of crop management practices such as irrigation, N fertilizer rates, planting dates and effect of E1Nino Southern Oscillation were studied (Persson et al. 2009).

6 Conclusion

Sustainable agriculture along with application of sophisticated computer appliance and exact prediction of crop growth/yield pattern based on forecasted weather is the utmost requirement at present. As we are on the edge of meeting the need of 9.4 billion people by 2050 and turning towards a green world, sustainable agriculture is a must. The application of crop simulation models in agricultural research has long been accepted and since then the development of a powerful and accurate crop model which will be able to predict crop growth and yield precisely has been started. DSSAT has been accepted as one of such kind of models along with decision support systems and some more versatile features in it.

The research studies described in this article shows that the DSSAT can be used as valuable tool by researchers and help farmers get the beneficial message in certain abrupt situations to extenuate the consequences of crop failure and increase crop productions in some difficult crop growth situations and in case of minimal resource availability. Researchers and scientists around the world have evaluated this model suite extensively so that it can be applied in agriculture for sufficient resource management, to choose suitable management practices, and suggest farmers the urgent actions that must be taken in time to abate the sudden changes in weather to avoid crop failure. One of the most useful applications of DSSAT is its powerful weather generator and weather application module which allows the scientists/researchers to simulate a crop or cropping system for the historical and future climate scenarios and help understand the stability and viability of it in long run under certain soil-climate condition. Thus, DSSAT becomes an unavoidable software application to simulate agricultural systems in effect of global warming and climate change concerns. The model suite also has a feature that calculates genetic factors of a specific variety of a crop and helps simulate the growth and yield of a crop more precisely after the right calibration. The model suite was also found applicable in calculating the bio-energy production based on crop produce under a certain soil-weather condition for future. Overall, the results from the various researches described in this article demonstrate that DSSAT can be a very practical tool to increase crop production, maintain sustainability of cropping system by retaining the stability of a system, keep the production most economical and help farmers apply the environmentally-sound management practices.

The crop models of DSSAT suite were used in several situations to predict crop yield and compare that with observed results. After comparison of predicted and observed results, if any unmatched results were found then those were seriously analyzed by the scientists and developers of DSSAT to extend the possibility of DSSAT for further improving its predictability and to meet the present and future need. For decades DSSAT has been improved and possible changes in different modules were also been made to reinvent the model suite. Despite the very few past researches on comparison of predicted results through different other models and DSSAT which apparently help understand the applicability of a model while selecting a model under certain criterion, DSSAT has been accepted enormously in different situations. Though these kinds of investigations which deal with comparisons of predictability of various models at same situation are being done presently, the need for more of them are suggested.

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Plant Growth Retardants and Mineral Fertilisers for Cotton

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Abstract The increase of Egypt population needs novel approaches to increase food supply to meet the needs of the Egyptian people. Cotton is the principal crop of Egyptian agriculture. Cotton is grown mainly for its fiber, but cottonseed products are also of economic importance. Cottonseed is the main source of edible oil and meal for livestock in Egypt. Economic conditions in modern agriculture demand high crop yields in order to be profitable and consequently meet the high demand for food that comes with population growth. Oil crop production can be improved by development of new high yielding varieties, and the application of appropriate agronomic practices. Most previous researches has focused on studying the effect of nitrogen, phosphorus, potassium, foliar application of zinc and calcium, the use of plant growth retardants (PGR) on cotton yield and fiber quality. However, there is limited information about the most suitable management practice for application of N, P, K, Zn, Ca and PGR in order to optimize the quantity and quality of oil and protein of cottonseed. To improve the quantity and quality of a crop's nutritional value in terms of fatty acids and protein, it is necessary to identify the constraints which may affect it and to devise methods of overcoming them through the use of inputs or changes in management practices. Field experiments were conducted to investigate the effect of nitrogen, phosphorus, potassium, foliar application of zinc and calcium, the use of plant growth retardants (Pix, Cycocel or Alar), on cottonseed, protein, oil yields, and oil properties of Egyptian cotton.

Here we review the effect of N, P, K, foliar application of Zn and Ca, the use of PGR, on cottonseed, protein, oil yields, and oil properties of Egyptian cotton. The major points found are: (1) application of N at a rate of 161 of kg ha^{-1}, spraying of cotton plants with plant PGR, and application of Zn has a positive impact on

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cottonseed yield, seed protein content, oil and protein yields, oil refractive index, unsaponifiable matter, and unsaturated fatty acids. On the other hand, there was a decrease in acid value and saponification value. The increase in seed yield and subsequent increase in oil and meal due to the application of PGR, Zn, and increased N fertilization were sufficient to cover the cost of using those chemicals and further attain an economical profit. (2) Addition of P at 74 kg ha^{-1}, and foliar application of Zn and Ca beneficially affected cottonseed yield, seed index, seed oil content, oil and protein yields ha^{-1}, seed oil unsaponifiable matter, and total unsaturated fatty acids. (3) Addition of K at 47.4 kg ha^{-1}, spraying cotton plants with Zn twice at 57.6 g ha^{-1}, and also with P twice along with the soil fertilization used P at sowing time have been proven beneficial to the quality and yield of cotton plants. These combinations are the most effective treatments, affecting not only the quantity but also the quality of oil, and to obtain higher oil and protein yields and a better fatty acid profile in the oil of cotton. (4) Application of N at the rate of 143 kg ha^{-1} and two applications of both K and mepiquat chloride have the most beneficial effects among the treatments examined in comparison with the usual cultural practices adopted by Egyptian cotton procedures.

Keywords Calcium • Nitrogen • Phosphorus • Plant growth retardants • Potassium • Zinc cotton

Abbreviations

Ca	calcium
K	potassium
N	nitrogen
P	phosphorus
PGRs	plant growth retardants
Zn	zinc cotton

1 Introduction

Plant nutrition, using a balanced fertilization program with both macro and micronutrients is becoming necessary in the production of high yield with high quality products especially with the large variation in soil fertility and the crop's need for macro and micro-nutrients. The breeding and production of cotton have traditionally been guided by consideration of fiber quality and yield. However, cottonseed characteristics except for viability and vigor have generally been ignored. Cottonseed oil is an important source of fat. Also, cottonseed meal is classed as a protein supplement in the feed trade and is almost as important as soybean meal (Sawan et al. 2007a).

1.1 Nitrogen

In cotton culture, nitrogen (N), have the most necessity role in production inputs, which controls growth and prevents abscission of squares and bolls, essential for photosynthetic activity (Reddy et al. 1996), and stimulates the mobilization and accumulation of metabolites in newly developed bolls, thus increasing their number and weight. Additionally, with a dynamic crop like cotton, excess N serves to delay maturity, promote vegetative tendencies, and usually results in lower yields (Rinehardt et al. 2004). Therefore, errors made in N management that can impact the crop can be through either deficiencies or excesses. Ansari and Mahey (2003) evaluate the effects of N level (0, 40, 80, 120 and 160 kg ha^{-1}) on the yield and found that seed yield increased with increasing N level up to 80 kg ha^{-1}. Nitrogen is an essential nutrient for the synthesis of fat, which requires both N and carbon skeletons during the course of seed development (Patil et al. 1996). On the other hand, nitrogen plays the most important role in building the protein structure (Frink et al. 1999). Another beneficial change in fatty acid composition due to N nutrition would be an increase in the linoleic and oleic acid contents, and an increase in the percentage of unsaturated fatty acids and a decrease in saturated fatty acids in the seed oil (Kheir et al. 1991).

1.2 Phosphorus

Phosphorus (P) is the second most limiting nutrient in cotton production after nitrogen. Its deficiency tends to limit the growth of cotton plants, especially when plants are deprived of P at early stages than later stages of growth. Further, P is an essential nutrient and an integral component of several important compounds in plant cells, including the sugar-phosphates involved in respiration, photosynthesis and the phospholipids of plant membranes, the nucleotides used in plant energy metabolism and in molecules of DNA and RNA (Taiz and Zeiger 1991). Phosphorus deficiency reduces the rate of leaf expansion and photosynthetic rate per unit leaf area (Rodriguez et al. 1998). Sasthri et al. (2001) found that application of 2% diammonium phosphate to cotton plants increased seed yield. Improvements in cotton yield resulting from P application were reported by Stewart et al. (2005), Singh et al. (2006) and Ibrahim et al. (2009).

1.3 Potassium

The physiological role of potassium (K) during fruit formation and maturation periods is mainly expressed in carbohydrate metabolism and translocation of metabolites from leaves and other vegetative organs to developing bolls. Potassium increases the photosynthetic rates of crop leaves, CO_2 assimilation and facilitating carbon movement (Sangakkara et al. 2000). The high concentration of K^+ is thought to be essential for normal protein synthesis. Potassium deficiency during the reproductive period can limit the accumulation of crop biomass (Colomb et al. 1995), markedly changes the structure of fruit-bearing organs, and decreases yield and quality. Improvements in cotton yield and quality resulting from K input have been reported by the following authors: Gormus (2002) applying K rates of 66.4, 132.8 and 199.2 kg ha^{-1} K; Aneela et al. (2003) increase K levels, the effect being highest at 166 kg K ha^{-1}; Pervez et al. (2004) using K rates of 62.5, 125 and 250 kg ha^{-1}; Pettigrew et al. (2005) with a K fertilizer rate of 112 kg ha^{-1}; and Sharma and Sundar (2007) with a foliar application of K at 4.15 kg ha^{-1}.

1.4 Zinc

Zinc (Zn) is critical for several key enzymes in the plant. Zinc binds tightly to Zn-containing essential metabolites in vegetative tissues, e.g., Zn-activated enzymes such as carbonic anhydrase (Welch 1995). Further, Zn is required in the biosynthesis of tryptophan, a precursor of the auxin – indole-3-acetic acid (IAA), which is the major hormone inhibiting abscission of squares and bolls. Zinc deficiency symptoms include: small leaves, shortened internodes, a stunted appearance, reduced boll set, and small bolls size (Oosterhuis et al. 1991). Zinc deficiency occurs in cotton on high-pH soils, and where high rates of P are applied (Oosterhuis et al. 1991). Rathinavel et al. (2000) found that application of $ZnSO_4$, to the soil at 50 kg ha^{-1} increased 100-seed weight. Li et al. (2004) found that when cotton was sprayed with 0.2% zinc sulfate at the seedling stage, the boll number $plant^{-1}$ increased by 17.3% and the cotton yield increased by 18.5% compared with the untreated control.

1.5 Calcium

Calcium (Ca) is essential in cell nucleus matrix. It activates enzymes, particularly those that are membrane-bound (Rensing and Cornelius 1980). It is thought that Ca is important in the formation of cell membranes and lipid structures. Ma and Sun (1997), suggested that Ca might be involved in light signal transduction chain for phototropism. Calcium deficiency as one of the causes of abscission and suggested this plus the role of Ca in the middle lamella (Ca pectates) as the possible reason. A likely reason was that Ca deficiency affected translocation of carbohydrates, causing accumulation in the leaves and a decline in stems and roots. It seems probable that young bolls abscised because of starvation. Thus, Ca may inhibit abscission because it is a component of the middle lamella, because it promotes translocation of sugars and auxin, and because it helps prevent senescence (Guinn 1984).

Ochiai (1977) notes that Ca^{2+} can bridge phosphate and carboxylate groups of phospholipids and proteins; that it increases hydrophobicity of membranes; that it generally increases membrane stability and reduces water permeability.

1.6 Plant Growth Regulators Retardants

An objective for using plant growth retardants (PGRs) (mepiquat chloride, "Pix", chloromequat chloride, "Cycocel", and daminozide, "Alar") in cotton is to balance vegetative and reproductive growth as well as to improve yield and its quality (Zhao and Oosterhuis 2000). Visual growth-regulating activity of Pix, Cycocel or Alar is similar, being expressed as reduced plant height and width, shortened stem and branch internodes and leaf petioles, influence leaf chlorophyll concentration, structure and CO_2 assimilation, and thicker leaves. This indicates that bolls on treated cotton plants have a larger photo synthetically sink for carbohydrates and other metabolites than those on untreated plants. More specific response from using PGRs include alteration of carbon partitioning, greater root/shoot ratios, enhanced photosynthesis, altered nutrient uptake, and altered crop canopy. In this connection, Wang et al. (1995) stated that application of the plant growth retardant Pix to the cotton plants at squaring decreased the partitioning of assimilates to the main stem, the branches and their growing points, and increased partitioning to the reproductive organs and roots. Also, they indicated that, from bloom to boll-setting, Pix application was very effective in restricting the vegetative growth of the cotton canopy and in promoting the partitioning of assimilates into reproductive organs. Kumar et al. (2004) evaluated the effects of Chamatkar, 5% Pix, 500, 750 and 1,000 ppm, on cotton. These treatments increased the values for photosynthetic rate, transpiration rate, total chlorophyll content, and nitrate reductase activity, number of bolls plant^{-1}, boll weight and yield.

Most previous has focused on studying the effect of nitrogen, phosphorus, potassium, foliar application of zinc and calcium, the use of PGRs on cotton yield and fiber quality (Palomo Gil and Chávez González 1997; Sarwar Cheema et al. 2009). However, there is limited information about the most suitable management practice for application of N, P, K, Zn, Ca and PGRs in order to optimize the quantity and quality of oil and protein of cottonseed (Patil et al. 1997). Due to the economic importance of cottonseed (presently the main source of edible oil and meal for livestock) in Egypt, this study was designed to identify the best combination of these production treatments in order to improve cottonseed, protein and oil yields and oil properties of Egyptian cotton (*G. barbadense* L.) (Sawan et al. 2001a, b; 2007a, b).

2 Methods and Measurements

Field experiments were conducted at the Agricultural Research Center, Ministry of Agriculture in Giza (30°N, 31°: 28′E and 19 m altitude), Egypt using the cotton cultivars "Giza 75" and "Giza 86" (*Gossypium barbadense* L.) in the two seasons

Table 1 Physical and chemical properties of the soil used in I and II seasons

Season	I	II
Soil texture		
Clay (%)	43.0	46.5
Silt (%)	28.4	26.4
Fine sand (%)	19.3	20.7
Coarse sand (%)	4.3	1.7
Soil texture	Clay	Loam
Chemical analysis		
Organic matter (%)	1.8	1.9
Calcium carbonate (%)	3.0	2.7
Total soluble salts (%)	0.13	0.13
pH (1:2.5)	8.1	8.1
Total nitrogen (%)[a]	0.12	0.12
Available nitrogen (mg kg^{-1} soil)[b] (1% K_2SO_4, extract)	50.0	57.5
Available phosphorus (mg kg^{-1} soil) ($NaHCO_3$ 0.5 N, extract)	15.7	14.2
Available potassium (mg kg^{-1} soil) (NH_4OAC 1 N, extract)	370.0	385.0
Total Sulphur (mg kg^{-1} soil)	21.3	21.2
Calcium (meq/100 g) (with Virsen, extract)	0.2	0.2

Sawan et al. (2009)
The Physical analysis (soil fraction) added to the organic matter, calcium carbonate and total soluble salts to a sum of about 100% (Sawan et al. 2009)
[a]Total nitrogen, i.e. organic N + inorganic N
[b]Available nitrogen, i.e. NH_4^+ & NO_3^-

Table 2 Range and mean values of the weather variables recorded during the growing seasons (April–October)

Weather variables	Season I		Season II		Overall date (Two seasons)	
	Range	Mean	Range	Mean	Range	Mean
Max Temp (°C)	20.8–44.0	32.6	24.6–43.4	32.7	20.8–44.0	32.6
Min Temp (°C)	10.4–24.5	19.4	12.0–24.3	19.3	10.4–24.5	19.3
Max-Min Temp (°C)	4.7–23.6	13.2	8.5–26.8	13.4	4.7–26.8	13.3
Sunshine (h day^{-1})	0.3–12.9	11.1	1.9–13.1	11.2	0.3–13.1	11.1
Max Hum (%)	48–96	79.5	46–94	74.7	46–96	77.2
Min Hum (%)	6–48	30.1	8–50	33.0	6–50	31.5
Wind speed (m s^{-1})	0.9–11.1	5.2	1.3–11.1	5.0	0.9–11.1	5.1

Sawan et al. (2009)

I and II. Seeds were planted on March, and seed cotton was harvest on October (Sawan et al. 2009). The soil type was a clay loam. Average textural and chemical properties of soil are reported in Table 1 (Sawan et al. 2009). Range and mean values of the climatic factors recorded during the growing seasons are presented in Table 2 (Sawan et al. 2009). No rainfall occurred during the two growing seasons.

The experiments were arranged as a randomized complete block design. The plot size was 1.95 × 4 m, including three ridges (beds). Hills were spaced 25 cm apart on one side of the ridge, and seedlings were thinned to two plants hill^{-1} 6 weeks after planting, providing plant density of 123,000 plants ha^{-1}. Total irrigation amount during the growing season (surface irrigation) was about 6,000 m^3 ha^{-1}. The first irrigation was applied 3 weeks after sowing, and the second one was 3 weeks later. Thereafter, the plots were irrigated every 2 weeks until the end of the season, thus providing a total of nine irrigations (Sawan et al. 2009). At harvest the seed cotton yield plot^{-1} (handpicking) was determined. Following ginning, the cotton seed yield in kg ha^{-1}as well as 100-seed weight in g was determined. A composite seed sample was collected from each treatment for chemical analyses. The following chemical analyses were conducted: (i) seed crude protein content according to AOAC standards (1985); (ii) seed oil content in which oil was extracted three times with chloroform/methanol (2:1, vol/vol) mixture according to the method outlined by Kates (1972); (iii) oil quality traits, i.e., refractive index, acid value, saponification value, unsaponifiable matter, and iodine value were determined according to methods described by AOCS (1985); and (iv) identification and determination of oil fatty acids by gas-liquid chromatography. The lipid materials were saponified, unsaponifiable matter was removed, and the fatty acids were separated after acidification of the saponifiable materials. The free fatty acids were methylated with diazomethane (Vogel 1975). The fatty acid methyl esters were analyzed by a Hewlett Packard model 5,890 gas chromatograph (Palo Alto, CA) equipped with dual flame-ionization detectors. The separation procedures were similar to those reported by Ashoub et al. (1989) (Sawan et al. 2007a). Data obtained for the cottonseed yield and seed weight were statistically analyzed as a factorial experiment in a RCBD following the procedure outlined by Snedecor and Cochran (1980) and the least significant difference (LSD) was used to determine the significance of differences between treatment means. As for the chemical properties considered in the study, the *t*-test computed in accordance with standard deviation was utilized to verify the significance between treatment means (Sawan et al. 2007a).

3 Experiments

3.1 Effect of N, Zn and PGR's on Cottonseed, Protein, Oil Yields, and Oil Properties

3.1.1 Materials

A field experiment was conducted, using the cotton cultivar Giza 75. Each experiment included 16 treatments the following combinations: (i) Two N-rtes (107 and 161 of N ha^{-1}) were applied as ammonium nitrate (33.5% N) in two equal amounts 6 and 8 weeks after sowing; each application (in the form of pinches beside each hill)

Table 3 Effect of N rate and foliar application of plant growth retardants and Zn on cottonseed yield, seed index, seed oil, seed protein, oil and protein yields

Treatments		Cottonseed yield (kg ha^{-1})[a]	Seed index (g)[a]	Seed oil (%)[b]	Oil yield (kg ha^{-1})[b]	Seed protein (%)[b]	Protein yield (kg ha^{-1})[b]
N-rate (kg ha^{-1})							
Control	107	1,907.7	10.29	19.92	380.1	21.96	418.8
	161	2,078.7	10.44	19.87	413.0	22.51	468.4
L.S.D. 0.05[c]		67.8	0.06	–	–	–	–
S.E.[d]		–	–	0.02	16.4	0.27	24.8
Plant growth retardants (ppm)							
Control	0	1,852.2	10.24	19.86	368.0	22.08	409.1
Pix	300	2,076.0	10.44	19.88	413.2	22.35	465.0
Cycocel	300	2,048.0	10.41	19.94	407.8	22.24	455.8
Alar	300	1,996.5	10.36	19.90	397.3	22.26	444.5
L.S.D. 0.05[c]		96.0	0.08	–	–	–	–
S.E.[d]		–	–	0.01	10.1	0.05	12.2
Zn rate (ppm)							
Control	0	1,912.4	10.30	19.82	379.2	22.10	422.8
	50	2,073.9	10.42	19.97	413.9	22.37	464.4
L.S.D. 0.05[c]		67.8	0.06	–	–	–	–
S.E.[d]		–	–	0.07	17.3	0.13	20.8

Sawan et al. (2001a)

[a] Combined statistical analysis from the two seasons

[b] Mean data from a four replicate composite for the two seasons

[d] L.S.D. = Least significant differences

[c] S.E. = standard error

was followed immediately by irrigation. (ii) Three PGR's, 1, 1-dimethylpiperidinium chloride (mepiquat chloride, or Pix), 2-chloroethyltrimethylammonium chloride (chloromequat chloride, or Cycocel), and succinic acid 2, 2-dimethylhydrazide (daminozide, or Alar) were used. Each was foliar-sprayed once at 288 g active ingredient ha^{-1}, 75 days after planting (during square initiation and boll setting stage) at solution volume of 960 lha^{-1}. Water was used as the control treatment. (iii) Two chelated Zn rates (0.0 and 48 g of Zn ha^{-1}) were foliar-sprayed twice, 80 and 95 days after planting at solution volume of 960 lha^{-1} (Sawan et al. 2001a).

3.1.2 Analyzed Data

Seed Yield

Seed yield ha^{-1}, was significantly ($P \leq 0.05$) increased (8.96%) by raising N rate (Table 3) (Sawan et al. 2001a). Abdel-Malak et al. (1997) stated that cotton yield was higher when N was applied at a rate of 190 kg ha^{-1} than at the rate of 143 kg ha^{-1}. Palomo Gil and Chávez González (1997) applied N at a rate ranging from 40 to

200 kg ha^{-1} to cotton plants and found highest yield was associated with high rates of applied N. Similar results were obtained by Sarwar Cheema et al. (2009) and Saleem et al. (2010a) when N was applied at 120 kg ha^{-1} . Nitrogen is an important nutrient which control growth and prevents abscission of squares and bolls, essential for photosynthetic activity (Reddy et al. 1996) and stimulate the mobilization and accumulation of metabolites in newly developed bolls and thus their number and weight are increased. All tested PGR (Pix, Cycocel and Alar) significantly increased seed yield ha^{-1} (7.79–12.08%), compared with the untreated control. The most effective was Pix (12.08%), followed by Cycocel (10.57%) (Sawan et al. 2001a). These results may be attributed to the promoting effect of these substances on numerous physiological processes, leading to improvement of all yield components. Pix applications increases CO_2 uptake and fixation in cotton plant leaves. In cotton stems, the xylem was expanded with Pix treatment, perhaps increasing the transport ability and accounting for heavier bolls. Alar and Pix also have been associated with increased photosynthesis (Gardner 1988; Nepomuceno et al. 1997) through increased total chlorophyll concentration of plant leaves, increased photosynthesis greatly increased flowering, boll retention and yield. Abdel-Al (1998) indicated that cotton yield significantly increased with Pix treatment at a rate 11.90 ml (formulation) ha^{-1}at the beginning of flowering. Pípolo et al. (1993) found that spraying cotton plants at an age of 70 days after emergence with Cycocel at rates ranging from 25 to 100 g ha^{-1} resulted in yield increases. Sawan et al. (1993) stated that application of Cycocel and Alar, at rates ranging from 250 to 700 ppm (105 days after planting) increased cotton seed yield ha^{-1}. Similar results were obtained by Sarwar Cheema et al. (2009). Application of Zn significantly increased seed yield ha^{-1} (8.44%), as compared with untreated plants (Sawan et al. 2001a). Zeng (1996) stated application of Zn to cotton plants on calcareous soil increased yield by 7.8–25.7%. Similar results were obtained by Ibrahim et al. (2009). Zinc is required in the synthesis of tryptophan, which is a precursor of IAA synthesis which is the hormone that inhibits abscission of squares and bolls. Also, this nutrient has favorable effect on the photosynthetic activity of leaves and plant metabolism (Li et al. 2004), which might account for higher accumulation of metabolites in reproductive organs (bolls).

Seed Index

Seed index significantly increased with increasing N rate (Table 3) (Sawan et al. 2001a). This may be partially due to enhanced photosynthetic activity (Reddy et al. 1996). Similar findings were obtained by Palomo Gil and Chávez González (1997). Application of all PGR significantly increased seed index as compared to untreated control; Pix gave the highest seed index, followed by Cycocel (Sawan et al. 2001a). These agree with previous works of Sawan et al. (1993), by applying Cycocel and Alar, Carvalho et al. (1994) by applying Pix and Cycocel and Abdel-Al (1998), by applying Pix. Zinc significantly increased seed index compared with the untreated control (Sawan et al. 2001a). In this connection Ibrahim et al. (2009) noted that seed weight increased due to the application of Zn.

Seed Oil Content and Yield

Seed oil content was unchanged with increased as N-rate. Oil yield ha^{-1} significantly (32.9 kg ha^{-1}), which is attributed to the increase in seed yield (Table 3) (Sawan et al. 2001a). Pandrangi et al. (1992) applied N at a rate of 25 or 50 kg ha^{-1} to cotton plants and found that the percentage of seed oil content decreased but oil yield increased with increasing N rate. Application of all growth retardants resulted in an insignificant increase in seed oil content above the control and also significantly increased the oil yield ha^{-1} over the control (29.3–45.2 kg oil ha^{-1}), with the clearest effect from Pix (45.2 kg ha^{-1}), followed by Cycocel (39.8 kg ha^{-1}) (Sawan et al. 2001a). Sawan et al. (1991) indicated that a slight increase in cottonseed oil content was detected with Pix application at rate ranging 10–100 ppm. Pix was sprayed once (90 day) or twice (90 and 110 days after planting). Oil yield also increased due to Pix application compared with the control. Sawan et al. (1993) observed that application of Cycocel and Alar (250–750 ppm, 105 days after planting) increased oil yield ha^{-1}. Application of Zn resulted in an insignificant increase in seed oil content over that of the control. The seed oil yield was also increased (34.7 kg oil ha^{-1}) compared with the untreated control (Sawan et al. 2001a). These results could be attributed to the increase of total photoassimilates (e.g. lipids) and the translocated assimilates to the sink as a result of applying Zn nutrient. Sawan et al. (1988) found that oil yield increased by the application of Zn to cotton plants at a rate of 12 g Zn ha^{-1}. Zinc was sprayed three times, i.e., 70, 85, and 100 day after sowing. Prabhuraj et al. (1993) found that applying Zn at 5 ppm rate increased seed and oil yields of sunflower. Similar results were obtained by Ibrahim et al. (2009) on cotton and Bybordi and Mamedov (2010) on canola.

Seed Protein Content and Yield

High N rate significantly increased the seed protein content and yield ha^{-1} (49.6 kg protein ha^{-1}) (Table 3) (Sawan et al. 2001a). According to Sugiyama et al. (1984), soluble proteins are increased with better N supply and favorable growth condition. These results suggest that the high N-rate increases the amino acids synthesis in the leaves, and this stimulates the accumulation of protein in the seed rather than oil content. Patil et al. (1997) found that N application (50 kg N ha^{-1}) increased the seed protein content. Seed protein content and yield ha^{-1} were increased insignificantly in plants in plants treated with the three growth retardants (35.4–55.9 kg protein ha^{-1}) compared with the untreated control. Highest protein content was produced by Pix application, followed by Alar, while the highest seed protein yield was obtained with Pix (55.9 kg ha^{-1}), and followed by Cycocel (46.7 kg ha^{-1}) (Sawan et al. 2001a). Hedin et al. (1988) found that Cycocel increased protein content by 17–50% in leaves and squares harvested 4 weeks after the first application. Kar et al. (1989) in safflower showed that Cycocel and Alar maintained the level of chlorophyll, protein, and RNA contents. Also, the increase in seed protein content may be caused by the role of Pix in protein synthesis, encouraging the conversion of amino acids into

Table 4 Effect of N rate and foliar application of plant growth retardants and Zn on seed oil properties[a]

Treatments		Refractive index	Acid value	Saponification value	Unsaponifiable matter (%)
N-rate (kg ha^{-1})					
Control	107	1.4733	0.1336	193.7	0.3700
	161	1.4734	0.1310	191.6	0.3738
S.E.[b]		0.0001	0.0013	1.0	0.0019
Plant growth retardant (ppm)					
Control	0	1.4729	0.1338	193.4	0.3675
Pix	300	1.4734	0.1327	192.9	0.3750
Cycocel	300	1.4738	0.1312	193.1	0.3725
Alar	300	1.4735	0.1317	191.2	0.3725
S.E.[b]		0.0002	0.0005	0.5	0.0015
Zn rate (ppm)					
Control	0	1.4732	0.1325	193.8	0.3688
	50	1.4735	0.1322	191.6	0.3750
S.E[b]		0.0001	0.0001	1.1	0.0031

Sawan et al. (2001a)
[a] Mean data from a four replicate composite for the two seasons
[b] S.E. = standard error

protein (Wang and Chen 1984). Sawan et al. (1991) stated that cottonseed protein content and yield ha^{-1} increased due to the application of Pix. Kler et al. (1991) found that when cotton was sprayed using Cycocel rates of 40, 60, or 80 ppm at the age 63 days after planting, seed protein content increased. Sawan et al. (1993) stated that application of Cycocel or Alar increased seed protein content and protein yield ha^{-1}. Application of zinc increased insignificantly the seed protein content and significantly increased protein yield ha^{-1} (41.6 kg protein ha^{-1}) over the untreated control (Sawan et al. 2001a). In these circumstances Ibrahim et al. (2009) found that application of Zn to cotton plants increased seed protein content and protein yield ha^{-1}.

Seed Oil Properties

The seed oil refractive index and unsaponifiable matter tended to increase insignificantly, while the oil acid value and saponification value tended to decrease by raising N-rate (Table 4) (Sawan et al. 2001a). The increase in unsaponifiable matter is beneficial as it increases the oil stability. Sawan et al. (1988) applied N to cotton plants at rates of 108 and 216 kg ha^{-1} and found that oil unsaponifiable matter tended to increase, while saponification value tended to decrease by raising N-rate. Application of all PGR significantly increased the oil refractive index. However, unsaponifiable matter was insignificantly increased, whereas acid value and saponification value tended to decrease insignificantly as compared with the untreated control (Sawan et al. 2001a). Applied Cycocel gave the highest refractive index and the lowest acid value, while Pix gave the highest unsaponifiable matter. Also, applied

Table 5 Effect of N rate and foliar application of plant growth retardants and Zn on the relative percentage of saturated fatty acids[a]

Treatments		Relative % of saturated fatty acids					
		Capric	Lauric	Myristic	Palmitic	Stearic	Total
N-rate (kg ha^{-1})							
Control	107	0.5887	0.4375	0.7700	20.72	2.767	25.283
	161	0.3212	0.8212	0.6812	18.67	2.152	22.646
S.E[b]		0.1337	0.1918	0.0444	1.02	0.307	1.319
Plant growth retardants (ppm)							
Control	0	0.3350	1.2325	1.4050	23.06	2.427	28.459
Pix	300	0.7500	0.7125	0.9225	20.88	1.982	25.247
Cycocel	300	0.3600	0.2600	0.3200	17.59	2.327	20.857
Alar	300	0.3750	0.3125	0.2550	17.25	3.102	21.294
S.E[b]		0.0986	0.2250	0.2717	1.38	0.234	1.794
Ca rate (ppm)							
Control	0	0.6325	0.5825	0.5825	22.41	2.472	26.679
	50	0.2775	0.6762	0.8687	16.98	2.447	21.249
S.E[b]		0.1775	0.0468	0.1431	2.71	0.012	2.715

Sawan et al. (2001a)
[a]Mean data from a four replicate composite for the two seasons
[b]S.E. = standard error

Alar gave the lowest saponification value. Sawan et al. (1993) stated that application of Cycocel and Alar to cotton plants increased oil refractive index and unsaponifiable matter and decreased oil acid value and saponification value. Osman and Abu-Lila (1985) found a negligible variation in refractive index of flax oil when the plants were treated with Cycocel at the application rates of 25–100 ppm twice; the first one 20 days after sowing and the second spray 2 months later. The oil refractive index and unsaponifiable matter tended to increase insignificantly, while acid value and saponification value decreased insignificantly by applied zinc compared with control (Sawan et al. 2001a). Sawan et al. (1988) found that application of Zn to cotton plants exhibited negligible effect upon oil-quality characters, i.e., refractive index, oil acid value, unsaponifiable matter, and saponification value.

Oil Fatty Acids Composition

The oil saturated fatty acids (capric, myristic, palmitic and stearic) decreased insignificantly, while lauric acid increased insignificantly in response to raising the N-rate (Table 5) (Sawan et al. 2001a). Palmitic acid was the dominant saturated fatty acid. Low content of saturated fatty acids is desirable for edible uses. Application of the three PGR's resulted in a decrease in the total saturated fatty acids compared with the untreated control. The decrease was significant with the Cycocel and Alar treatments. Cycocel gave the lowest total saturated fatty acids in oil contents, followed by Alar and also tended to increase insignificantly the saturated fatty acid capric acid compared with the untreated control. Applied Pix gave the

Table 6 Effect of N rate and foliar application of plant growth retardants and Zn on the relative percentage of unsaturated fatty acids[a]

Treatments		Relative % of unsaturated fatty acids			
		Oleic	Linoleic	Total	TU/TS [b] ratio
N rate (kg ha^{-1})					
Control	107	21.67	53.04	74.71	2.95
	161	22.57	54.78	77.35	3.42
S.E.[c]		0.45	0.87	1.32	0.23
Plant growth retardants (ppm)					
Control	0	20.67	50.86	71.53	2.51
Pix	300	21.20	53.55	74.75	2.96
Cycocel	300	23.07	56.07	79.14	3.79
Alar	300	23.54	55.16	78.70	3.69
S.E.[c]		0.69	1.14	1.79	0.30
Zn rate (ppm)					
Control	0	21.46	51.86	73.32	2.74
	50	22.79	55.96	78.75	3.70
S.E[c]		0.66	2.05	2.71	0.48

Sawan et al. (2001a)
[a] Mean data from a four replicate composite for the two seasons
[b] TU/TS ratio = (total unsaturated fatty acids)/(total saturated fatty acids)
[c] S.E. = standard error

highest capric and the lowest stearic acid content, while applied Cycocel gave the lowest lauric acid content. Alar application tended to give the lowest myristic and palmitic acids contents compared with control. Application of Zn resulted in a significant decrease in the total saturated fatty acids (capric, palmitic and stearic) while it resulted in an increase in the lauric and myristic saturated fatty acids, compared with untreated plants (Sawan et al. 2001a).

The total unsaturated fatty acids (oleic and linoleic) and the ratio between total unsaturated fatty acids and total saturated fatty acids (TU/TS) increased insignificantly (3.53 and 15.93%, respectively) by raising N-rate (Table 6) (Sawan et al. 2001a). Linoleic acid was the most abundant of the unsaturated fatty acids. Kheir et al. (1991) found that the higher N-rate increased the percentage of unsaturated fatty acids and decreased saturated fatty acids of flax oil. All PGR's increased the total unsaturated fatty acids and TU/TS ratio, compared with the control. The increase was significant by the application of Cycocel and Alar. Applied Cycocel gave the highest linoleic acid content, total unsaturated fatty acids (10.64%), and TU/TS ratio (51.0%), and followed by Alar (10.02 and 47.01%, respectively) (Sawan et al. 2001a). The increase in TU/TS as a result of the application of the three PGR may be attributed to their encouraging effects on enzymes that catalyzed the biosynthesis of the unsaturated fatty acids. Spraying plants with Zn significantly increased the total unsaturated fatty acids (7.4%) and TU/TS ratio (35.04%), compared with untreated control (Sawan et al. 2001a). Sawan et al. (1991) reported that applying Pix to cotton plants caused a general decrease in oil saturated fatty acids, associated with an increase in oil unsaturated fatty acids. Sawan et al. (1993) stated that application of Cycocel and Alar to cotton increased oil unsaturated fatty acids.

Osman and Abu-Lila (1985) when applied Cycocel at rates of 25–100 ppm to flax plants found that generally the higher concentrations (50 and 100 ppm) caused in the total oil saturated fatty acids, while they increased the unsaturated fatty acids.

3.1.3 Conclusion

From the findings of this study, it seems rational to recommended application of N at a rate of 161 of kg ha^{-1}, spraying of cotton plants with plant PGR, and application of Zn in comparison with the ordinary cultural practices adopted by Egyptian cotton producers, it is quite apparent that applications of such PGR, Zn, and increased N fertilization rates could bring about better impact on cottonseed yield, seed protein content, oil and protein yields, oil refractive index, unsaponifiable matter, and unsaturated fatty acids. On the other hand, there was a decrease in acid value and saponification value. The increase in seed yield and subsequent increase in oil and meal due to the application of PGR, Zn, and increased N fertilization were sufficient to cover the cost of using those chemicals and further attain an economical profit. (Sawan et al. 2001a).

3.2 Effect of P, Zn and Ca on Cottonseed, Protein and Oil Yields and Oil Properties

3.2.1 Materials

A field experiment was conducted on the cotton cultivar Giza 75. Each experiment included 16 treatments, using combinations: (i) Two P rates, 44 (farmer's dose) and 74 kg of P_2O_5 ha^{-1} were applied (as a concentrated band close to the seed ridge) as calcium super-phosphate (15% P_2O_5) before the first irrigation, i.e. 3 weeks after planting (during seedling stage). (ii) Two Zn rates at 0.0 and 40 ppm, as chelated form [ethylenediaminetetraacetic acid (EDTA)] each was foliar sprayed twice, 75 and 90 days after planting (during square initiation and boll setting stage) at solution volume of 960 l ha^{-1}. (iii) Four chelated Ca rates at 0.0, 20, 40 and 60 ppm were each foliar sprayed twice, 80 and 95 days after planting, at solution volume of 960 l ha^{-1} (Sawan et al. 2001b).

3.2.2 Analyzed Data

Seed Yield

Seed yield ha^{-1} was significantly increased (11.24%) when phosphorus was applied at the highest rate (Table 7) (Sawan et al. 2001b). Phosphorus as a constituent of cell nuclei is essential for cell division and development of meristematic tissue, and

Table 7 Effect of P rate and foliar application of Zn and Ca on cottonseed yield, seed index, seed oil, seed protein, oil and protein yields

Treatments		Cottonseed yield (kg ha^{-1})[a]	Seed index (g)[a]	Seed oil (%)[b]	Oil yield (kg ha^{-1})[b]	Seed protein (%)[b]	Protein yield (kg ha^{-1})[b]
P_2O_5 rate (kg ha^{-1})							
Control	44	1,837.1	10.19	19.67	361.6	22.35	410.6
	74	2,043.5	10.40	19.86	406.0	22.38	457.5
L.S.D. 0.05[c]		41.2	0.05	–	–	–	–
S.E.[d]		–	–	0.09	22.2	0.01	23.4
Zn rate (ppm)							
Control	0	1,860.2	10.24	19.59	364.5	22.22	413.4
	40	2,020.4	10.36	19.94	403.0	22.51	454.7
L.S.D. 0.05 [c]		41.2	0.05	–	–	–	–
S.E.[d]		–	–	0.17	19.2	0.14	20.6
Ca rate (ppm)							
Control	0	1,807.1	10.16	19.74	356.8	22.43	405.3
	20	1,934.6	10.31	19.76	382.7	22.36	432.9
	40	1,992.7	10.34	19.75	394.2	22.34	445.5
	60	2,026.8	10.37	19.82	401.3	22.34	452.4
L.S.D. 0.05 [c]		58.2	0.07	–	–	–	–
S.E.[d]		–	–	0.01	9.7	0.02	10.3

Sawan et al. (2001b)
[a] Combined statistical analysis from the two seasons
[b] Mean data from a four replicate composite for the two seasons
[c] L.S.D. = Least significant differences
[d] S.E. = standard error

hence it should have a stimulating effect on the plants, increasing the number of flowers and bolls per plant. Further, P has a well known impact in photosynthesis as well as synthesis of nucleic acids, proteins, lipids and other essential compounds (Guinn 1984), all of which are major factors affecting boll weight and consequently cottonseed. These results are confirmed by those of Abdel-Malak et al. (1997), Ibrahim et al. (2009), and Saleem et al. (2010b). Application of Zn significantly increased cottonseed yield ha^{-1} (8.61%), as compared with the untreated control (Sawan et al. 2001b). This may be due to its favorable effect on photosynthetic activity, which improves mobilization of photosynthates and directly influences of boll weight (Glass 1989). Also, Zn enhances the activity of tryptophan synthesis, which is involved in the synthesis of the growth control compound IAA, the major hormone that inhibits abscission of squares and bolls. The application of Zn increased the number of retained bolls $plant^{-1}$. Similar results were obtained by Zeng (1996), Ibrahim et al. (2009) on cotton, and Bybordi and Mamedov (2010) on canola. Calcium application also significantly increased seed yield (7.06–12.16%), as yields resulting from the three concentrations applied exceeded the control. In general, it can be stated that the highest Ca concentration (60 ppm) was more effective than the other two concentrations (20 or 40 ppm) (Sawan et al. 2001b). The role of Ca in increasing seed yield can possibly be ascribed to its involvement in the process of photosynthesis and the translocation of carbohydrates to young bolls. Calcium deficiency depressed the rate of photosynthesis (rate of CO_2 fixation). Guinn (1984) stated that Ca deficiency would cause carbohydrates to accumulate in leaves and not in young bolls. The results obtained agree with those reported by Shui and Meng (1990) and Wright et al. (1995).

Seed Index

The application of P at the rate of 74 kg P_2O_5 ha^{-1} significantly increased seed index (weight of 100 seed in g) relative to the application at 44 kg P_2O_5 ha^{-1} (Table 7) (Sawan et al. 2001b). A possible explanation for increased seed weight due to the application of P at the higher rate is that this nutrient activated biological reactions in the cotton plants, particularly CO_2 fixation and the synthesis of sugar, amino acids, protein, lipids and other organic compounds. It also increased the translocation of assimilates from photosynthetic organs to the sink (Kosheleva et al. 1984). Similar results were obtained by El-Debaby et al. (1995). Application of Zn significantly increased seed index, compared to the control (Sawan et al. 2001b). This may be due to its favorable effect on photosynthetic activity. Zinc improves mobilization of photosynthates and directly influences boll weight, that coincides directly with increased seed index. These results are confirmed by those obtained by Ibrahim et al. (2009). Calcium applied at all rates significantly increased seed index over the control (Sawan et al. 2001b). The highest rate of Ca (60 ppm) showed the highest numerical value of seed index. Similar results were obtained by Ibrahim et al. (2009).

Seed Oil Content and Yield

Raising the phosphorus rate increased seed oil content and oil yield ha^{-1} (Table 7) (Sawan et al. 2001b). This may be attributed to the fact that P is required for production of high quality seed, since it occurs in coenzymes involved in energy transfer reactions. Energy is tapped in photosynthesis in the form of adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADP). This energy is then used in photosynthetic fixation of CO_2 and in the synthesis of lipids and other essential organic compounds (Taiz and Zeiger 1991). These results agree with those obtained by Pandrangi et al. (1992) in studies conducted on cotton and Tomar et al. (1996) in studies conducted on sunflower. Spraying plants with zinc resulted in an increase of seed oil content and oil yield ha^{-1} when compared with the untreated control (Sawan et al. 2001b). This could be attributed to the increase of total photo assimilates (e.g. lipids) and the translocated assimilates to the sink as a result of applying zinc. Similar results were reached by Ibrahim et al. (2009). Application of Ca at all concentration tended to increase the seed oil content and oil yield ha^{-1} over the control; the best result was from the highest Ca concentration (60 ppm) (Sawan et al. 2001b). These results agreed with those obtained by Bora (1997) on rape, and Ibrahim et al. (2009) on cotton, and Bybordi and Mamedov (2010) on canola. A possible role of Ca as an activator of the enzyme phospholipase in cabbage leaves has been investigated by Davidson and Long (1958).

Seed Protein Content and Yield

Applying P at the higher rate slightly increased seed protein content (Table 7) (Sawan et al. 2001b). It also increased the protein yield ha^{-1}, resulting from an improvement in both seed yield and seed protein content. Phosphorus is a component of nucleic acids which are necessary for protein synthesis (Guinn 1984). Similar results were obtained by Tomar et al. (1996) in sunflower and Ibrahim et al. (2009) in cotton. The application of Zn increased the seed protein content and protein yield ha^{-1}, compared with the untreated control (Sawan et al. 2001b). Shchitaeva (1984) found that the synthesis of metabolically active amino acids depends on Zn, which increases the synthesis of asparagine and tryptophan. These results agree with studies reported by Ibrahim et al. (2009). Calcium applied at all rates tended to decrease the seed protein content slightly, but protein yield ha^{-1} increased compared with the untreated control, which is attributed to the increase in cottonseed yield. The best protein yield was obtained at the highest Ca concentration (60 ppm) (Sawan et al. 2001b).

Seed Oil Properties

The oil refractive index and unsaponifiable matter tended to increase, while the acid value and saponification value tended to decrease as phosphorus rate was raised (Table 8) (Sawan et al. 2001b). The increase in unsaponifiable matter is known to be beneficial, as it increases oil stability. Spraying plants with Zn resulted in a slight increase in the oil refractive index and unsaponifiable matter and a slight decrease in acid value and saponification value, compared with the untreated control (Sawan et al. 2001b). Similar results were obtained by Sawan et al. (1988) concerning the effect of applied Zn on oil refractive index, unsaponifiable matter and saponification value. Application of Ca at any concentration tended to decrease the oil acid value and saponification value and to increase the unsaponifiable matter, especially as the applied Ca concentration increased, compared with the untreated control (Sawan et al. 2001b). This became especially apparent as the applied calcium concentration was increased. The effect of Ca concentrations on oil refractive index was very limited and without a defined trend. These results are in agreement with those reported by Sawan et al. (1988) concerning the effect of applied Ca on oil refractive index, saponification value and unsaponifiable matter. The studied oil quality characters seemed to be genetically controlled.

Table 8 Effect of P rate and foliar application of Zn and Ca on seed oil properties[a]

Treatments		Refractive index	Acid value	Saponification value	Unsaponifiable matter (%)
P_2O_5 rate (kg ha^{-1})					
Control	44	1.4688	0.1332	192.9	0.3575
	74	1.4691	0.1327	191.5	0.3662
S.E[b]		0.0001	0.0002	0.7	0.0043
Zn rate (ppm)					
Control	0	1.4687	0.1331	192.4	0.3538
	40	1.4692	0.1328	192.0	0.3700
S.E[b]		0.0002	0.0001	0.2	0.0081
Ca rate (ppm)					
Control	0	1.4689	1.1340	194.9	0.3550
	20	1.4688	0.1330	191.4	0.3575
	40	1.4688	0.1324	191.3	0.3650
	60	1.4692	0.1324	191.2	0.3700
S.E[b]		0.0001	0.0003	0.9	0.0034

Sawan et al. (2001b)
[a]Mean data from a four replicate composite for the two seasons
[b]S.E. = standard error

Table 9 Effect of P rate and foliar application of Zn and Ca on the relative percentage of saturated fatty acids[a]

Treatments		Relative % of saturated fatty acids					
		Capric	Lauric	Myristic	Palmitic	Stearic	Total
P_2O_5 rate (kg ha^{-1})							
Control	44	0.0812	0.1212	0.5100	21.65	1.844	24.206
	74	0.0688	0.1538	0.2612	19.95	1.746	22.180
S.E[b]		0.0062	0.0163	0.1244	0.85	0.049	1.013
Zn rate (ppm)							
Control	0	0.0500	0.0988	0.3912	21.67	1.752	23.962
	40	0.1000	0.1762	0.3800	19.93	1.838	22.424
S.E[b]		0.0250	0.0387	0.0056	0.87	0.043	0.769
Ca rate (ppm)							
Control	0	0.1375	0.2575	0.5025	22.36	2.090	25.347
	20	0.0600	0.1100	0.2900	21.15	1.742	23.352
	40	0.0300	0.0825	0.3000	19.59	1.090	21.092
	60	0.0725	0.1000	0.4500	20.09	2.258	22.970
S.E[b]		0.0226	0.0404	0.0534	0.61	0.258	0.872

Sawan et al. (2001b)
[a]Mean data from a four replicate composite for the two seasons
[b]S.E. = standard error

Oil Fatty Acids Composition

The high rate of applied P decreased the oil saturated fatty acids capric, myristic, palmitic and stearic, while it increased lauric acid (Table 9). The total saturated fatty acids also decreased. Palmitic acid was the predominant saturated fatty acid. Low

Table 10 Effect of P rate and foliar application of Zn and Ca on the relative percentage of unsaturated fatty acids[a]

Treatments		Relative % of unsaturated fatty acids			
		Oleic	Linoleic	Total	TU/TS[b] ratio
P_2O_5 rate (kg ha^{-1})					
Control	44	21.89	53.90	75.79	3.13
	74	21.91	55.91	77.82	3.51
S.E[c]		0.01	1.00	1.01	0.19
Zn rate (ppm)					
Control	0	21.70	54.33	76.03	3.17
	40	22.09	55.48	77.57	3.46
S.E[c]		0.19	0.57	0.77	0.14
Ca rate (ppm)					
Control	0	21.34	53.31	74.65	2.94
	20	22.26	54.38	76.64	3.28
	40	22.00	56.90	78.90	3.74
	60	22.00	55.02	77.02	3.35
S.E[c]		0.19	0.75	0.87	0.16

Sawan et al. (2001b)
[a] Mean data from a four replicate composite for the two seasons
[b] TU/TS ratio = (total unsaturated fatty acids) / (total saturated fatty acids)
[c] S.E. = standard error

content of saturated fatty acids is desirable for edible uses (Sawan et al. 2001b). The application of Zn decreased the abundant saturated fatty acids palmitic and myristic, while it increased capric, lauric and stearic saturated fatty acids, compared to the control. The total saturated fatty acids decreased (Sawan et al. 2001b). Calcium applied at all concentrations decreased in the saturated fatty acids capric, lauric, myristic, palmitic and stearica as well as the saturated fatty acids compared with the untreated control with one exception (Sawan et al. 2001b). Spraying plants with Ca at 60 ppm tended to increase stearic acid, compared with the control. Applied Ca at 40 ppm gave the lowest capric, lauric, palmitic and stearic acids contents, compared with the other two concentrations (20 and 60 ppm). Calcium at 20 ppm gave the lowest myristic acid content, compared with 40 and 60 ppm. The total unsaturated fatty acids (oleic and linoleic) and the ratio between total unsaturated fatty acids and total saturated fatty acids (TU/TS) were increased by raising P rate (Table 10). Linoleic acid was the most abundant unsaturated fatty acid. Gushevilov and Palaveeva (1991) studied the changes in sunflower oil contents of linoleic, oleic, stearic and palmitic acids due to application rate of phosphorus and found that oil quality remained high at a high P rate. The application of Zn resulted in an increase in total unsaturated fatty acids and TU/TS ratio, over the control (Sawan et al. 2001b). Calcium applied at all rates increased the total unsaturated fatty acid and TU/TS ratio, compared with untreated control. Calcium at 40 ppm gave the highest increment, total unsaturated fatty acid and TU/TS ratio, followed by 60 ppm concentration. Spraying plants with Ca at 20 ppm produced seed oil characterized by the highest oleic acid content, while spraying with 40 ppm gave the highest linoleic acid content, compared with the other concentrations (Sawan et al. 2001b).

3.2.3 Conclusion

Under the conditions of this study, it can be concluded that addition of P at 74 kg ha^{-1}, and foliar application of Zn and Ca at different concentrations (especially Ca concentration of 60 ppm) beneficially affected cottonseed yield, seed index, seed oil content, oil and protein yields ha^{-1}, seed oil unsaponifiable matter, and total unsaturated fatty acids (oleic and linoleic) (sawan et al. 2001b).

3.3 Cottonseed, Protein, Oil Yields, and Oil Properties as Influenced by K, P and Zn

3.3.1 Materials

A field experiment was conducted on the cotton cultivar “Giza 86”. Each experiment included 16 treatment combinations of the following: (i) Two K rates (0.0 and 47.4 kg of K ha^{-1}) were applied as K sulfate (K_2SO_4, 48% K_2O), 8 weeks after sowing (as a concentrated band close to the seed ridge) and the application was followed immediately by irrigation. (ii) Two Zn rates (0.0 or 57.6 g of Zn ha^{-1}) were applied as chelated form and each was foliar sprayed two times (70 and 85 days after planting, during square initiation and boll setting stage). (iii) Four phosphorus rates (0.0, 576, 1,152 and 1,728 g of P ha^{-1}) were applied as calcium super phosphate (15% P_2O_5) and each was foliar sprayed two times (80 and 95 days after planting). The Zn and P were both applied to the leaves with uniform coverage at a solution volume of 960 l ha^{-1}, using a knapsack sprayer (Sawan et al. 2007a).

3.3.2 Analyzed Data

Seed Yield

Seed yield ha^{-1} significantly increased when K was applied (by as much as 13.99%) (Table 11) (Sawan et al. 2007a). Potassium would have a favorable impact on yield components, including a number of open bolls $plant^{-1}$ and boll weight, leading to a higher cotton yield. The role of K suggests that it affects abscission (reduced boll shedding) and it certainly affects yield (Zeng 1996). Gormus (2002) and Ibrahim et al. (2009) also found that K application increased yield. Application of Zn significantly increased seed yield ha^{-1}, as compared with the untreated control (by 9.38%) (Sawan et al. 2007a). A possible explanation of such results might be the improvement of yield components due to the application of Zn. Zinc could have a favorable effect on photosynthetic activity of leaves (Welch 1995), which improves mobilization of photosynthates and directly influences boll weight. Further, Zn is required in the synthesis of tryptophan, a precursor of indole-3-acetic acid (Oosterhuis et al. 1991), which is the major hormone inhibits abscission of squares and bolls. Thus the number of retained bolls $plant^{-1}$ and consequently seed yield ha^{-1} would be

Table 11 Effect of K rate and foliar application of Zn and foliar, additional P on cottonseed yield, seed index, seed oil, seed protein, oil and protein yields

Treatments	Cottonseed yield (kg ha^{-1})[a]	Seed index (g)[a]	Seed Oil (%)[b]	Oil yield (kg ha^{-1})[b]	Seed protein (%)[b]	Protein yield (kg ha^{-1})[b]
K rate (kg ha^{-1})						
0, control	1,828.0	10.01	19.55	357.5	22.24	406.6
47.4	2,083.8	10.16	19.82	413.2	22.27	464.1
L.S.D. 0.05[c]	80.6	0.05	–	–	–	–
S.D.[c]	–	–	0.15	34.2	0.03	36.2
Zn rate (g ha^{-1})						
0, control	1,868.3	10.04	19.59	366.2	22.25	415.7
57.6	2,043.5	10.13	19.78	404.4	22.26	455.0
L.S.D. 0.05[c]	80.6	0.05	–	–	–	–
S.D.[c]	–	–	0.18	40.5	0.04	42.6
P rate (g ha^{-1})						
0, control	1,775.8	9.97	19.56	347.5	22.23	394.8
576	1,944.3	10.08	19.64	382.1	22.25	432.7
1,152	2,023.7	10.13	19.76	400.3	22.26	450.5
1,728	2,079.8	10.16	19.77	411.5	22.28	463.3
L.S.D. 0.05[c]	114.0	0.07	–	–	–	–
S.D.[c]	–	–	0.20	40.2	0.04	41.7

Sawan et al. (2007a)
[a] Combined statistical analysis from the two seasons
[b] Mean data from a four replicate composites for the two seasons
[c] L.S.D. = least significant differences
[d] S.D. = standard deviation was used to conduct *t*-test to verify the significance between every two treatment means at 0.05 level

increased (Rathinavel et al. 2000) Similar results were obtained by Ibrahim et al. (2009). Phosphorus extra foliar application at all the three concentrations (576, 1,152 and 1,728 g of P ha^{-1}) also significantly increased seed yield ha^{-1}, where the three concentrations applied proved to excel the control (by 9.49–17.12%). The best yield was obtained at the highest P concentration tested (Sawan et al. 2007a). Such results reflect the pronounced improvement of yield components due to application of P which is possibly ascribed to its involvement in photosynthesis and translocation of carbohydrates to young bolls (Rodriguez et al. 1998). Phosphorus as a constituent of cell nucleus is essential for cell division and the development of meristematic tissue and hence it would have a stimulating effect on increasing the number of flowers and bolls $plant^{-1}$ (Russell 1973). These results agree with that reported by Katkar et al. (2002), Ibrahim et al. (2009) and Saleem et al. (2010b).

Seed Index

Seed index significantly increased with applying K (Table 11) (Sawan et al. 2007a). A possible explanation for the increased seed index due to the application of K may be due in part to its favorable effects on photosynthetic activity rate of crop leaves and CO_2 assimilation (Sangakkara et al. 2000), which improves mobilization of photosynthates and directly influences boll weight which in turn directly affect seed weight (Ghourab et al. 2000). The application of Zn significantly increased seed index, as compared to control (Sawan et al. 2007a). The increased seed weight might be due to an increased photosynthesis activity resulting from the application of Zn (Welch 1995) which improves mobilization of photosynthates and the amount of photosynthate available for reproductive sinks and thereby influences boll weight, factors that coincide with increased in seed weight (Rathinavel et al. 2000). The phosphorus applied at all three rates significantly increased seed index over the control. The highest rate of P (1,728 g ha^{-1}) showed the highest numerical value of seed index (Sawan et al. 2007a). This increased seed weight may be due to the fact that P activated the biological reaction in cotton plant, particularly photosynthesis fixation of CO_2 and synthesis of sugar, and other organic compounds (Welch 1995; Wiatrak et al. 2006). This indicates that treated cotton bolls had larger photosynthetically supplied sinks for carbohydrates and other metabolites than untreated bolls (Sawan et al. 2007a).

Seed Oil Content and Yield

The applied K caused significant increase in seed oil content and oil yield ha^{-1} (55.7 kg oil ha^{-1}), compared with untreated control (Table 11) (Sawan et al. 2007a). This could be attributed to the role of K in biochemical pathways in plants. Potassium increases the photosynthetic rates of crop leaves, CO_2 assimilation and facilitates carbon movement (Sangakkara et al. 2000). The favorable effects of K on seed oil content and oil yield were mentioned by Abou El-Nour et al. (2000) and Ibrahim et al. (2009). Spraying plants with Zn resulted in an increase in seed oil content and oil yield ha^{-1} (38.2 kg oil ha^{-1}), compared with the untreated control. Cakmak (2000) has speculated that Zn deficiency stress may inhibit some antioxidant enzymes, resulting in extensive oxidative damage to membrane lipids. Similar results were obtained by Ibrahim et al. (2009). The foliar application of P at all the three concentrations tended to increase the seed oil content and oil yield ha^{-1} (34.6–64.0 kg oil ha^{-1}), over the control (Sawan et al. 2007a). The effect was the most significant at the highest P concentration (1,728 g ha^{-1}) on oil yield ha^{-1}. These results agree with those obtained by Rajendran and Veeraputhiran (2001), in sunflower, and Ibrahim et al. (2009) in cotton.

Seed Protein Content and Yield

The applied K caused a slight increase in seed protein content and significantly increased protein yield ha^{-1} (57.5 kg protein ha^{-1}), compared with the untreated control (Table 11) (Sawan et al. 2007a). It also increased the protein yield ha^{-1}, resulting in an improvement in both seed yield and seed protein content. This could be attributed to the role of K in biochemical pathways in plants. Potassium increases the photosynthetic rates of crop leaves, CO_2 assimilation and facilitates carbon movement (Sangakkara et al. 2000). Also, K has favorable effects on metabolism of nucleic acids, and proteins (Bednarz and Oosterhuis 1999). These are manifested in metabolites formed in plant tissues and directly influence the growth and development processes. Similar results were obtained by Ghourab et al. (2000), and Ibrahim et al. (2009). The application of Zn slightly increased the seed protein content, and increased protein yield ha^{-1} (39.3 kg protein ha^{-1}) numerically compared with the untreated control. Because Zn is directly involved in both gene expression and protein synthesis. Cakmak (2000) has speculated that Zn deficiency stress may inhibit the activities of a number of antioxidant enzymes, resulting in extensive oxidative damage to proteins, chlorophyll and nucleic acids. These results agree with those reported by Babhulkar et al. (2000) in safflower and Ghourab et al. (2000) in cotton. Phosphorus applied at all rates tended to increase the seed protein content and the protein yield ha^{-1} (37.9–68.5 kg protein ha^{-1}) compared with the untreated control (Sawan et al. 2007a). The effect was significant on protein yield ha^{-1} when applied the high P concentration (1,728 g ha^{-1}), resulting from an improvement in both seed yield and seed protein content. Phosphorus is a component of nucleic acids, which are necessary for protein synthesis (Taiz and Zeiger 1991). Similar results were obtained by Tomar et al. (1996) in sunflower and Ghourab et al. (2000) in cotton.

Seed Oil Properties

The oil refractive index, unsaponifiable matter and iodine value significantly increased, while saponification value significantly decreased by applied K, compared with the untreated control (Table 12) (Sawan et al. 2007a). On the other hand, the acid value was not significantly affected due to the K application. Potassium is an essential nutrient and an integral component of several important compounds in plant cells. This attributed to the role of K in biochemical pathways in plants (Marschner 1995). These may be reflected in distinct changes in seed oil quality. Mekki et al. (1999) stated that, foliar application with K (0 or 3.5% K_2O) on sunflower at the seed-filling stage resulted in decreased oil acid content. Froment et al. (2000), in linseed, found that the iodine value, which indicates the degree of unsaturation in the final oil, was highest in treatments receiving extra K. Spraying plants with Zn resulted in a significant increase in oil refractive index, and a significant decrease in unsaponifiable matter, compared with untreated control. The other oil properties (acid, saponification, and iodine values) were not significantly affected. Zinc activates a large number of enzymes, either due to binding enzymes and substrates, or the effects of Zn on conformation of enzymes or substrate, or both (Klug and Rhodes 1987; Romheld and Marschner 1991). These would have a direct impact through utilization in the growth processes, which are reflected in distinct changes in seed oil quality (Sawan et al. 2007a). The application of P at all concentrations significantly increased iodine value, compared with the untreated control, while the other oil properties (oil refractive index; acid and saponification values, and the unsaponifiable matter) were not significantly affected.

Table 12 Effect of K rate and foliar application of Zn and foliar, additional P on seed oil properties[a]

Treatments	Refractive index	Acid value	Saponification value	Unsaponifiable matter (%)	Iodine value
K rate (kg ha^{-1})					
0, control	1.4684	0.1343	190.81	0.3538	127.48
47.4	1.4698	0.1316	189.74	0.3950	132.76
S.D.[b]	0.0013	0.0032	0.74	0.0223	3.63
Zn rate (g ha^{-1})					
0, control	1.4683	0.1336	190.71	0.3625	128.39
57.6	1.4699	0.1323	189.84	0.3863	131.85
S.D.[b]	0.0012	0.0034	0.80	0.0287	4.21
P rate (g ha^{-1})					
0, control	1.4681	0.1350	190.75	0.3525	125.33
576	1.4693	0.1343	190.33	0.3725	131.46
1,152	1.4696	0.1323	190.10	0.3800	131.93
1,728	1.4695	0.1309	189.92	0.3925	131.76
S.D.[b]	0.0015	0.0033	0.94	0.0294	3.80

Sawan et al. (2007a)
[a] Mean data from a four replicate composites for the two seasons
[b] S.D. = standard deviation

Oil Fatty Acids Composition

The applied K decreased the oil-saturated fatty acids (capric, lauric, myristic, palmitic, and stearic) (Table 13) (Sawan et al. 2007a). A significant effect was found only on capric, palmitic, and the total saturated fatty acids. The total unsaturated fatty acids (oleic and linoleic) and the ratio between total unsaturated fatty acids and total saturated fatty acids (TU/TS) were increased (by 4.31, and 19.77%, respectively) by applied K (Table 14) (Sawan et al. 2007a). The effect was significant on linoleic acid, the total unsaturated fatty acids (oleic and linoleic), and TU/TS ratio. The beneficial effect of applied K on TU and TU/TS ratio may be due to the regulated effect of K, which acts as an activator on many enzymatic processes, where some of these enzymes may affect the seed oil content from these organic matters. To our knowledge, no information on the effect of K on the cottonseed oil fatty acids is available in the literatures (Sawan et al. 2007a). Mekki et al. (1999) stated that, foliar application with K on sunflower increased the oleic acid fatty acid. Froment et al. (2000), in linseed oil, found that the linoleic acid content was greatest in treatment receiving extra K. The application of Zn resulted in a decrease of the saturated fatty acids, i.e. palmitic, capric, myristic, and stearic, and the total, but resulted in an increase in lauric acid, compared to the untreated control (Sawan et al. 2007a). The effect was significant only on palmitic acid, and the total saturated fatty acids in the oil. The application of Zn resulted in an increase in the total unsaturated fatty acids (by 3.49%) and TU/TS ratio (by 15.25%), over the control. The effect was significant on oleic acid, the total unsaturated fatty acids (oleic and linoleic), and TU/TS ratio. The stimulatory residual effects of the application Zn on TU and TU/TS ratio

Table 13 Effect of K rate and foliar application of Zn and foliar, additional P on the relative percentage of saturated fatty acids[a]

	Relative % of saturated fatty acids					
Treatments	Capric	Lauric	Myristic	Palmitic	Stearic	Total
K rate (kg ha^{-1})						
0, control	0.0774	0.0626	0.8275	22.21	2.271	25.452
47.4	0.0728	0.0599	0.4863	19.72	1.915	22.250
S.D.[b]	0.0036	0.0079	0.3407	1.48	0.451	2.331
Zn rate (g ha^{-1})						
0, control	0.0769	0.0609	0.6763	22.16	2.185	25.159
57.6	0.0733	0.0616	0.6375	19.77	2.001	22.544
S.D.[b]	0.0040	0.0049	0.3859	1.79	0.479	2.532
P rate (g ha^{-1})						
0, control	0.0795	0.0665	1.1075	22.80	2.728	26.776
576	0.0748	0.0623	0.5925	20.70	1.855	23.287
1,152	0.0733	0.0595	0.4375	20.30	1.905	22.770
1,728	0.0728	0.0568	0.4900	20.07	1.885	22.572
S.D.[b]	0.0036	0.0034	0.2826	2.02	0.317	2.422

Sawan et al. (2007a)
[a] Mean data from a four replicate composites for the two seasons
[b] S.D. = standard deviation

Table 14 Effect of K rate and foliar application of Zn and foliar, additional P on the relative percentage of unsaturated fatty acids[a]

	Relative % of unsaturated fatty acids			
Treatments	Oleic	Linoleic	Total	TU/TS[b] ratio
K rate (kg ha^{-1})				
0, control	21.61	52.94	74.54	2.954
47.4	22.73	55.01	77.75	3.538
S.D.[c]	1.40	1.49	2.33	0.403
Zn rate (g ha^{-1})				
0, control	21.43	53.40	74.84	3.016
57.6	22.90	54.55	77.45	3.476
S.D.[c]	1.31	1.76	2.53	0.446
P rate (g ha^{-1})				
0, control	21.11	52.11	73.22	2.755
576	21.96	54.75	76.70	3.331
1,152	22.52	54.70	77.23	3.427
1,728	23.09	54.33	77.43	3.472
S.D.[c]	1.42	1.57	2.42	0.439

Sawan et al. (2007a)
[a] Mean data from a four replicate composite for the two seasons
[b] TU/TS ratio = (total unsaturated fatty acids)/(total saturated fatty acids)
[c] S.D. = standard deviation

were probably due to the favorable effects of Zn on fundamental metabolic reactions in plant tissues. Phosphorus applied at all concentrations resulted in a decrease in the total saturated fatty acids compared with the untreated control. Spraying plants with P at 1,728 g ha^{-1} gave the lowest total saturated fatty acids oil, followed by P at 1,152 g ha^{-1} concentration, compared with the control (Sawan et al. 2007a). Application the high P concentration (1,728 g ha^{-1}) gave the lowest capric, lauric, palmitic, and stearic acid contents compared with the other two concentrations (576 and 1,152 g of P ha^{-1}), while applied P at 1,152 g ha^{-1} gave the lowest myristic acid content compared with the other two concentrations (576 and 1,728 g of P ha^{-1}). The effect was significant for the two concentrations1,152 and 1,728 g of P ha^{-1} on capric acid and the total saturated fatty acids in the oil, and for all different P concentrations on lauric, myristic, and stearic. Phosphorus applied at all rates increased the total unsaturated fatty acid (by 4.77–5.75%) and TU/TS ratio (by 20.91–26.03%) compared with the untreated control. Applied P at 1,728 g ha^{-1} gave the highest increment, followed by the concentration 1,152 g of P ha^{-1} (Sawan et al. 2007a). Spraying plants with P at 1,728 g ha^{-1} produced seed oil characterized by the highest oleic acid content, while spraying with 576 g of P ha^{-1} gave the highest linoleic acid content compared with the other concentrations. The effect was significant for the high P concentration (1,728 g ha^{-1}) on oleic, for the two concentrations, i.e., 1,152 and 1,728 g of P ha^{-1} on the TU/TS ratio, and for all different concentrations on linoleic, and the total unsaturated fatty acid (Sawan et al. 2007a). The beneficial effect of applied P at different concentrations on TU and TU/TS ratio may be due to the regulated effect of P on many enzymatic processes and the fact that P acts as an activator of some enzymes which may affect the seed oil fatty acids composition. Gushevilov and Palaveeva (1991) studied the changes in the contents of linoleic, oleic, stearic, and palmitic acids in sunflower oil due to the P-application rate and found that oil quality remained high at a high P-rate. Khan et al. (1997) indicated that oleic acid increased by increasing levels of P added to rapeseed mustard.

3.3.3 Conclusion

From the findings of this study, the addition of K at 47.4 kg ha^{-1}, spraying cotton plants with Zn twice (at 57.6 g ha^{-1}), and also with P twice (especially the P concentration of 1,728 g ha^{-1}) along with the soil fertilization used P at sowing time have been proven beneficial to the quality and yield of cotton plants. These combinations appeared to be the most effective treatments, affecting not only the quantity but also the quality of oil, and to obtain higher oil and protein yields and a better fatty acid profile in the oil of cotton. In comparison with the ordinary cultural practices adopted by Egyptian cotton producers, it is apparent that the applications of such treatments could produce an improvement in cottonseed yield, seed protein content, oil and protein yields, oil refractive index, unsaponifiable matter, iodine value, unsaturated fatty acids and a decrease in oil acid value and saponification value. The increase in seed yield and subsequent increase in oil and meal due to the addition of K, spraying cotton plants with Zn and of P are believed to be sufficient enough to cover the cost of using those chemicals and obtain an economic profit at the same time (Sawan et al. 2007a).

3.4 Effects N, K and PGR on Oil Content and Quality of Cotton Seed

3.4.1 Materials

A field experiment was conducted, using the cotton cultivar 'Giza 86'. The experiment included 16 treatments: (i) soil application of N (95.2 'the ordinary', and 142.8 kg of N ha^{-1} as ammonium nitrate), (ii) foliar application of K (0, 319, 638 and 957 g K ha^{-1} as potassium sulfate) and (iii) foliar spray of the PGR (1,1-dimethylpiperidinium chloride (mepiquat chloride 'MC' or 'Pix') 75 days after planting at 0 or 48 g *a.i.* ha^{-1}, and 90 days after planting at 0 or 24 g *a.i.* ha^{-1}). The solution volume applied was also 960 L ha^{-1}. Nitrogen fertilizer (NH_4NO_3, '3.5% N') was applied half at 6 and the rest at 8 weeks after planting. The fertilizer was placed beside each hill in the form of pinches and followed immediately by irrigation. Potassium (K_2SO_4, '40% K') was applied as foliar spray during square initiation and boll development stage, 70 and 95 days after planting, respectively. The solution volume applied was 960 l ha^{-1}. The K and MC were applied to the leaves uniformly using a knapsack sprayer. (Sawan et al. 2007b).

3.4.2 Analyzed Data

Seed Yield

The seed yield of cotton significantly ($P<0.05$) increased (as much as 13.03%) by increasing N-application rate from 95.2 to 142.8 kg ha^{-1} (Table 15) (Sawan et al. 2007b). There is an optimal relationship between the nitrogen content in the plant and CO_2 assimilation, where decreases in CO_2 fixation are well documented for N-deficient plants. Nitrogen deficiency is associated with elevated levels of ethylene (which increase boll shedding), suggesting ethylene production in response to N-deficiency stress (Legé et al. 1997). Nitrogen is also an essential nutrient in creating plant dry matter, as well as many energy-rich compounds which regulate photosynthesis and plant production, thus influencing boll development, increasing the number of bolls per plant and boll weight. Similar findings were obtained by McConnell and Mozaffari (2004) and Saleem et al. (2010a) when N fertilizer was applied at 120 kg ha^{-1} and Wiatrak et al. (2006) when N fertilizer was applied at 67–202 kg ha^{-1}. Also, similar results were obtained by Sarwar Cheema et al. (2009). On the other hand Boquet (2005) reported that increasing N from 90 to 157 kg ha^{-1} did not result in increased cotton yield in irrigated or rain-fed cotton. Foliar application of K significantly increased seed yield by 10.02 to 16.25% as compared to the control (0 g K ha^{-1}) (Table 15) (Sawan et al. 2007b). The differences between the effects of the three concerned K rates were statistically insignificant; with the exception of the 957 g K ha^{-1} concentration that proved to produce significantly higher seed yield ha^{-1} (5.66%) than the 319 g K ha^{-1} concentration. These increases could

Table 15 Effect of N rate and foliar application of K and mepiquat chloride (MC) on the yield, 100-seed weight, oil and protein of the cotton

Treatments	Cottonseed yield (kg ha^{-1})[a]	100-seed weight (g)[a]	Seed oil (%)[b]	Oil yield (kg ha^{-1})[b]	Seed protein (%)[b]	Protein yield (kg ha^{-1})[b]
N rate (kg ha^{-1})						
95.2	1,862.4	10.09	19.73	367.5	22.24	414.2
142.8	2,105.0	10.32	19.60	413.0	22.44	472.2
L.S.D. 0.05[c]	78.7	0.07	–	–	–	–
S.D.[c]	–	–	0.16	33.6	0.11	35.5
K rate (g ha^{-1})						
0	1,804.4	10.03	19.49	351.6	22.32	402.9
319	1,985.2	10.19	19.61	389.3	22.32	443.1
638	2,047.7	10.27	19.73	404.2	22.34	457.7
957	2,097.6	10.32	19.83	415.8	22.37	469.3
L.S.D. 0.05[c]	111.4	0.10	–	–	–	–
S.D.[c]	–	–	0.12	35.0	0.16	41.8
MC rate (g ha^{-1})						
0	1,891.8	10.13	19.61	371.1	22.31	422.1
48+24	2,075.6	10.27	19.72	409.4	22.37	464.4
L.S.D. 0.05[c]	78.7	0.075	–	–	–	–
S.D.[d]	–	–	0.17	36.1	0.15	41.3

Sawan et al. (2007b)

[a] Combined statistical analysis from the two seasons

[b] Mean data from a four replicate composites for the two seasons

[c] L.S.D. = least significant differences

[d] S.D. = standard deviation was used to conduct *t*-test to verify the significance between every two treatment means at 0.05 level

be due to the favorable effects of this nutrient on yield components such as number of opened bolls plant^{-1}, boll weight, or both, leading to higher cotton yield. Zeng (1996) indicated that, K fertilizer reduced boll shedding. Pettigrew (1999) stated that, the elevated carbohydrate concentrations remaining in source tissue, such as leaves, appear to be part of the overall effect of K deficiency in reducing the amount of photosynthate available for reproductive sinks and thereby producing changes in boll weight. Cakmak et al. (1994) found that, the K nutrition had pronounced effects on carbohydrate partitioning by affecting either the phloem export of photosynthates (sucrose) or growth rate of sink and/or source organs. Mullins et al. (1999) evaluated cotton yield under a long-term soil application of K at 75–225 kg K_2O ha^{-1}, and found that K application increased yield. Results obtained here confirmed those obtained by Aneela et al. (2003) when applying 200 kg K_2O ha^{-1}, Pervez et al. (2004) under 62.5, 125, 250 kg K ha ha^{-1}, and Pettigrew et al. (2005) under K fertilizer (112 kg ha^{-1}). Application of the PGR mepiquat chloride significantly increased seed yield ha^{-1} (by 9.72%), as compared with untreated plants. Such increases could be due to the fact that, the application of mepiquat chloride restrict vegetative growth and thus enhance reproductive organs by allowing plants to direct more energy towards the reproductive structure (Pípolo et al. 1993). This means that bolls on treated cotton would have a larger photo synthetically supplied sink of carbohydrates and other metabolites than did those on untreated cotton (Wang et al. 1995). Results agreed with those obtained by Prakash et al. (2001) when mepiquat chloride was applied at 50 ppm, Mekki (1999) when mepiquat chloride was applied at 100 ppm, and Kumar et al. (2004). Also, similar results were obtained by Sarwar Cheema et al. (2009)

100-Seed Weight

100-seed weight significantly increased by adding the high N-rate (Table 15) (Sawan et al. 2007b). This may be due to increased photosynthetic activity that increases accumulation of metabolites, with direct impact on seed weight. Reddy et al. (1996), in a pot experiment under natural environmental conditions, where 20-day old cotton plants received 0, 0.5, 1.5 or 6 mM NO_3, found that, net photosynthetic rates, stomatal conductance and transpiration were positively correlated with leaf N concentration. Similar findings were reported by Palomo et al. (1999), when N was applied at 40–200 kg ha^{-1}, and Ali and El-Sayed (2001), when N was applied at 95–190 kg ha^{-1}. 100-seed weight significantly increased with K application at all the three concentrations as compared to the control (Sawan et al. 2007b). The highest rate of K (957 g K ha^{-1}) resulted the highest seed weight. The difference between the high rate and low rate (319 g K ha^{-1}) was also significant. Increase in seed weight might be due to the effect of K on mobilization of photosynthates, which would directly influence boll weight and increase seed weight (Pettigrew 1999; Sawan et al. 2009). Ghourab et al. (2000), and Ibrahim et al. (2009) reported that, the application of K fertilizer resulted in an increase in seed weight. The application of mepiquat chloride significantly increased 100-seed weight as compared to the plots that had not received mepiquat chloride, the untreated control (Sawan et al. 2007b). Increased seed weight as a result of mepiquat chloride applications may be due to an increase in photosynthetic activity, which stimulates photosynthetic activity, and dry matter accumulation (Bednarz and Oosterhuis 1999; Kumar et al. 2004), and in turn increases the formation of fully-mature seed and thus increases seed weight. Similar results to the present study were obtained by Ghourab et al. (2000) and Lamas (2001).

Seed Oil Content and Yield

Seed oil content was slightly decreased with an increase in the N rate from 95.2 to 142.8 kg ha^{-1}, but seed oil yield ha^{-1} had significantly increased (45.5 kg oil ha^{-1}), which is attributed to the significant increase in seed yield (Table 15) (Sawan et al. 2007b). Similar results were obtained by Froment et al. (2000), in linseed, and Zubillaga et al. (2002) in sunflower. Yield increases in this study were attributed to the fact that N was an important nutrient in controlling new growth, thus influencing boll development, increasing the number of bolls $plant^{-1}$ and boll weight. Synthesis of fat requires both N and carbon skeletons during the course of seed development (Patil et al. 1996). The application of K at all the three concentrations tended to increase seed oil content and yield over the control (37.7–64.2 kg oil ha^{-1}), but was statistically significant only for 638 and 957 g K ha^{-1} concentrations on the seed oil content, and with K application at all the three concentrations on the oil yield ha^{-1} (Sawan et al. 2007b). The highest rate of K (957 g K ha^{-1}) showed the highest numerical values of seed oil content and oil yield ha^{-1} compared with the other two concentrations (319 and 638 g K ha^{-1}) (Sawan et al. 2007b). This could be attributed to the role of K in biochemical pathways in plants. Pettigrew (1999) stated that, the elevated carbohydrate concentrations remaining in source tissue, such as leaves, appear to be part of the overall effect of K deficiency in reducing the amount of photosynthate available for reproductive sinks and thereby producing changes in yield and quality found in cotton. Madraimov (1984) indicated that, increasing the rates of applied K_2O from 0 kg ha^{-1} to 150 kg ha^{-1} produced linear increases in cottonseed oil contents. Previously, favorable effects of K on seed oil content and oil yield were mentioned by Ibrahim et al. (2009). They reported that, increasing K supply to maternal cotton plants increased crude fat content of seed. The application of mepiquat chloride resulted in an insignificant increase in seed oil content over that of the control (Sawan et al. 2007b). Also significantly increased the seed oil yield ha^{-1} compared with the untreated control (by 38.3 kg oil ha^{-1}). These results could be attributed to the increase of total photoassimilates (e.g. lipids) and the translocated assimilates to the sink as a result of applying mepiquat chloride (Fan et al. 1999). This result agreed with those obtained by Mekki and El-Kholy (1999) in rape.

Seed Protein Content and Yield

High N-rate significantly increased the seed protein content and yields (58.0 kg protein ha^{-1}) (Table 15) (Sawan et al. 2007b). Stitt (1999) indicated that, nitrate (NO_3^-) induces genes involved in different aspects of carbon metabolism, including the synthesis of organic acids used for amino acid synthesis. These results suggest that the highest N rate of the added N in this study compared with the lowest rate increases the amino acids synthesis in the leaves and this stimulate the accumulation of protein in the seed. The present results confirmed the findings of Patil et al. (1997). Averaged seed protein content tended to increase when applying 638 and 957 g K ha^{-1} compared with untreated control (0 g K ha^{-1}) (Sawan et al. 2007b). Applied K at all rates also, increased the protein yield numerically (40.2–66.4 kg protein ha^{-1}), resulting from an improvement in both seed yield and seed protein content. The increase in protein yield ha^{-1} was statistically significant when applying the 638 and 957 g K ha^{-1} concentrations. Best protein yield was obtained at the high K concentration (957 g K ha^{-1}) compared with the other two concentrations (319 and 638 g K ha^{-1}) (Sawan et al. 2007b). This could be attributed to the role of K in biochemical pathways in plants. Potassium has favorable effects on metabolism of nucleic acids and proteins (Bednarz and Oosterhuis 1999). These are manifested in metabolites formed in plant tissues, and directly influence the growth and

Table 16 Effect of N rate and foliar application of K and mepiquat chloride (MC) on seed oil properties[a]

Treatments	Refractive index	Acid value	Saponification value	Unsaponifiable matter (%)	Iodine value
N rate (kg ha^{-1})					
95.2	1.4684	0.1339	190.8	0.3762	128.9
142.8	1.4695	0.1313	189.7	0.3913	131.1
S.D.[b]	0.0011	0.0025	1.4	0.0178	3.3
K rate (g ha^{-1})					
0	1.4682	0.1352	190.8	0.3675	125.8
319	1.4689	0.1337	190.1	0.3825	130.3
638	1.4692	0.1315	190.3	0.3875	131.6
957	1.4694	0.1300	190.1	0.3975	132.4
S.D.[b]	0.0012	0.0021	1.5	0.0170	2.5
MC rate (g ha^{-1})					
0	1.4683	0.1331	190.6	0.3750	128.3
48 + 24	1.4696	0.1321	189.9	0.3925	131.7
S.D.[b]	0.0011	0.0028	1.6	0.0172	3.0

Sawan et al. (2007b)
[a] Mean data from a four replicate composites for the two seasons
[b] S.D. = standard deviation

development processes, thereby producing changes in yield and quality of cotton (Sawan et al. 2007b). These results were in agreement with those obtained by Ghourab et al. (2000) and Ibrahim et al. (2009). Seed protein content tended to increase numerically, while seed protein yield was significantly increased (42.3 kg protein ha^{-1}) in plants treated with mepiquat chloride as compared with the untreated plants. The increase in seed protein content and yield may be caused by the role of mepiquat chloride in protein synthesis, encouraging the conversion of amino acids into protein (Wang and Chen 1984) along with the favorable and significant effect of mepiquat chloride on cottonseed yield. These results were confirmed by Abdel-Al et al. (1986).

Seed Oil Properties

The seed oil refractive index, unsaponifiable matter and iodine value tended to increase, while the oil saponification and acid values tended to decrease by raising N-rate (Table 16) (Sawan et al. 2007b). Narang et al. (1993) indicated that, N application increased the oil-quality index (iodine number) in rape. The application of K at different concentrations tended to increase the seed oil refractive index, unsaponifiable matter and iodine value, and to decrease the oil saponification value and acid value, numerically, compared with the untreated control, especially when applied K at the high concentration (957 g K ha^{-1}) (Sawan et al. 2007b). The effect was significant for the two concentrations 638 and 957 g K ha^{-1} on acid value, and

Table 17 Effect of N rate and foliar application of K and mepiquat chloride (MC) on the relative percentage of saturated fatty acids[a]

	Relative % of saturated fatty acids					
Treatments	Capric	Lauric	Myristic	Palmitic	Stearic	Total
N rate (kg ha^{-1})						
95.2	0.068	0.068	0.691	21.77	2.157	24.753
142.8	0.069	0.067	0.645	20.18	2.969	22.934
S.D.[c]	0.009	0.006	0.451	1.44	0.470	2.283
K rate (g ha^{-1})						
0	0.077	0.074	1.307	22.40	2.602	26.467
319	0.072	0.070	0.675	21.02	1.955	23.792
638	0.065	0.063	0.350	20.52	1.905	22.903
957	0.061	0.062	0.340	19.96	1.790	22.212
S.D.[c]	0.006	0.004	0.180	1.47	0.369	1.925
MC rate (g ha^{-1})						
0	0.074	0.065	0.775	21.97	2.336	25.221
48+24	0.064	0.069	0.561	19.98	1.790	22.465
S.D.[c]	0.007	0.006	0.437	1.29	0.382	1.998

Sawan et al. (2007b)

[a] Mean data from a four replicate composite for the two seasons

[b] TU/TS ratio = (total unsaturated fatty acids)/(total saturated fatty acids)

[c] S.D. = standard deviation

unsaponifiable matter, and for all different concentrations on iodine value. The effect of K concentrations on oil refractive index was very limited (Sawan et al. 2007b). Potassium is an essential nutrient and an integral component of several important compounds in plant cells. This attributed to the role of K in biochemical pathways in plants, where K acts as an activator for several enzymes involved in carbohydrates metabolism (Taiz and Zeiger 1991). These may be reflected in distinct changes in seed oil quality (Sawan et al. 2007b). Mekki et al. (1999) stated that, foliar application with K (0 or 3.5% K_2O) on sunflower at the seed-filling stage, decreased oil acid value. Froment et al. (2000), when working with linseed found that, the iodine value, which indicates the degree of unsaturation of the final oil, was highest in treatment receiving extra K. The application of mepiquat chloride tended to significantly increase the oil refractive index, unsaponifiable matter and iodine value, while it tended to insignificantly decrease the oil acid value and saponification value, compared with the untreated control (Sawan et al. 2007b). The application of plant growth regulators, particularly growth retardants may maintain internal hormonal balance, and efficient sink source relationship (Singh et al. 1987). This may be reflected in distinct changes in seed oil quality.

Oil Fatty Acids Composition

Saturated fatty acids in oil, lauric, myristic, palmitic and their total decreased, while capric and stearic increased by raising the N-rate (Table 17) (Sawan et al. 2007b).

Table 18 Effect of N rate and foliar application of K and mepiquat chloride (MC) on the relative percentage of unsaturated fatty acids[a]

Treatments	Relative % of unsaturated fatty acids			
	Oleic	Linoleic	Total	TU/TS [b] ratio
N rate (kg ha^{-1})				
95.2	21.59	53.65	75.24	3.069
142.8	22.99	54.08	77.06	3.397
S.D.[c]	1.35	1.14	2.28	0.403
K rate (g ha^{-1})				
0	21.26	52.26	73.53	2.790
319	22.11	54.10	76.20	3.228
638	22.60	54.50	77.09	3.390
957	23.18	54.60	77.78	3.523
S.D.[c]	1.37	0.63	1.92	0.351
MC rate (g ha^{-1})				
0	21.27	53.51	74.77	2.974
48+24	23.31	54.22	77.53	3.451
S.D.[c]	1.09	1.10	1.99	0.349

Sawan et al. (2007b)
[a] Mean data from a four replicate composite for the two seasons
[b] TU/TS ratio = (total unsaturated fatty acids)/(total saturated fatty acids)
[c] S.D. = standard deviation

The effect was significant only on palmitic acid, which was the dominant saturated fatty acid (Sawan et al. 2007b). A low content of saturated fatty acids is desirable for edible. The total unsaturated fatty acids (oleic and linoleic) and the ratio between total unsaturated fatty acids and total saturated fatty acids (TU/TS) were increased (by 2.42, and 10.69%, respectively) by raising N-rate (Table 18) (Sawan et al. 2007b). The effect was significant only on oleic acid. Linoleic acid was the most abundant unsaturated fatty acid (Sawan et al. 2007b). Holmes and Bennett (1979) commented that, the fatty acid composition of rape oil is mainly under genetic control, but can be modified to some extent by N nutrition. Seo et al. (1986) found that, when sesame was given 0–160 kg N, oleic acid content was highest at the highest N rates and linoleic acid content was highest at the intermediate rates. Khan et al. (1997) indicated that, oleic acid increased by increasing levels of N added to rapeseed-mustard. Kheir et al. (1991), in flax, found that the higher N-rate increased the percentage of unsaturated fatty acids and decreased saturated fatty acids in the seed oil. Potassium applied at all concentrations resulted in a decrease in the total saturated fatty acids (capric, lauric, myristic, palmitic and stearic) compared with the untreated control (Table 17) (Sawan et al. 2007b). Spraying plants with the high K concentration 957 g K ha^{-1} gave the lowest total saturated fatty acids oil, compared with the other two concentrations (638 and 957 g K ha^{-1}). The effect was significant for the two concentrations 638 and 957 g K ha^{-1} on capric, and palmitic, and for all different concentrations on lauric, myristic, stearic, and the total saturated fatty acids (Sawan et al. 2007b). Potassium applied at all rates increased the total unsaturated fatty acid (oleic and linoleic) and TU/TS ratio (by 1.84–4.48, and 15.70–26.27%, respectively), compared with untreated control (Table 18) (Sawan et al. 2007b). Applied K at 957 g ha^{-1} gave the highest increment, followed by 638 g ha^{-1} concentration (Sawan et al. 2007b). The effect was significant for all different concentrations on linoleic, the total unsaturated fatty acid and TU/TS ratio (Sawan et al. 2007b). Linoleic acid was the most abundant unsaturated fatty acid. The beneficial effect of applied K on TU and TU/TS ratio suggests that it might be due to the regulated effect of K which acts as an activator on many enzymic processes, where some of these enzymes may affect the seed oil content from these organic matters. Seo et al. (1986) found that, when sesame was given 0–180 kg K_2O, oleic acid content was the highest at the highest K rates and linoleic acid content was the highest at the intermediate rates. Salama (1987) indicated that, K fertilizer applied to sunflower, favored fatty acid composition (high oleic acid content). Mekki et al. (1999) stated that, foliar application with K on sunflower increased the oleic acid fatty acid. Froment et al. (2000) found that, linoleic acid content was greatest in linseed oil in treatments receiving extra K. The application of MC resulted in a decrease in the total saturated fatty acids, the abundant saturated fatty acid palmitic, capric, myristic, and stearic, while it resulted in an increase in lauric saturated fatty acid, compared to the untreated control (Table 17) (Sawan et al. 2007b). The effect was significant only on capric, palmitic, stearic and the total (Sawan et al. 2007b). The application of mepiquat chloride resulted in an increase in total unsaturated fatty acids (oleic and linoleic) and TU/TS ratio (by 3.69, and 16.69%, respectively), over the control (Table 18). The effect was significant only on the total unsaturated fatty acid, oleic and TU/TS ratio (Sawan et al. 2007b). The stimulatory residual effects of the application mepiquat chloride on TU and TU/TS ratio was probably due to its favorable effects on fundamental metabolic reactions in plant tissues, and would have direct impact through utilization on growth processes, which are reflected in distinct changes in seed oil quality (Sawan et al. 2007b). Some of these changes may affect the seed oil fatty acids composition, which may attribute to their encouraging effects on enzymes that catalyzed the biosynthesis of unsaturated fatty acids (Sawan et al. 2007b). Mekki and El-Kholy (1999) investigated the response of rape oilseed to 0, 200 or 400 ppm mepiquat chloride and found that; palmitic acid was only decreased by using 400 ppm mepiquat chloride as compared with 200-ppm treatment or control plants. A low content of saturated fatty acids is desirable for edible purposes. Also, regarding oil quality, higher levels of linoleic acid and oleic acid are considered good for oil quality (Downey and Rimmer 1993).

3.4.3 Conclusion

Application of N at the rate of 143 kg ha^{-1} and two applications of both K (foliar; at the rate of 957 g K ha^{-1}) and mepiquat chloride (at a rate of 48 + 24 g *a.i.* ha^{-1}, respectively) have the most beneficial effects among the treatments examined, affecting not only the seed quantity (to obtain higher oil and protein yields ha^{-1}) but also the oil seed quality (as indicated by better fatty acid profile in the oil of cotton) in comparison with the usual cultural practices adopted by Egyptian cotton procedures (Sawan et al. 2007b).

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