David Dent
Boris Boincean *Editors*

Regenerative Agriculture

What's Missing? What Do We Still Need to Know?

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Foreword: The Future of the Land, The Future of Farming

More than 25 years ago, I happened to be one to the editors of a large volume of papers presented at a conference which we gave the same title as the book: *The Future of the Land*. David Dent was one of the contributors. The focus was on land use planning but many of the issues raised there are still relevant today. Figures on land use are sometimes inaccurate and not detailed enough, environmental effects are difficult to measure over time and cannot be extrapolated easily, policies and governance are unclear, notwithstanding the need to unite all actors and disciplines. The conference took place at Wageningen University and Research, then as now an international centre for education and research with a long tradition in soil and crop science, as well as animal production, forestry, biodiversity and nutrition. When I look at *Wageningen* now, it strikes me how much we have grown in terms of interdisciplinarity and fundamental research, and international collaboration.

I take the liberty to indulge in this memory of a not-too-distant past to demonstrate both the continuity and the changes with respect to a past that is only a generation away. The book in your hands poses many of the questions that occupied us then. This is not because science has not made any progress in the last decades. On the contrary, the progress in our understanding has been immense, especially when it comes to the tools at our disposal such as big data, modelling and artificial intelligence. However, the similarity of today's and yesterday's questions emphasizes how tenacious and complex are the issues around land and its use. Indeed, comparing the two books shows how this new volume testifies to the growing depth of our understanding: interdisciplinarity and the coupling of fundamental and practical research are found in nearly every contribution. Above all, within the broad geographical spread, the powerful contribution of the East and South of Europe is a bonus.

Where do we stand, what is missing, what else do we need to know, the key sections in the book, are universal questions for all fields of science but they take on a special meaning here. This is a field that is so often forgotten. Food may have become a fashionable preoccupation of the middle classes everywhere: very rarely is this interest extended to the land and the landscapes where this food is grown. And if it is, then, as with food, misunderstandings abound. No, organic agriculture is not always the solution to improving soil quality but, then, nor is conventional agriculture.

Large scale agriculture is not always bad, nor is small scale always good. No, not all natural vegetation should be considered untouchable, nor are all species to be protected. Agriculture always means disturbing natural ecosystems and exploiting precious organic matter and nutrients. There is no free lunch and it is important to communicate the effects and nuances of human interventions to the public at large.

There is much to like in this book and, occasionally, to disagree with. But then, scientific understanding has always progressed through debate and the thorough review of facts and opinions. I do not concur with those authors who believe international trade has caused food shortages in general. Although there are certainly many unwanted consequences of international trade, such as workers' wages and factory safety and environmental costs, there is plenty of evidence that trade has led to lower food prices, higher food safety standards, and fewer severe supply fluctuations. In fact, the last serious price fluctuations, in 2008–2010 (too early to judge what the fall-out of the COVID-19 crisis will bring) were mostly due to export restrictions and protectionism by some of the big cereal producers. Agriculture and food for the world are best carried out in those areas where the conditions are optimal from a natural and economic point of view. What that means, particularly in terms of soils and land, is one of the themes of this book.

On biodiversity and the natural environment, too, it is important to examine the evidence. The most destructive form of agriculture, in terms of loss of topsoil, organic matter and vegetation is unfertilised annual cropping in the tropics. This is still a sizeable proportion of the cultivated area. It is undeniable that big farming, especially in the case of feckless use of chemicals, has had devastating effects on water, soil biodiversity, and air. However, it should not be forgotten that yield increases, i.e. the efficiency of land, water and input use, have freed up enormous areas of land that can be dedicated to the conservation of nature.

What has changed radically in recent decades is the emergence of new technologies such as drones, CRISPR-Cas9 gene editing, artificial intelligence and big data. What they bring, collectively, is a greater control of the environment and the plant or the animal. To be precise, they allow precision farming and precision breeding, even to the extent of bringing back, one day, the possibility of modern mixed farming and mixed cropping; and the better we are able to monitor the effects of our actions, the better we can control any negative side effects. We are now able to apply what we used to dream about: to fertilize the root zone of a single plant at the right moment in time, to close the cycles of nutrients and energy and, perhaps, even to fix enough carbon to counterbalance the emissions of greenhouse gases.

Last but not least, the key question that should worry us is: Who will be the farmers of the future? Clearly, young people everywhere aspire to something other than working the land for little money and little social status. The future must entail investments in mechanisation, increasing labour productivity, and fostering entrepreneurship. And, ultimately, the question is: Will the farms of the future still be land based? My short answer, and surely the subject for a tantalising new book: blue farming of algae and other species, plant proteins and vertical greenhouses in urban environments will all have their place but, in the end, when it comes to carbohydrates and much of our protein, the land will remain the foundation for our future.

As this rich volume shows, there is no future for mankind without care for the land (even on Mars, we will need to construct some equivalent of a soil). I think that David and Boris and their authors have done a remarkable job to show farming, soils, land and nature in all their diversity and similarity.

Amsterdam/Wageningen, The Netherlands Louise O. Fresco
April 2020

Introduction

The first lesson learnt by men and women in the field of rural development after the Second World War was that *it's not all the same out there.* We learned the hard way. Reliable knowledge of the land is indispensible. The second lesson, learned some thirty years later, was that it is not enough. Development turned out to be not so simple as we had thought: some of the goals now seem illusory, the constraints more intractable, the contribution of science disappointing in the absence of ways and means of using it (Young 2007).

The mantra of the Brundtland Report—*sustainable development* that 'meets the needs of the present without compromising the ability of future generations to meet their own needs' was an attempt to square the circle of poverty, land degradation and under-development. It blossomed alongside the *Green Revolution* and the expansion of trade after the fall of the Berlin Wall in 1989: Malthus was banished by tripling the yields of the main food crops, and spending power came to far-flung parts of the world. The Green Revolution came with high-yielding crop varieties, cheap power and fertilizers, potent pesticides, and expansion of irrigation. These industrial inputs are no longer cheap and the system expends more energy than it produces. Unknowingly, industrialised agriculture is flaring off soil organic matter—the energy supply of life in the soil that breaks down wastes and toxins, regenerates plant nutrients, combats pests and diseases, and maintains the pore space that allows infiltration of rainfall, water supply to plants, and drainage to streams and groundwater. And mineralisation of soil organic matter is a major source of the greenhouse gases. Things cannot go on like this; sustainability demands that agriculture observes Hippocrates' dictum: *At least, do no harm.*

For the time being, we are growing more than enough food. It is unequally distributed but international trade means that shortages are not an issue of supply but an issue of inaccessibility—from combinations of poverty, war, displacement of peoples, and bad governance. But markets offer no protection to the weak, nor to resources that have no market value like air, water and biodiversity—so environmental trends continue to deteriorate alarmingly (UNEP 2007, FAO 2018, IPCC 2019). If water quality had a price tag, then no chemical waste would be dumped in rivers, no fertilizers would leach to streams, groundwater and the dead zones of shallow seas. If the air had a price on its head, factory chimneys, power stations and exhaust pipes would pump out a no poison. If emission of greenhouse gases was costed, we should be well on the path to bring it into line with the sink capacity of plants and soils. And what is the price of biodiversity?

Our title *Regenerative Agriculture* does not refer to any particular alternative farming system. We simply mean farming that is both productive and sustainable; farming that does no harm but, more than that, farming that rebuilds soils, landscapes and communities. It is within reach. This symposium demonstrates that many of the ideas we need are already out there; farmers and researchers will always come up with more good ideas but we need to bring them together and different times and places need different combinations. But whereas governments and big business can act effectively because they can invest and bear the risks but it is harder for smallholders who barely keep their heads above water—and few ways of farming are as destructive as small-scale cultivation of annual crops in the tropics. Moreover, the existence of sustainable practices doesn't banish human error, ignorance, corruption, short-sighted policies, and unscrupulous profiteering.

At an earlier fork in the road, John F. Kennedy's Commencement Address at the American University, (1963) helped rescue the world from a path of self-destruction. He argued that we can translate the *will for peace* into achievable goals and, so, progress step-by-step. Within a few weeks, the limited test ban treaty was negotiated and the course of history changed. Louise Fresco (2016) reminds us that, in the same way, we can translate the *will for sustainability* into achievable steps towards sustainability, for instance:

- Make production processes more efficient by using less raw materials and energy per unit of production, e.g. using less fertilizer by better placement and timing
- Find alternatives to non-renewable inputs like fossil fuels and their derivatives, e.g. substitute biological nitrogen and biological pest controls for chemicals
- Re-use raw materials—close the cycles so that outputs become inputs: e.g. crop residues become mulch or stock feed, then manure or bio-fuels, then a source of soil organic matter
- Zero tillage
- Perennial grains and legumes to replace annuals
- Land use planning: plants and products for places, produce where there is a competitive advantage, at the same time avoid unnecessary transport. So tropical fruits are best grown in the tropics, perennial vegetation to capture carbon in places where it is always warm and wet, and the steeper the slope, the more complete the ground cover.

These were amongst the topics of the symposium in Bălţi on 30 November/1 December 2019 under the banner of *Farming Forever*. We have arranged the proceedings in four parts. Part I, *Where We Stand*, scans some overarching issues of politics and economics. Farmers find themselves between the tyranny of farm gate prices, highlighted by Tony Allan and David Dent in *The cost of food*, and the menace of global heating underscored by Lennart Olsson in *Politics of soils and agriculture in a warming world*. Far from being an actively managed carbon sink, agriculture is responsible for one third of global emissions, and land degradation is compounded by exploitation of water resources and mass extinction of species. The price of food is not the cost of food because the damage done along the way is not accounted for, so producers are subsidizing consumers and exporting countries are subsidizing importers. Things cannot go on like this. If farmers are to be good stewards of the land, the price of food must go up or farmers have to be paid for environmental services. Either way, Society must take more responsibility for its food, water, and environment.

Part II, *Known Knowns*, embraces the community of practice known as Conservation Agriculture (CA), born out of necessity and adopted across 15% of global cropland. It is no less productive than industrial agriculture and, at least, it does no harm. In *Carbon management in Conservation Agriculture systems*, Don Reicosky underscores the significance of replacing the dominant agricultural system that depends on intensive application of industrial inputs by one that makes a better fist of carbon management. In *Resilient cropping systems in a Mediterranean climate*, Johann Strauss provides a South African perspective facing acute water scarcity, where cereal monocropping loses three tons of soil per ton of grain produced. He emphasises the need for simultaneous adoption of the three principles of CA—zero tillage, continuous ground cover and crop rotation—against a backdrop where 40% of his farmers follow at least one of these practices but only 14% adhere to all three. Indeed, drylands everywhere present hard-to-handle problems illustrated by Lazizakhon Gafurova and Mukhiddin Juliev in Central Asia; the catastrophe of the Aral Sea is a stark warning of the irreversible changes brought about by reckless exploitation of land and water resources.

Luca Montanarella, Panos Panagos and Simone Scarpa consider *The relevance of Black Soils for sustainable development,* the significance of *Chernozem, Kastanozem* and *Phaeozem* to global food security as well as in achieving the UN Sustainable Development Goals. This theme is taken up by Rattan Lal in *Managing Chernozem for reducing global warming*. Rattan flags the opportunity for a win:win situation by restoring the natural fertility of Chernozem, thereby achieving agronomic, economic, environmental and societal benefits, not least mitigating and adaptating to climate change.

But science is not enough. Pragmatic, far-sighted policies are needed to put science to work. In *Climate change policy for agriculture offsets in Alberta, Canada*, Tom Goddard provides a practical example. In 2002, Alberta decided to go-it-alone with its climate change policy and, in 2007, promulgated an Act of Parliament requiring big emitters of greenhouse gases to cut their emissions or, either, pay cash-down or purchase carbon offsets, thereby creating a carbon market. Since then, no-till farmers have supplied the market with 14 million tons of carbon offsets valued at 143 million euro. Public procurement can be another lever for change. Kathryn Wilson's contribution illustrates the health and social benefits of cooperation between local producers and consumers, not least the empowerment of rural communities. This power has not been used overtly to leverage changes to the farming system, but the power is there.

In Part III: *What's Missing?* We examine what more is needed to create truly regenerative agriculture that rebuilds soils, rural economies and Society. Timothy Crews argues that *Diverse perennial vegetation is missing.* By replacing diverse perennial vegetation with just a handful of domesticated species, we have come to depend on a poorly-functioning ecosystem that is vulnerable to pests and diseases, and loses organic matter, nutrients and soil in spades. Perennial grains could be the vaccine to protect the food system from its own pandemic. We now have the capacity to re-invent grain growing to resemble the structure and function of natural ecosystems and, thereby, greatly improve the sustainability of agriculture and our own prospects. Tim is followed by a phalanx of contributors who draw on long-term field experiments to show how to make better use of the domesticated species we already have. Sergei Lukin and Vladislav Minin identify *A biological way to intensify agriculture* and improve the fertility of *Sod-podzolic soils* of the Central and North-Western regions of Russia through increasing the share of legumes in crop rotations and the use of organic fertilizers, green manure and microbiological drugs. *The LOME concept* (**L**egumes **O**il seeds, **Me**thanation) introduced by Eugene Triboi and Anne-Marie Triboi-Blondel offers a future agriculture based on self-sufficiency in nitrogen from symbiotic fixation by legumes and energy from methanation of green biomass and crop residues. The nutrient cycle is closed by returning the biogas digestate to the soil and, with it, a good portion of the captured carbon. Boris Boincean, Marin Cebotari and Lidia Bulat reinforce this message with *Diversity of crops in rotations: a key factor in soil health and crop yields.* Long-term field experiments on *Typical Chernozem* demonstrate that the effect of crop rotation is significantly greater than the effect of fertilization, although the effect of fertilization is greater in continuous mono-cropping than in rotations because of poor soil health; diverse crop rotations cut dependence on industrial inputs, grow better crops, and provide better ecosystem services. Following up, Boris and his colleagues analyse the economic *Performance of crops in rotations under mineral and organic fertilization.* Generally, even low rates of mineral fertilizers don't repay their cost with extra yields and there is no financial advantage in supplementing a base dressing of manure with synthetic fertilizers, at least not on *Chernozem.*

Direct drilling saves about 60% of farm fuel and labour costs but it's not suitable for compacted soils. Valerian Cerbari and Tamara Leah report on *Preventative restoration of Ordinary Chernozem before implementing zero tillage* by deep cultivation followed by sequential green manure crops. *Step-by-step along the path to sustainability* by Hans Ramseier and his colleagues describes integrated farming systems with a range of sustainable management practices: organic farming, cover crops, intercropping, under-sowing and green manures. They also appeal to consumers to adapt their eating habits and to pay the proper price for food, and to governments to create supportive policy and legal frameworks.

Several contributors raise the need for standards as a management tool: Tony Allan and David Dent noted the emergence of Bcorp certification of companies that demonstrate high standards of social and environmental performance; Luca Montanarella and his colleagues urge legislation, perhaps a re-launch of the abandoned EC Soils

Directive; but, as yet, only where there is an acute hazard to public health are standards enforced by legislation—as outlined by Sviatoslav Baliuk, Marina Zakharova and Ludmila Vorotynteva in *Standards for heavy-metal contamination of irrigated land in Ukraine.* Several authors also argue for payments for environmental services. This would require farmers to demonstrate good stewardship by delivering public goods, for instance by such as arresting soil erosion, abating floods and mitigating global heating; discerning consumers also seek guarantees that are not met by prices or labelling. In *Giving credit where credit's due*, David Dent proposes a tangible Standard for Soil Health that matches the condition of the soil with its potential capacity to grow crops and deliver environmental services. The criteria are ground cover, biological status represented by soil organic matter, and physical status represented by bulk density; these yardsticks also reveal trends, so credit may be given for good management as well as for inherent soil quality.

Two recent developments that link what's missing with what we need to know are, unfortunately, missing from this volume: in-depth treatment of agroforestry which has emerged from a field of research to large-scale practical application, for instance in the transformation of big cattle stations in tropical Queensland by *Leucaena* hedgerows (Shelton and Dalzell 2007, Conrad and others 2018); and the System of Rice Intensification where rice is grown as a dryland crop (Uphoff 2015).

Part IV, *What Else Do We Need to Know? Pesticides, insects and birds on conventional and organic cattle farms in the Netherlands* by Jelmer Buijs and Margriet Mantingh come into the category of unknown unknowns. In spite of protection measures, the population of meadow birds has plummeted. Micro-analysis of samples of concentrated feed, manure and soil from conventional and organic stock farms reveals ecologically significant concentrations of 134 different fungicides, herbicides, insecticides and biocides. No sample was free of pesticides. On average, there was less pesticide residue in organic concentrated feed than in conventionally produced concentrates but there was little difference between conventional and organic farms in levels of pesticides in the soil and manure. This is the more troubling because the combined effects of all these substances and their cumulative effects on the ecosystem are unknown; the dose-time-dependent effects of the action of most pesticides are unknown; and the majority of the pesticide metabolites are unknown—so could not be measured. The obvious conclusion is that wild bird populations cannot be maintained because their insect food has been poisoned—*vide* the almost complete absence of dung beetles on Dutch cow pats. The implications go beyond the sustainability of organic farms.

Considering just the nitrogen cycle, agricultural soils are a source of concern—directly affecting the air we breathe, the water we drink, the food we eat, UV radiation that we are exposed to, biodiversity and the environment all around us. Conventional wisdom has it that farmland releases a lot of reactive nitrogen and greenhouse gases, especially farmland getting big inputs of nitrogen fertilizer. But in-situ measurements of *Fluxes of reactive nitrogen and greenhouse gases from arable land in south-western Ukraine* by Sergiy Medinets and colleagues prove them to be a modest source of N_2O, far below the levels suggested by IPCC. Moreover, under winter crops with low N-fertilizer application, they are a sink for CH_4 and NH_3.

Weeds are an issue whether or not herbicides are available but crop rotation can be an effective control measure. Gheorghe Sin and Elena Partal in *Long-term effects of crop rotation and fertilization on weed infestation in winter wheat* find the greatest infestation in continuous wheat and the least in diverse crop rotations; the greater the number of different crops in the rotation, the fewer the weeds. Alternation of different crops—each with its own practices of tillage, fertilization, weed and pest control, time of sowing and harvesting—disturbs the life cycle and proliferation of weeds.

Since the early 19th century, plant breeders have sought to create robust new varieties to cope with our changing world and keep pace with the evolution of pests and diseases. In *Phenotyping of wheat in heat-and- drought-stressed environments*, Karolin Kunz and her colleagues investigate pre-adaptation of existing wheat varieties for future breeding programs in a large-scale experiment on the steppes. Unsurprisingly, local varieties performed much better under steppe conditions than lines and hybrids from western Europe and, yet, hundreds of thousands of landraces of every major crop species have been lost during the Green Revolution. As we write, our host institution in Bălţi faces termination of sixty years of crop breeding for lack of funding but, on the bright side and in the best traditions of Vavilov, Sulukhan Temirbekova and her colleagues report on *New safflower oil crops in Russia: agronomy and adaptability* not only to produce high-value edible oil but, also, as cover crop and green manure.

In *Agronomic benefits of perennial crops and farmyard manure in crop rotations*, Boincean and his colleagues point out big savings in the costs of fertilizers, pesticides and tillage, quite apart from better soil health. Long experience has also shown that winter cereals yield much better after early-harvested predecessors compared with late-harvested predecessors but, in *No-till for cereal crops on the Bălţi steppe of Moldova*, Dorin Cebanu and his colleagues find that, under no-till, yields are not diminished by late-harvested predecessors. This is attributed to greater stocks of soil water accumulated during the autumn-winter period under the combination of no-till and a mulch of crop residues. Boincean and colleagues also scrutinize *Long-term irrigation and fertilization of Typical Chernozem.* They find that, under irrigation, the annual loss of soil organic matter by mineralization can't be compensated, even under a crop rotation with 50% of perennial legumes with application of 13.3 t/ha of farmyard manure. Accelerated loss of humus is also reported by Yaroslav Bilanchin and colleagues in *Post-irrigation state of Black Soils in South-Western Ukraine*, as well as increases in carbonates and sodicity after cessation of irrigation. In the third of our irrigation troika, Oksana Tsurkan and colleagues report on the local *Effects of drip irrigation on the composition and fertility of Black Soils in Odesa Region.*

Soil erosion is a scourge. Sergiy Chornyy and Oleg Pismenny give a timely reminder in *Verification of the Wind Erosion Equation on the Ukrainian Steppe* as a basis for the design of anti-deflationary measures. CA may be the best way to arrest it but CA isn't practised over 85% of the world's arable and global exposure is well illustrated by the continental maps presented earlier by Montanarella, Panagos and Scarpa. Networks of shelter belts were one of the earliest and most successful soil conservation measures. They still are, and in *Promoting agroforestry* *within the Agricultural Competitiveness Project in Moldova*, Ion Talmaci and his colleagues illustrate the benefits of shelterbelts for increasing the competitiveness of farms through soil protection, carbon capture in soils and biomass, and increased biodiversity in the landscape.

And finally, farmers are responsible for one third of greenhouse gas emissions and there is no plan to deal with this. Their impact on land and water resources, floods, droughts, and the global extinction of species also cries out for attention. Unprecedented action is needed to achieve transition to sustainability by 2030. David Dent and Boris Boincean make *An investable proposal for regenerative agriculture across the Steppes*. It is firmly based on 35 years of satellite observation, long-term field experiments, and proven technology. It just needs to be done. That is what politicians are for. Don't think small—it is futile. Think how big it could be—and double it!

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Contents

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Part IV What Else Do We Need to Know?

Part I
Where We Stand

Here I stand, I can do no other. God help me.

Martin Luther 1521

Chapter 1
The Cost of Food: Consequences of Not Valuing Soil and Water and the People Who Manage Them

Tony Allan and David Dent

Abstract Affordable food is a political imperative. There is nothing more expensive: the food system delivers cheap food, but it takes no account of the damage done along the way. It operates in three modes. In *Mode 1*, farmers manage land and water to produce crops and livestock. Incidentally, they manage the landscape and carbon capture from the atmosphere by crops and its conversion to soil organic matter. Soil organic matter matters: it fuels the world of the soil that breaks down wastes and toxins, regenerates crop nutrients and controls pests and diseases; it maintains soil structure that enables infiltration and storage of rainfall; and it holds more carbon than the atmosphere and all standing vegetation put together. If these services are considered at all, they're taken for granted. Nowadays, Mode 1 accounts for only one-tenth of the value added in the food system; farm-gate prices have been driven down relentlessly so farms have had to get bigger or get out. Production certainly benefits from economies of scale and the gifts of technology: ever-more-powerful machines, new crop varieties, fertilisers, pesticides, irrigation—but these gifts exact a cost by exposing topsoil to the elements, turning it upside down with every pass of the plough and raiding soil organic matter. So, more power and more chemicals are needed; soil erosion, floods and droughts are exacerbated; groundwater isn't recharged; and agriculture burns up more energy than it harvests. None of this is accounted in the cost of food but, over millennia, agriculture has amassed rights and vested interests that have resisted reforms that could take these costs into account. In the *second mode*, food is traded, processed and retailed; these activities now account for most of the value added in the food system. Comprehensive legal foundations and accounting rules that have been impossible to install in primary production have proven politically feasible in trade, processing and retail. In the *third mode*, food consumption, public policy again overrides the market to enable poor people to get food that is still too costly for them. The system is unsustainable—ecologically,

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environmentally and economically. It will only be sustainable economically if the power relations across the food system can be redressed; if consumers paid the costs of maintaining environmental services, farmers in a viable commercial system might be able to remedy some of the ecological ills.

Keywords Food system · Political economy · Sustainability · Market failure · Environmental services

Food-Water, Soil and Society: Competing Claims and Their Consequences

The Food System is a Political Economy, Not an Economy

Most people assume that the food system is an efficient, seamless conveyor of affordable food from farm to fork. Not so. It does deliver cheap food but takes no account of the damage done along the way. On top of the legacy of the previous 40 centuries, twenty per cent of the land has been degraded in the last quarter century (Bai et al. 2015), and agriculture consumes 92% of all the water we use. IPCC (2019) estimates that land use generates 23% of manmade greenhouse gas emissions—but this is just from above ground; if we take account of the loss of soil organic matter, one-third of emissions is nearer the mark. Food supply chains are at risk, and there is no certainty that they will be able to meet future needs. Julian of Norwich affirmed: ‘All shall be well, and all shall be well, and all manner of thing shall be well’ (Serranus de Cressy 1670). And politicians of all stripes promote this reassuring myth—just imagine what would happen if people were to think there won’t be food on the shelves next week!

The system is unsustainable: first, because farmers are trashing soil and water resources—whether knowingly or not. Secondly, it’s a secure market system only so long as governments are willing and able to fund public subsidies—to farmers at the beginning of the supply chain, and at the end of the chain to enable the employed and unemployed poor to obtain food that is, otherwise, still too costly. Food prices are misleading: farm-gate prices don’t include all the costs of farm labour; they certainly don’t reflect the environmental costs of mining the soil and polluting water resources, of floods and droughts, or the climate crisis. So, growers subsidise consumers and exporting countries subsidise importers that receive this food at much less than its real cost.

The political economy of the food system is a composite of three quite different modes (Allan 2019). In the first, which has been operating for more than 4000 years, there are no effective accounting rules. The political imperative—*affordable food*—has imposed a system in which farmers deliver food at well below its real cost. The financial difference is made up by farm subsidies but, as we explain, these come nowhere near the real cost. In Mode 2, food is traded, processed and delivered to consumers in an effective market where profits are made and taxes paid. Shelf prices do capture most of the costs of inputs beyond the farm gate but not the enormous public health costs of poor diet. In Mode 3, where food is consumed, governments have to intervene again to ensure access to food that may still not affordable.

Ghettos of the Mind

For centuries, farmers and Society lived with volatile food prices. In England, prices fluctuated wildly but progressively increased until the repeal of the Corn Laws, in 1846 (Fig. 1.1). This was a decisive shift from a protected market to a version of free trade that has driven down the international floor price ever since (Fig. 1.2). This is remarkable when, over the same period, the demand for food has grown by an order of magnitude.

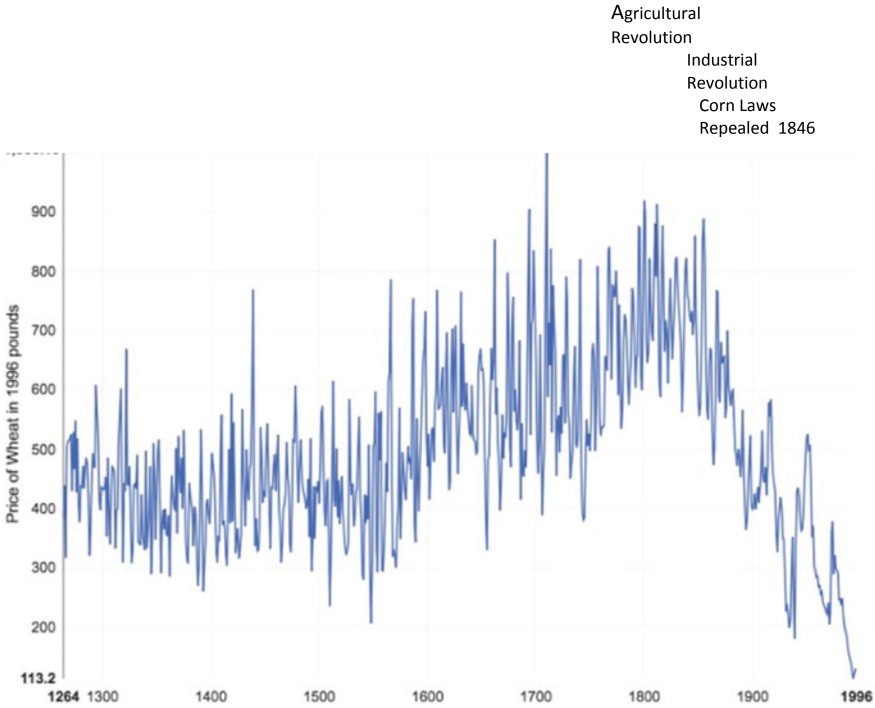
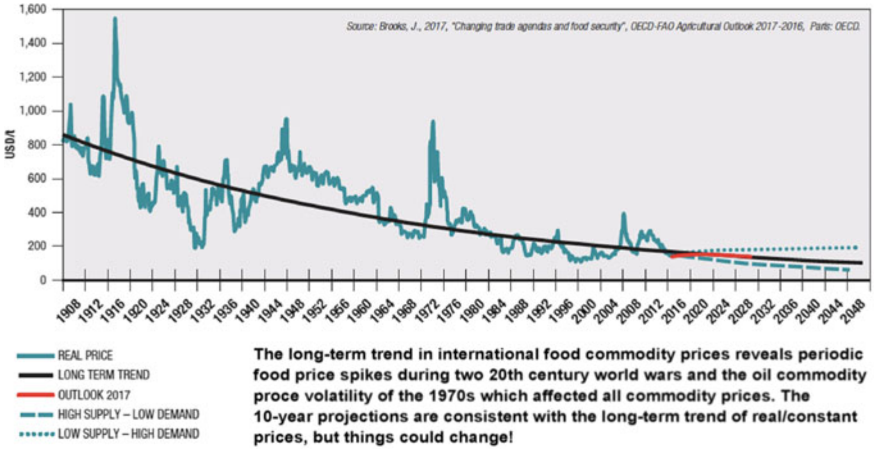


Fig. 1.1 Wheat prices 1264–1998 in constant 1996 UK pounds (Rosner 1997)



Source: Brooks, J., 2017, "Changing trade agendas and food security", OECD-FAO Agricultural Outlook 2017-2016, Paris: OECD.

The long-term trend in international food commodity prices reveals periodic food price spikes during two 20th century world wars and the oil commodity proce volatility of the 1970s which affected all commodity prices. The 10-year projections are consistent with the long-term trend of real/constant prices, but things could change!

Fig. 1.2 Long-term trends and projections of international food prices (Brooks 2017)

The Profound Effects of Mode 1 Markets on Farmers

Comparing the distribution of profits between three sectors of the food system in the USA—the farm sector, manufacture of the means of production (machinery, fertilisers, etc.), and the market sector that connects producers and consumers—the share of profits accruing to the farm sector shrank from 41% in 1910 to 9% in 1990, the industrial sector increased its share from 15 to 24%, the market sector increased its share from 44 to 67% (Smith 1991). In OECD countries, the market sector now accounts for 90% of the value added in the food system and, by 2008, the share of the farm sector had shrunk to only 3% (Eurostat 2009).

Farmers are price-takers, not the price setters, so farms must get bigger or go out of business. Untold millions of small farms have gone bankrupt. Big farms have got bigger but have shed labour and adopted simplified farming systems that depend on ever-more-powerful machinery, more potent pesticides and fertilisers, smarter irrigation, and new crop varieties that take advantage of the technology. Farmers are trapped in a system that forces them to rely on costly inputs promoted by powerful purveyors. They are struggling for survival; they believe they are under siege; this is a lethal ghetto of the mind, revealed by the extraordinary suicide rate across the farming community (Weingarten 2017; USDA 2017). Meanwhile, the environmental services they render are unrecognised and unrewarded. Sustainability needs nothing short of a revolution. Only farmers can deliver it—but it's hard to be green when you're in the red.

The Second Ghetto: Weakness of Regulation and Absence of Accounting Rules

Much has changed over four millennia but production and supply of food is still driven by *who owns what, who does what, who gets what, and what they do with it*. Ownership and access to fertile land are eternally contested; there has never been any shortage of laws but, even in good times, there are disputes about private rights *v* communal rights, private *v* public interests, water rights tied to land rights… Now, as we push against planetary boundaries (Rockström et al. 2009), we have been caught off-guard by the absence of any legal protection, or effective accounting rules that capture the value of environmental services like the supply of fresh water—on which food security depends; or carbon capture—on which the stability of climate depends. Water has never been valued or accounted for in Mode 1 markets; carbon capture has hardly been valued or accounted anywhere.

The Third Ghetto: Complacency

This mindset has become firmly embedded as consumers have become distanced from the risks faced by farmers, and the stewardship needed to maintain essential services is taken for granted. In the absence of effective accounting and regulation, consumers are blithely unaware that their choices are destroying the ecosystems on which food and water security depend. Legislators are unwilling to break out of these ghettos: the unwritten contract that governments have struck with Society is that everyone is entitled to affordable food. The outcome is a political economy kept in place by direct payments to farmers and to consumers. Mobilising these payments is politically feasible: the politics of legislating for effective accounting rules that would reveal and capture the costs to the environment and the price of stewardship are not feasible—at present, without radical change. Unfortunately, these legislative and accounting measures are prerequisites of reforms that would create effective Mode 1 markets and attract urgently needed investment. Radical change calls for a shift in power relations between Mode 1 and Mode 2, and Society needs to give legislators the political space that frees them from their own ghetto of the mind—walled in by the imperative of delivering cheap food.

Discord: How We Produce Food Confronts the Ghettos of the Mind

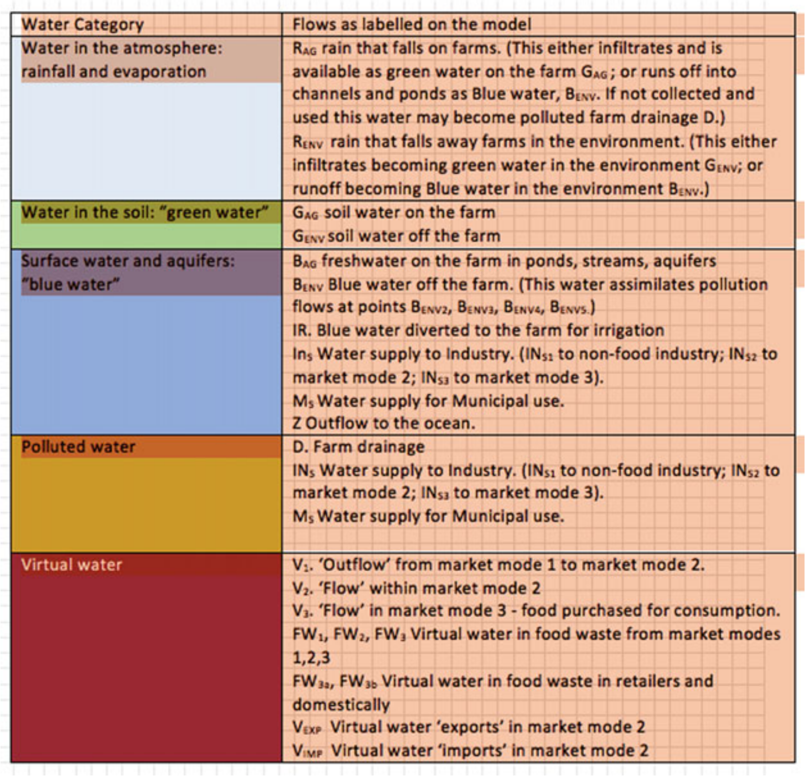
Growing crops the way we do trashes the land (Crews et al. 2018). Every year, we root them out, turn the soil upside down and start again. Bare soil invites invasion by weeds. Rain splash turns bare soil into mud—mud that clogs the pores so that rainwater ponds or runs off the surface carrying the soil with it. When the rain stops, the pulverised surface sets as a crust that yields immediate runoff from the next rainstorm. Bare soil bakes in the sun—so do earthworms and myriad smaller creatures that should be maintaining soil permeability. And bare soil is carried off by the wind—three quarters of the topsoil and three and a half million people and left the Dust Bowl of the American Plains States in the 1930s. None of this is accounted in the price of food.

Arable farming is not as productive as natural vegetation, crops are carried off, and separation of crops and livestock has cut the supply of manure—so farming is running down soil organic matter. This matters because soil organic matter is a bigger carbon pool than the atmosphere and all the standing vegetation put together (IPCC 2010). It is a brake on global heating; it is a bank of plant nutrients and fuel for soil life that cycles nutrients, disposes of wastes and toxins and controls weeds, pests and diseases; and it stabilises the architecture of the pore space that receives rainfall, releases water to plant roots and drains any surplus to streams and groundwater. So, agriculture exacerbates droughts and floods, burns up more energy than it harvests and emits clouds of greenhouse gases. None of this is accounted for in the cost of food. Sooner or later, a tipping point is reached when the soil itself leaves the stage. Then it's too late to keep better accounts.

Food production accounts for more than 90% of the water consumed in the food chain (Mekonnen and Hoekstra 2011). But only a little of this water is used to make new plant material; most of it is transpired back to the atmosphere—the more green leaves, the more transpiration. Let us call this *green water*. Runoff and water entering the soil over-and-above its water-holding capacity drains to streams and groundwater. Let us call this *blue water*. The distinction is important: green water makes up two-thirds of all fresh water, but blue water gets all the attention because it can be tapped for many other uses. Setting aside water locked up in ice caps and glaciers, all fresh water is delivered by the soil. There are two critical junctures: the first when rain hits the ground, where it may infiltrate or run off carrying the soil with it; the second in the soil itself—soil water may evaporate from a bare surface, be taken up by roots or drain to streams and groundwater. Both junctures are managed by farmers. Rainfed farming cannot use last year's rain, or anticipate next year's, but irrigators can draw on groundwater stored over centuries; they consume 70% of water withdrawn from streams and aquifers but this is hardly ever regulated—groundwater is overdrawn wherever irrigation is practised, with the exception of Israel (Wada et al. 2012; Perry 2019).

Figure 1.3 depicts how water flows through the food system from the farm to the consumer. Our analytical framework introduces a further abstraction beyond green and blue water, to consider the water embedded in commodities as it moves along the food chain, commonly to the other side of the world. Let us call this *virtual water*.

Compared with the water consumed on farms, the flows of real water consumed in Modes 2 and 3 are negligible. Modes 2 and 3 pay for their blue water but pay nothing for the unaccounted virtual water embedded in the commodities they deal in. This raises a question about the international food trade (Fig. 1.4). *Food exporters are exporting their environment*. Is this good news? And for whom?



Water Category	Flows as labelled on the model
Water in the atmosphere: rainfall and evaporation	R_{AG} rain that falls on farms. (This either infiltrates and is available as green water on the farm G_{AG} ; or runs off into channels and ponds as Blue water, B_{ENV}. If not collected and used this water may become polluted farm drainage D.) R_{ENV} rain that falls away farms in the environment. (This either infiltrates becoming green water in the environment G_{ENV}; or runoff becoming Blue water in the environment B_{ENV}.)
Water in the soil: "green water"	G_{AG} soil water on the farm G_{ENV} soil water off the farm
Surface water and aquifers: "blue water"	B_{AG} freshwater on the farm in ponds, streams, aquifers B_{ENV} Blue water off the farm. (This water assimilates pollution flows at points B_{ENV2}, B_{ENV3}, B_{ENV4}, B_{ENV5}.) IR. Blue water diverted to the farm for irrigation In_S Water supply to Industry. (IN_{S1} to non-food industry; IN_{S2} to market mode 2; IN_{S3} to market mode 3). M_S Water supply for Municipal use. Z Outflow to the ocean.
Polluted water	D. Farm drainage IN_S Water supply to Industry. (IN_{S1} to non-food industry; IN_{S2} to market mode 2; IN_{S3} to market mode 3). M_S Water supply for Municipal use.
Virtual water	V_1. 'Outflow' from market mode 1 to market mode 2. V_2. 'Flow' within market mode 2 V_3. 'Flow' in market mode 3 - food purchased for consumption. FW_1, FW_2, FW_3 Virtual water in food waste from market modes 1,2,3 FW_{3a}, FW_{3b} Virtual water in food waste in retailers and domestically V_{EXP} Virtual water 'exports' in market mode 2 V_{IMP} Virtual water 'imports' in market mode 2

Fig. 1.3 Green, blue, brown and virtual water flows in the three market modes of the food system (Allan 2019)

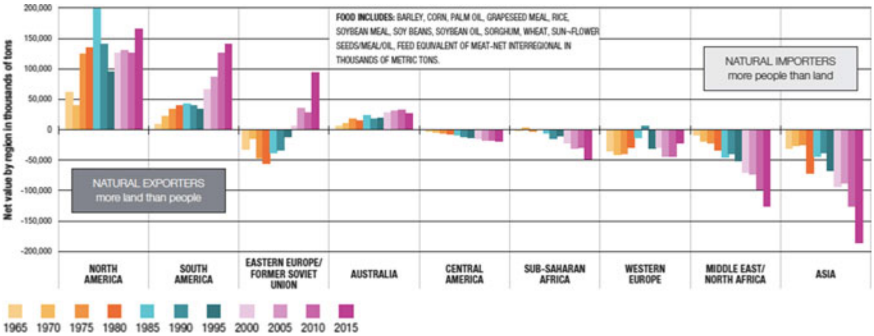


Fig. 1.4 Global trade in major food commodities 1965–2015 showing, on the left, the seven economies that export virtual water resources to 160 or so other economies, on the right, grouped in five regions that are dependent on food and virtual water imports (Cargill 2017, reproduced in *World Energy* 46, 2020)

Power Relations in the Food System

Power Shifts but Farmers, Farm Labour and the Environment Are Always Weak

Farmers and graziers manage land and water but the food system dictates *how* they are managed. For a long time, farming was the mainstay of nearly every economy and the livelihood of many farmers. In rich countries, farmers are now few and governments have to ensure *cheap* food for the many. Figure 1.5 shows how the proportions of the value added in the first two modes of the food system have changed since the onset of industrialisation: in OECD economies, farmers and growers now account for less than 10% of the value added; food traders, processors and retailers add 90% and generate lots of jobs, especially in retailing and hospitality.

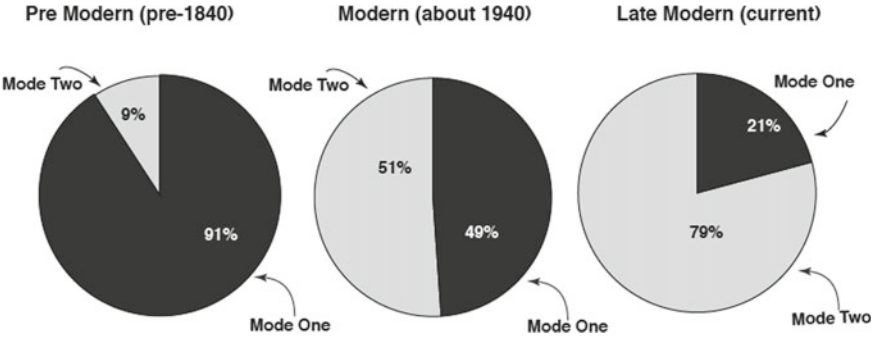


Fig. 1.5 Value added in the food chain in market modes 1 and 2

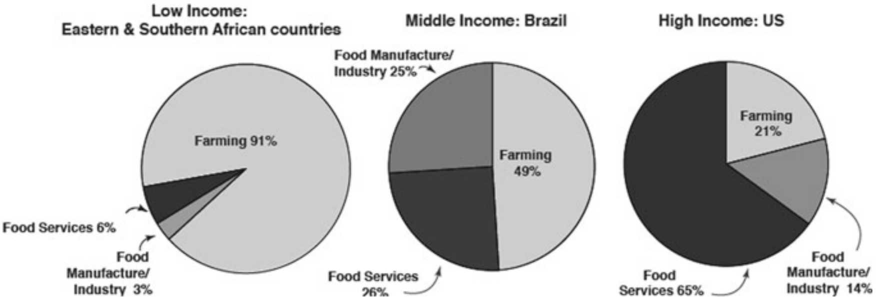


Fig. 1.6 Jobs in the food systems of low-, middle- and high-income countries

Nowadays, in high-income countries, food accounts for only a fraction of household expenditure and of gross domestic product (Fig. 1.6). For example, in the USA in 2017, the farm sector accounted for 0.9% of GDP; the whole food system accounted for about 5% (CIA 2018). The economic transition from low to high income is marked by an increase in the value added in trading, manufacturing, retailing and food services, matched by an increase in the proportion of jobs, from 9 to 79%. At the same time, jobs in the farm sector shrank from 91 to 21%; in the case of the UK to 8% (DEFRA 2015).

The Role of the State in Mode 1 Markets

Governments have not established sound legal and accounting regimes in Mode 1 of the supply chain. Instead, they subsidise farmers. They do this to support livelihoods, maintain rural economies and guarantee a degree of food self-sufficiency. These interventions have provided some protection for landscapes and ecosystem services, reinforced more recently by compliance conditions and agri-environment payments, but the bar has never been set very high; this is an area of policy-making where the state is learning on the hoof. Producer support from governments ranges from nil to more than 50% with a mean value of about 20%; OECD countries have cut back producer support since the early 1990s when the EU changed its Common Agricultural Policy from the payments for production that resulted in a butter mountain and a wine lake, to area-based payments; New Zealand and Australia have all but eliminated farm payments; but farm payments have been rising in emerging economies.

The first instinct of politicians is to pay more attention to people's livelihoods than to environmental services; food prices and food security are existential issues for politicians as well as consumers. In England, protection of landed interests has a long history but, since the early nineteenth century, governments have had to grapple with the competing claims of farming, manufacturing and popular interests. The repeal of the Corn Laws, which opened the gate to food imports from North America, was a victory for popular interests. Ever since, Society has been comfortably deluded that the food system works; it delivers cheap food to consumers but pain to farmers and farm workers and serious harm to the environment at home and in food-exporting economies. Governments nurture the delusion, hide the harm by making payments to farmers and ignore the erosion of the natural capital on which the system depends. *And the system doesn't deliver cheap food*—it delivers under-priced food. The real price is being paid by under-paid labour, the taxpayer and our ultimate life-support system.

What Needs to Be Done if We Are to Have a Sustainable, Commercially Viable Food System—And Who Needs to Do It?

Table 1.1 lists the main private sector, public sector and societal players in the food system. The right-hand column highlights those that need to be strengthened or that should exert responsible influence.

This crude analysis indicates the need to: (1) enable farmers to be good stewards of the land as well as growing food, fibre and fuel, which means higher farm-gate prices or payments for environmental services; (2) introduce regulations to safeguard land and water resources and environmental services, which will require effective audit and accounting of these assets; (3) promote responsible investment; (4) convince consumers to change their behaviour. Five main players need to do things differently: farmers, accountants, the State, investors, consumers and Society. Corporate institutions in Mode 2 are important but they are already relatively well regulated. Some food and beverage companies are moving towards ecosystem-aware contracts with farmers, but their language suggests it is possible to achieve parallel financial and societal/environmental goals with no trade-offs—a kind of market environmentalism (Bakker 2014; Rudebeck 2019). The rarity of such transactions reflects the balance of power. The silence of the corporate providers of hardware and chemicals is deafening. They have the capacity to watch and wait; content to keep wrecking systems in place.

Considering the main players, what do Society's consumers and its legislators need to do to make the food system sustainable?

1. ***Farmers*** are and will remain key players. The issue is this: farmers could be effective producers and stewards if they were properly paid—*but they are not*. Food is too cheap. But are consumers willing to pay more? Most, probably, are not; in any case, there will always be many who cannot. As individuals, farmers are weak although some corporate farms operate at a scale enjoyed by the big food manufacturers and retailers. Collectively, however, they can exert political influence beyond their numbers; for example, in Europe because of the complex political economy involving arcane land ownership, under-paid farm labour and cultural/emotional lock-ins.

Table 1.1 Strengths and weaknesses of players in the food supply chain

Main players	Players that are currently strong (in black)	Players and functions that Society needs to strengthen (in black)
Mode 1 supply chain market		
1. Farmers		Remunerate properly
Operators of water and other natural-resource infrastructure	■	
Seed, fertilizer, chemical and equipment corporates		
Mode 2 supply chain market		
Food-commodity traders	Operate within an effective legal and accounting regime	Contracts with farmers should reflect stewardship costs
Food and beverage corporates		
Big supermarkets		
Food and water NGOs		
Multilateral and bilateral lenders and aid agencies		
Mode 3 supply chain market		
5. Society by adopting sound ideas and behaviour	Consumers	Badly informed
Functions that impact all 3 Modes		
2. The State — through law and regulation	The main player especially in Mode 1	
3. Accountants, reporting rules and regulations	Ignore soil and water costs and farming impacts	Fix the legal regime and accounting of Mode 1
4. Investors	Few invest responsibly	Invest responsibly

In many countries, farmers receive direct and indirect payments that enable them to provide well-understood production services but do not pay for vital but invisible environmental services. The path of least resistance appears to be direct payments for environmental services and audited compliance with specified conditions of stewardship. For instance, carbon credits may be paid for by imposing cap-and-trade legislation on emitters of greenhouse gases. In the case of water supply, non-farm water users will pay for their modest consumption but, ultimately, irrigators will have their water consumption capped. This will be contentious, and many wetlands and water resources will be lost because regulation will have come too late. Whichever path is taken, credible accounts will be needed.

2. ***The State*** *has not enacted a legal framework and accounting rules that internalise all the costs of on-farm food production.* Instead, it subsidises farmers. Even then, poor people may need further support to buy food. The State is the most influential player in the food system. It has had to ensure that food is cheap and always available, and it is the only player that can impose the regulations, accounting rules and an investment regime that would make farming commercially and environmentally sustainable. Politicians need Society to give them political space to implement reforms that will properly price food and conserve the natural resources on which food production depends. *But Society has not signalled that this is what it wants.*
3. ***Accounting and Reporting Rules***: *Information is material if omitting it or misstating it could influence decisions that users make on the basis of financial information.* In the food system, this basic principle of accounting is more honoured in the breach than the observance. Emmanuel Faber, CEO of Danone, remarked in an interview for *Der Spiegel* on 8 June 2019: 'There is no cheap food. Every consumer must realise that if food has a low price, someone else is paying the real price. It's either the farmer, the degraded soil, or the consumers themselves with their health. At the end of the day, someone is paying the bill for cheap food.'
   Effective markets depend on effective regulations, and there is no better example of what happens without effective regulation and accounting rules than Mode 1 food production. Peter Bakker, an exceptional accountant and President of the World Business Council for Sustainable Development, has argued that accountants would save the world (Bakker 2013). Unfortunately, his perspective is not shared by the accounting profession—which has not advanced ways and means to deal with environmental capital. Accountants are no less expert than sustainability departments of the food supply chain corporates in keeping abreast of the discourse but, when it comes to the actual protection of soil, water and biodiversity, they ignore information that is material. The financial system needs to be rebooted (Allan et al. 2015; Bakker 2017). Even then, accounting for intangibles like soil carbon or groundwater status won't change behaviour unless taxes, subsidies and trade restrictions are managed effectively.
4. ***Investors***. Investors also have immense power. If they choose to use it, they could change the behaviour of corporate institutions that contract with food producers. But investors, in general, are blind to the value of natural capital and the rights of those who produce and prepare food. Investors who only prioritise profit and returns on capital (currently the fiduciary duty of a CEO of a Mode 2 food corporate) should be an endangered species—*but they are not.*
   The CEOs of some food manufacturing corporates *have* got the message. Emmanuel Faber has said: 'The food industry is going nowhere. Big companies have disconnected people from their sustenance. Consumers, especially millennials, are sceptics about industrial-scale food production. Even sellers of healthy products, such as mineral water, spread harm—just look at the billions of their plastic bottles that choke the ocean … A revolution and the end of globalisation are nigh' (*The Economist* 2018). These people know all about investment

and operational risks; they are familiar with the reasons for market failure; they curse the darkness—but where is the candle to illuminate the reason why we have the current accounting rules and legal regime in Mode 1? Danone aims to convert from the conventional company approach to a *BCorp approach.* BCorp certification provides information on for-profit companies that demonstrate high standards of social and environmental performance; the idea is to drive a cultural shift to redefine business success, to provide an alternative legal norm—but it is a voluntary system as compared with a mandatory one established by regulation. The predominant private-sector institution, the conventional for-profit company, remains a serious environmental risk (Newborne 2012a, b). The revolution has yet to come and, without it, evolution is slow.

5. ***Consumers and Society****. Food consumers could significantly influence food security; they could be the voluntary regulators of the food system by consuming responsibly.* At present, their food consumption choices impair their own health and that of the planet. It is widely estimated that they waste about one-third of all the food purchased; unhealthy food choices and unnecessary consumption add to the volume of wasted and degraded resources. Quite clearly, consumers could significantly influence food and water security; they could be the voluntary regulators—*but they are not, yet*.

   We have not focussed on corporate food traders, processors and manufacturers and the big supermarkets because they operate in markets that have rules and auditing systems that account for almost all of their inputs. For instance, all of the little water they consume—about 1% of food-water—is accounted for; they have adopted more efficient and more environmentally responsible practices that have halved their own water consumption during the past two decades, and they have reduced their costs. Their accountants and their shareholders are content; it has all made commercial sense. Perversely, there has been no equivalent enlightenment of farmers who actually manage and, on occasion, mismanage nearly all of Society's food-water consumption.

   How has Society adapted? Consumers have not starved. Farmers, mostly, make a living but it is troubling that suicide is an extreme component of the adaptation of the part of Society involved in Mode 1 food production. That Society as a whole has hardly begun to adapt to the Laws of Nature via the food system should also be troubling. The State and its taxpayers mitigate, to some extent, the market failures by providing subsidies to farmers but the State can only try to fix Nature's degraded ecosystems with unwelcome regulation—as opposed to effective incentives. As yet, there is no political will to fix the failures of natural resource mismanagement.

Conclusions

Governments dare not meddle with the certainty that affordable food will be available—they remain in power only as long as this certainty is in place—and practical policy advice concerns itself with piecemeal improvements (Lipsey 2007). It might be argued that the food system is a miracle of which governments and the private sector can be proud. Public payments to farmers and consumers have kept in place a political economy that delivers a version of food and water security. For two centuries, it has delivered ever-cheaper food to a burgeoning population. For all its failings, in the arcane calculus of political economy, it is cost-effective. Governments of industrialised economies will always be able to make the payments that fix the availability and affordability of food—although paying farm labour properly will remain an untidy, politicised issue and one of the lethal challenges faced by those who farm.

But because the cost of food is not reflected in the price of food, it impossible to introduce best, as opposed to second-best or worse, solutions to the problems of allocating and managing land and water. Whether current and future food systems will meet future demands for food and, therefore, increased food-water, depends on Society, its expectations and its political systems. Society determines demand—it determines global population and population hotspots; and it is forcing global heating with all its uncertainties. *The capacity to fix the availability and affordability of food for low-income economies of Africa heading for a population explosion is not certain.* And what the existing food system certainly does not do is protect and conserve the land, water and ecosystems, stabilise the climate and protect public health. Society needs to recognise that if farmers are to do the right thing, legislators need to be given political space to install an effective legal regime and effective accounting and investing rules in Mode 1 of the food system. Can it be that something so prosaic will control our destiny?

Afterword on the Covid-19 Crisis that Disrupted Global Systems in 2020

Global systems are periodically tested. We introduced our analysis with divine revelation and asked you to imagine what would happen if people were to think there won't be food on the shelves next week. We have now seen what happens even when shelves are replenished. We also identified the major economic crises of the past half century; the 1974–1979 oil crisis and the financial crisis of 2008–11 triggered exceptional commodity price spikes. We concluded that the food system—dysfunctional economically, environmentally as well as socially according to economists, ecologists and social scientists—is able to cope with exceptional market conditions. It has repeatedly adapted to volatility and resumed the long-term trend of falling international food commodity prices, remarkably quickly on each occasion. International agencies and analysts predicted, emphatically, that the 2008–2011 financial crisis had shifted the food system to a new normal of volatile and higher prices: OECD did not recant until 2017 (Brooks 2017).

What will be the impact of the Covid-19 crisis on the global food system? Scientists analyse the past impressively. They have made a few spectacular predictions about the future but have a poor record in predicting political economy outcomes. The future political economy of the food system is certainly difficult to call. The first few months of the Covid-19 crisis have highlighted important differences between global food supply chains and other global systems. The food system and its supply chains have proven remarkably flexible, responsive and pragmatic: there was no stressful politics associated with keeping food stores open, nor with the contradiction of allowing access to food stores despite lockdowns that kept most people isolated at home. The demand side was disrupted by the closure of pubs and restaurants but supermarkets, corner shops and food supply chains adapted quickly. Contrast the situation in energy services, public transport, entertainment, hospitality and tourism, manufacturing, health and education. Some of these ceased to function and many companies will fail.

Part of the adjustment in the food system has come via modest public funding but the sums are negligible compared with the trillions devoted to non-food sector corporations via subsidies and unprecedented social security payments. On the supply side, the food system was already encountering labour problems exacerbated by restrictions on the international movement of farm labour. Legislators have yet to grapple with the pressure from northern-hemisphere farmers wanting labour for vegetable production, vineyards and orchards. Meanwhile, farm gate prices are falling, especially in the OECD economies. Alarmists highlighted the tendency of rice prices to increase, but rice prices are always very sensitive to actual, or anticipated, market volatility and international trade in rice is tiny compared with the other staples such as wheat, corn and soya. There is plenty to meet global demand.

What will be the impact of Covid-19 crisis on local food supply chains? Only 15–20% of food is traded internationally: most of the food consumed worldwide is produced by farmers for themselves and their national markets. Family farms in Asia and Africa remain essential providers of food, but they operate under the heel of low farm-gate prices brought about by rich countries exporting under-priced food so farmers on small farms cannot invest to increase efficiency and make profits. The Covid-19 crisis might nudge up farm-gate prices in low-income economies but, if history repeats itself, the governments of these countries will still find it easier to import under-priced staples than face volatile food politics played out on their streets.

Business-as-usual is, unfortunately, unsustainable. That the Covid-19 crisis will not be a food crisis is welcome amidst the chaos in other sectors. The system will keep consumers fed ‘affordably’, and keep farmers and farm labour in place, dependent on subsidies and direct payments. But it remains unsustainable and uninvestable—that is to say uninvestable for private investors. Higher farm-gate prices would, amongst other things, make private investment feasible in Mode 1 food production but this is not yet politically feasible. Would-be reformers should continue to struggle with the contradictions; at the same time they must recognise why the dysfunctional system stays stubbornly in place. Will we all remain complicit in complying with the imperative of under-priced food for the under-paid?

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Chapter 2
Politics of Soils and Agriculture in a Warming World

Lennart Olsson

Abstract Soils are essential for life and civilization. They have a long history of political attention, documented at least since Ancient Greece and the Roman Empire. Soil played a key political role in the founding of the USA but gradually lost its clout in the last hundred years. The recent IPCC *Special Report on Climate Change and Land* may symbolize a return of soils to the political arena. The renewed political interest should be harnessed to leverage sustainable land management, which can create synergies between climate-change mitigation and adaptation while attending to a nexus of additional environmental and socio-economic predicaments. This chapter provides a brief history of the political importance of soils, its links to climate change, and how vested economic and political interests perpetuate unsustainable agricultural practices. It ends on a positive note by outlining a pathway towards a sustainable agricultural future.

Keywords Soil erosion · History · Future · Political economy · Climate change · IPCC

Politics of Soils—A Short History

It is no problem finding support in literature that soils are essential for Society. Already, Plato (427–347 BC) claimed that the prosperity of Athens was a result of the fertile soils of the surrounding country but he also warned, graphically, that soil degradation was already a problem (Montgomery 2007). Later, many of the founding scholars of modern thinking—Leonardo da Vinci, Francis Bacon, Robert Boyle, Galileo Galilei, and Charles Darwin, to mention a few—carried out research on soils and stressed the importance of soils for Society (Brevik and Hartemink 2010).

Apart from ancient Rome where soil and water management was strictly regulated (Milde 1950), nowhere in the world has soil erosion been such a hot political issue

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as in the USA. George Washington, himself, experimented with soil conservation at his home in Mount Vernon as early as 1769 and continued to be concerned about soil degradation as the first president of the USA. Some years later, the first (and sixth) post-colonial governor of Virginia expressed his appreciation and awareness of soil erosion in a political speech before the Virginia Assembly in 1777, saying: '*Since the achievement of our independence, he is the greatest patriot who stops the most gullies*'. And, yet, despite the high degree of awareness and political rhetoric, soil erosion continued apace because '*farming was then the most individualistic of enterprises*' (Hugh Hammond Bennett, in his Foreword to Hall 1937).

'*Shall we throw away our soils?*' asked Bennett, then Head of the USDA Bureau of Soils, in an article in Scientific American in 1926. '*The soil is literally man's most valuable asset…*'. In a harbinger of the Dust Bowl tragedy, he concluded: '*Surely something more than is now being done, should be done to check this enormous wastage. It is a national duty – if not the personal duty of every citizen who can think beyond the absolute needs of the moment – to take some active part in opposition to unrestrained soil erosion*' (Bennett 1926). A few years later, the southern part of the Great Plains was hit by the most severe environmental crisis to that date, the Dust Bowl, brought about by a combination of drought and unfettered ploughing of the Prairies to plant wheat. It left deep marks not only in politics in the form of a suite of government regulations and in economics with support to farmers to promote soil conservation but, also, elsewhere in society. In literature, John Steinbeck published *The Grapes of Wrath* in 1939; in music, Woody Guthrie released his first album, *Dust Bowl Ballads*, in 1940; in science the Soil Conservation Service was established in 1935 within USDA and it continues to be a scientific leader of sustainable land management, since 1994 under the name of Natural Resources Conservation Service. With hindsight, the responses to the Dust Bowl crisis can be seen as a successful, if late, lesson from early warnings (Jerneck and Olsson 2008).

On the global political scene, soils rose to prominence again in the period 1968–1974 in response to drought and famine in the Sahel that was understood, at the time, as a humanitarian crisis caused by human-induced land degradation or desertification (Olsson 1993). The United Nations organized its first thematic summit on an environmental issue, the UN Conference to Combat Desertification, in Nairobi in 1977. But for all the political attention and rhetoric (Andersson et al. 2011), land degradation continued unabated (Bai et al. 2008, 2015) and remains a pressing global issue (Montanarella et al. 2018; Olsson 2019a).

If land degradation was the poster child of the global environmental movement in the 1970s, climate change and more recently, also, loss of biodiversity have taken over that role. Even if soils play a key role in both climate change and loss of biodiversity, it has been hard for the environmental political discourse to maintain soils as a priority. But, perhaps, the time has come to address soil erosion (or land degradation) again; this time as a golden opportunity to mitigate climate change while helping food systems adapt to climate change.

Soils and Climate Change

Land degradation is driven by factors operating at time scales from very short intervals, such as individual rain storms lasting a few minutes that can initiate a gully or landslide, to gradual, century-scale depletion of nutrients and/or degradation of the soil physical and biological quality. There are several reasons to expect climate change to exacerbate land degradation. The two most obvious are changes in rainfall patterns and rising temperatures, both with significant observed changes over recent decades.

The fact that the atmosphere is heating means that it can hold more water. This leads to an increase in the intensity of rainfall and its erosive power. Shifts to fewer but more intense rainfall events have been observed, even if the pattern varies between regions and places (Capolongo et al. 2008; Ma et al. 2017; Mondal et al. 2016). Some studies project that this will lead to a 15–20% increase in the risk of erosion within the next few decades (Almagro et al. 2017; Burt et al. 2016; Olsson 2019a). Increase in temperature exacerbates the risk of soil erosion in several ways, not least through changes in vegetation dynamics, but it also affects the soil more directly by increasing the rate of decomposition of soil organic matter leading, in turn, to greater susceptibility of the soil to erosion (Barraclough et al. 2015; Burt et al. 2016; Sanchis et al. 2008).

Protecting soils from erosion is becoming ever more important, but will dire warnings result in relevant and rapid political responses? Given that the IPCC is intergovernmental, that is to say, the process and its scientific assessments are owned by 187 governments, the summary for policy makers of each and every IPCC report should inform national policies. Therefore, it is significant that the IPCC convened a special report on climate change and land (SRCCL)—with the longest title, yet, to accommodate a range of interests: *IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (IPCC 2019).

Until recently, above-ground carbon (primarily forests) has been, almost exclusively, the focus of land-based climate change policies, even though it is well established that soils contain five times more carbon than the above-ground biomass (Lal 2004). Much has been written about the potential synergies between land management and climate-change action but, so far, it has not entered formal negotiations under the United Nations Framework Convention on Climate Change (Chabbi et al. 2017). In retrospect, the previous policy framework, the 1997 Kyoto protocol, was a spectacular mistake for at least two reasons. The first was that it created a rift between the old industrialized countries (Annex I countries) with legally binding commitments to reduce emissions, and the rest of the world (Annex II countries) without any commitments. Thereby, the Annex II countries had no incentive to reduce emissions through better land management. The second reason is that it was based on the idea of *burden sharing*, that is to say reducing emissions was understood as a necessary but evil act resulting in negative consequences for Society, at least in the short term. The mechanisms were primarily based on strict rules and regulations—the discredited philosophy of *command and control*. The more recent policy framework, the 2015 Paris Accord, is fundamentally different. It includes all countries, using the principle of *common but differentiated responsibilities*, and it fully embraces nationally determined best practices to reduce emissions—let us call it *inspire and engage*. The hope is now that the SRCCL will inspire governments to develop best practices and deploy them in a way that is nationally and locally adapted so as to reduce emissions and take advantage of the many possibilities for synergies between land management and climate actions. The IPCC report identified many and various options for climate change mitigation in synergy with improved cropland management. The estimated potential to mitigate climate change with improved management of cropland was in the range of 1.4–2.3 GtCO_2e/yr. More radical changes such as shifting to agroforestry or to perennial cropping systems would result in substantially higher mitigation potential (de Oliveira et al. 2018; Smith and Nkem 2019).

Soils in Agricultural Politics

Agriculture as practised in most parts of the world has bad and far-reaching implications for the environment. Despite being the foundation of Society as we know it, the current state of agricultural soils and the ecosystems they are part of is one of degradation, depletion, and pollution (Olsson 2019a). Modern agriculture sits at the intersection of mounting concerns over food security, biodiversity loss, climate change, soil degradation, water use, eutrophication of marine environments, and land-use change (Mbow et al. 2019). Food systems are estimated to contribute 21–37% of global greenhouse gas emissions, of which agricultural activities (livestock, fertilizers, and emission from soils) contribute 9–14%, and indirect land-use change 7–14% (Mbow et al. 2019). Many social implications of agriculture are also problematic; most people living in extreme poverty are rural and employed in agriculture, a sector characterized by inequality and gender disparities (World Bank 2018). In developed and affluent countries, agriculture suffers from high and increasing debt, decreasing returns, and high levels of stress (Crews et al. 2018).

Climate change is expected to exacerbate many of agriculture's challenges, causing more extreme weather events and reducing yields. Transition to more-climate-resilient agricultural practices is, therefore, imperative. Meeting these challenges will require radically new ways of thinking, far-reaching cooperation between different players, and attention to new or previously marginalized forms of agricultural knowledge and technologies (IAASTD 2009). Speaking in terms of the Sustainable Development Goals (SDG), agriculture probably interacts with more SDGs than any other sector. With only a decade left, it is becoming increasingly clear that most of the SDGs will not be met by 2030; according to a recent editorial in *Nature* (Nature 2020) only two of the 17 goals are on track to be achieved globally. Lack of funding and political will are the main barriers, so creating synergies between goals might be a way forward. Equally important is to avoid conflicts between goals.

Various agricultural practices have been suggested, and promoted by different stakeholders, to meet the challenges posed by climate change:

- Climate-smart agriculture (CSA) is a broad approach for transforming and reorienting agricultural systems to support food security under the new conditions expected from climate change. Even if CSA is loosely defined and interpretations differ among stakeholders, its three overarching goals are a sustainable increase in food production, adaptation to and building resilience to climate change, and reducing emission of greenhouse gases and/or remove emissions where possible (Alexander 2019; Boincean and Dent 2019).
- Sustainable intensification is a related umbrella term for various ways of changing agricultural practices to increase productivity while reducing the environmental impact—how to produce more on less land with less inputs (Pretty 2018).
- Smart Farming is an umbrella term for harnessing the exponentially increasing use of information and communication technologies for optimizing and automating farming through precision agriculture. The aim is to provide optimum conditions in terms of nutrients and moisture and thereby reduce the losses and increase the efficiency (Walter et al. 2017).
- Organic agriculture is a term used explicitly for production systems that do not make use of synthetic fertilizers and pesticides. Instead, they rely on animal manure, biological fixation, and biological pest control.

All these approaches rely on incremental changes of existing practice. But a fundamental problem for soil health is the continual disturbance that comes with our dependency on monocultures of annual crops. Their shallow root systems cannot enrich the soil with organic matter beyond the upper 30–50 cm; and frequent disturbance prevents the development of functioning soil ecosystems, without which soils cannot maintain their long-term productive capacity by themselves.

A more radical approach would be a shift to agro-ecosystems that more closely resemble the diverse natural ecosystems that preceded agriculture (Eisler 2019). This involves a transition to the cultivation of perennial grain crops that are planted once and can be harvested for several years. Plant breeders have shown that it is possible to create perennial varieties of, or alternatives to, staple crops such as wheat, rice, oilseeds, and sorghum (Crews and Cattani 2018). A shift to agriculture dominated by perennial polycultures is, of course, a long-term strategy that can only be achieved with sustained commitment to research over the coming decades, but it holds the promise of putting agriculture onto a path towards long-term sustainability, an agriculture where soil health improves as we cultivate and simultaneously helps to mitigate climate change (Olsson et al. 2019; Crews 2021).

Barriers and Potential for Change

In theory, there are many opportunities to improve the environmental performance of agriculture, reduce emissions of greenhouse gases, clean-up streams, lakes, and coastal waters, and do it in a way that would benefit most farmers economically. So why is this not happening everywhere? For answers, we must look at the political economy of modern agriculture, in particular, the close interaction of agricultural technologies, corporate power, and state regulation—all vested interests that drive agriculture in the direction of *productivism*. That is to say: growth (often expressed as land productivity in tons/ha) is the very purpose of agriculture and, thereby, also the organizing principle. This was expressed by Cochrane (1958) as the agricultural treadmill theory (Fig. 2.1).

The agricultural treadmill forces farmers into increasingly unsustainable means of production, such as increasing use of agro-chemicals, because of increasing costs of production and decreasing revenues for their produce (Crews et al. 2018; Allan and Dent 2021); and because of increasing indebtedness, farmers cannot get off the treadmill. But the treadmill is not entirely socio-economic, it interacts with soil processes.

It is well known that crops respond to fertilizers very differently depending on the quality and health of the soil. Adding fertilizers to a good healthy soil will have only marginal effects; the same goes for very poor soils but, in between, there is usually a significant positive response on crop yields when adding nutrients. The fertilizer response can be expressed as in the diagram (Fig. 2.2) from Tittonell and Giller (2013).

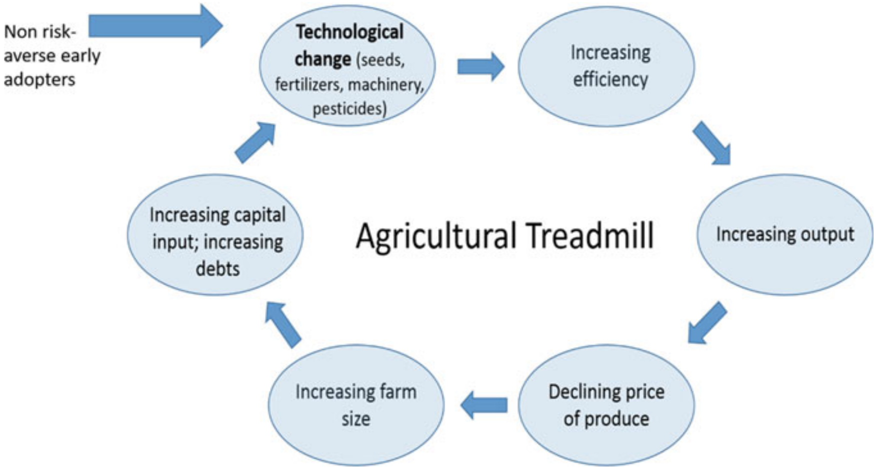

Fig. 2.1 The agricultural treadmill theory (Cochrane 1958, illustration modified from Crews et al. 2018)

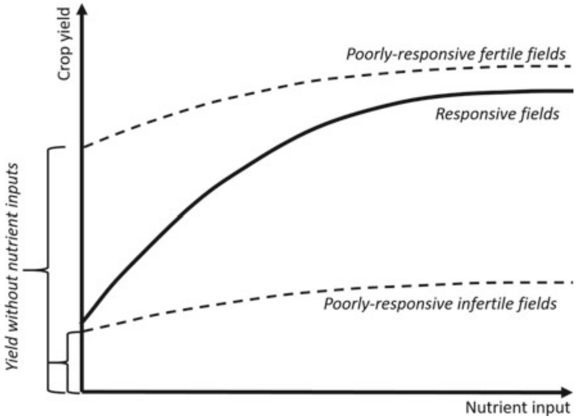

Fig. 2.2 Theoretical crop yield responses to fertilizer (Tittonell and Giller 2013)

When soils are frequently disturbed by tillage and nutrients added as mineral fertilizers only, organic matter content and other soil health indicators are kept at low levels (Celik et al. 2010; Fließbach et al. 2007; Kapkiyai et al. 1999; Menšík et al. 2018). This means that soils are prevented from reaching the high fertility where external nutrient input is less important or even superfluous. The frequent use of herbicides also disrupts ecological processes and thereby suppresses soil health. Some studies suggest minimal impacts (Rose et al. 2016) while other studies show significant negative impacts on many aspects of soil health (Myers et al. 2016): in particular, nitrogen uptake (Angelini et al. 2013; Druille et al. 2016; Fan et al. 2017), and soil biota such as earthworms (Gaupp-Berghausen et al. 2015; Lydy and Linck 2003; Zaller et al. 2014) and, in some cases, also mycorrhiza (Hage-Ahmed et al. 2019; Helander et al. 2018; Lekberg et al. 2017).

So the socio-economic cycle of the agricultural treadmill interacts with the soil processes to keep soils relatively infertile (where they respond to external nutrient inputs) which makes it harder and harder to break away from the destructive practices. But incentives and practices for building soil fertility sufficiently high would, in the short to medium term, benefit farmers by reducing the need for external inputs of nutrients—one of the most costly and environmentally destructive aspects of farming. Over one to two decades, the shift to perennial crops cultivated in mixed cultures with nitrogen-fixing cultivars would be a game changer (Crews et al. 2018). The current and unprecedented political awareness of the Covid-19 crisis and the imminent, even greater global crisis of climate change has resulted in potentially massive programs for change. The Green New Deal in the USA and the European Green Deal are potentially powerful political initiatives that should be harnessed for promoting soil health through radical change of agricultural policies and to accelerate research and development of radically new agricultural practices (Olsson 2019a, b), such as a shift from annual monocultures to perennial polycultures (Crews et al. 2016, 2018; Crews and Cattani 2018).

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Part II
Known Knowns

As we know, there are known knowns.
There are things we know we know.
We also know there are known unknowns.
That is to say, we know that there are some things we don't know.
But there are also unknown unknowns,
The ones we don't know we don't know.
Donald Rumsfeld, Pentagon briefing 2004

Chapter 3
Carbon Management in Conservation Agriculture Systems

Don C. Reicosky

Abstract As food demands rise, we need to keep our soil healthy and productive. The practice of no-tillage (NT), initially evolved as a way to combat the soil erosion associated with intensive tillage, also improves soil health and function. The favourable effect on soil properties and processes led to the transition from NT to bio-diverse, regenerative NT, generally known as Conservation Agriculture (CA) systems. CA integrates three key principles: (1) continuous crop residue cover on the soil surface, (2) minimum soil disturbance, and (3) diverse crop rotations and cover-crop mixes with location-specific, complementary practices. The potential increase in stored carbon under CA, especially in response to no-tillage, is an important benefit; many studies, worldwide, have documented higher carbon storage under no-till compared with conventional tillage. Biodiversity with carbon cycling and flow is necessary for harmony and stability in nature and for global food security. Global environmental preservation may well require soil carbon storage as the main goal for improved management of carbon flow management in regenerative farming systems.

Keywords No-till · Soil cover · Crop rotation · Soil health · Carbon cycling

Introduction

There have been many reports about intensive agriculture and environmental degradation. This is about *how* we can make agriculture sustainable, regenerative and climate resilient—as well as economically profitable and environmentally friendly. As world population and its demand for food increase, we need to keep our soil healthy and productive. Tillage has been integral to crop production for more than 10,000 years (Lal et al. 2007) but it does nothing for soil health and gives only a brief boost to production. On the other hand, it degrades soil, water, and air quality and can exacerbate soil erosion.

This is a brief review of the evolution of *No-Tillage* (NT) practice, its effect on physical, chemical, and biological properties and processes and, therefore, its positive

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impact on the environment. A further objective encompasses the transition from NT practices to bio-diverse, regenerative Conservation Agriculture (CA) systems based on three coherent principles: (1) minimum soil disturbance (no-tillage), (2) continuous crop residue cover on the soil surface, and (3) diverse crop rotations and cover-crop mixes with location-specific complementary practices. In concert, these practices foster food security and enhance ecosystem services.

No-Tillage Effects on Soil Properties

As compared to ploughing, leaving crop residues on the soil surface with no mechanical mixing of residues and soil amendments enhances soil biological, chemical, and physical properties. A comparison of NT with conventional tillage systems will include differences in the microbial environment, number and activity of soil microorganisms, soil animals, decomposition of organic matter, nitrogen transformations, chemical properties, influence of mulches on soil physical properties and effect of tillage on soil density and porosity (Shepherd et al. 2001).

Intensive tillage destroys macro-pores and, at the same time, the larger soil fauna such as earthworms and other burrowing and surface-layer organisms that create macro-pores, so infiltration and root penetration are inhibited (Kladivko 2001; Kemper et al. 2011). Tillage disrupts fungal hyphae networks and upsets the balance between fungi and bacteria in the soil (Bailey et al. 2002) so tilled soils have less fungal activity and less stored carbon than those maintained under native vegetation or NT systems; Six et al. (2006) found that most agricultural soils are dominated by bacterial activity. Basche and DeLonge (2017) used meta-analysis to compare intensively tilled systems with perennial systems and no-till annual systems combined with living-cover practices. They found that the reduced-disturbance, surface-cover systems increased porosity and water storage capacity. They further suggest that continuous living cover may be an adaptation strategy to combat variability of rainfall amount and intensity by allowing more water to infiltrate to a greater depth (Kell 2011; Kemper et al. 2011).

Soil-binding forces may be of organic or inorganic origin but, in most soils, the organic forces are more significant for building large, stable aggregates. Examples of organic binding agents include plant carbon and microbial polysaccharides, fungal hyphae, and plant roots (Wilson et al. 2009; Helgason et al. 2010a). Helgason et al. (2010b) demonstrated greater microbial biomass and altered microbial community structure in soils under NT as opposed to conventional tillage. Inorganic binding forces include charge attractions between mineral particles and/or organic matter, cycles of freezing/thawing and wetting/drying, compression, and deformation within the soil.

Conservation Agriculture/Soil Health Systems

The initial adoption of NT was aimed at minimizing soil erosion. Nowadays, many people look at it as a way to sustainable intensification of cropping, both to meet conservation ethics and future agricultural demands (Montgomery 2007a). Although NT suggests merely the absence of tillage, NT benefits critical soil properties that contribute to equal or higher crop yields, lesser input costs and better environmental performance than under conventional tillage. The more coherent and complex concept of CA has evolved from NT: key conservation strategies include the three principles of CA as well as best management practices for livestock, irrigation systems, and precision agriculture to achieve economically, ecologically, and socially sustainable agricultural production (Jat et al. 2013). Conservation practices can reduce soil erosion rates that may occur under climate extremes—whether greater total rainfall with greater intensity or a change to a drier climate that will potentially bring higher rates of erosion (Montgomery 2007b; Lindwall and Sonntag 2010). Delgado et al. (2013) argue that conservation practices will be key to adapting to climate change.

Conservation Agriculture has become a global agricultural movement (Kassam et al. 2018). Recent reviews include Baker et al. (2007a), Govaerts et al. (2009), Kassam et al. (2014), Friedrich et al. (2012, 2014), Jat et al. (2013), Kertész and Madarász (2014), Reicosky and Janzen (2018), Mitchell et al. (2019), and Reicosky (2019). The system combines NT with two additional principles (Fig. 3.1) to include

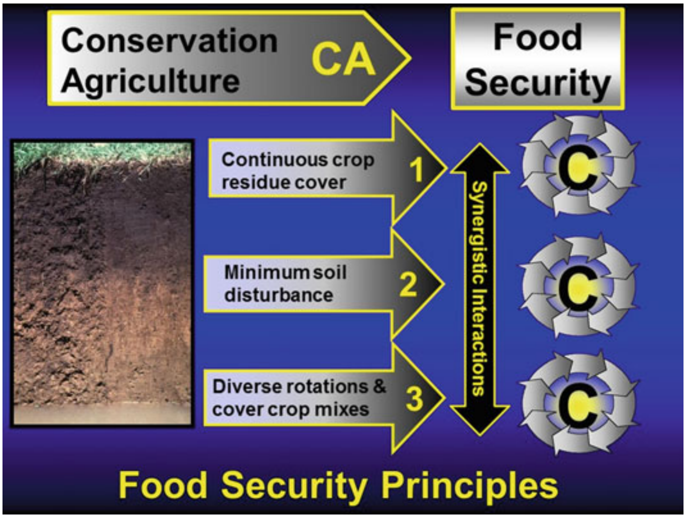


Fig. 3.1 Conservation Agriculture systems integrating three principles of soil health

concomitant application of minimum soil disturbance, crop residue mulch, and soil–plant diversification with multiple species of cover crops for maximum photosynthesis and carbon capture (Friedrich et al. 2012, 2014; Farooq and Siddique 2015; Al-Kaisi and Lal 2017; González-Sánchez et al. 2017; Mitchell et al. 2019). The system requires all three principles operating simultaneously and continuously, supplemented by local complementary agricultural practices. Integration and synchronization of these fundamental principles enhance the development and functionality of crops' root systems as a consequence of an increased depth and more regular water and nutrient uptake.

A meta-analysis by Pittelkow et al. (2015) embraced 5463 yield comparisons from 43 crops across 63 countries. We may debate whether they compare like with like but, measured across all data for a variety of crops, they found that NT lowers yields by an average of 5.7% relative to tillage. However, the addition of rotations and residue-retention to NT reduced yield loss by 2.5% and, in drylands, crop productivity was significantly increased over NT alone. All of which suggests that CA, incorporating minimum soil disturbance, permanent mulch cover and diverse crop rotations, may be an important strategy for adapting to climate change in drylands—and the only way to cope with climate extremes (Corsi et al. 2012; Pretty and Bharucha 2014; Reicosky and Janzen 2018; Mitchell et al. 2019; Schwarzer 2019). Diverse cover-crop mixes will help ensure adequate carbon input to CA systems (Anderson 2008; Corsi et al. 2012; Lal 2015a, b; Chatterjee et al. 2016; Schwarzer 2019).

There have been calls for improvements to the evidence-base on CA (Philibert et al. 2012; Brouder and Gomez-MacPherson 2014). Meta-analyses and reviews across cases show that the evidence on yield impacts and C-sequestration potential is mixed (Stevenson et al. 2014). This may reflect context-sensitivity, where outcomes depend on the precise combination of practices used and differ by crop type, or may reflect the uncertainties associated with the definition of NT and CA. This is not a trivial issue; miscommunication between researchers and farmers may contribute to limited acceptance of the coherent CA package. Promotional strategies that depend on farmers' clear understanding of CA may unintentionally encourage adoption of no-till alone with negative effects on crop yields, at least in the short term (Findlater et al. 2019; Brouder and Gomez-MacPherson 2014). It may also hinder adoption amongst smallholders who may 'attribute more value to immediate costs and benefits than those incurred in the future' as they must navigate precarious and pressing concerns over food and livelihood security (Giller et al. 2009).

There is certainly need for more evidence on the implications of improved land management across agricultural sectors and farming systems. And for this, we need clear and accurate communication and understanding (Baker et al. 2007b; Hobbs et al. 2008; Derpsch et al. 2014; Reicosky 2015; Schwarzer 2019). In a national survey of South Africa's commercial grain farmers, Findlater et al. (2019) found farmers' definition of *conservation* differed substantially from that of the local experts most likely to be asked to contribute adoption estimates to global monitoring efforts. Each component of the *CA coherent package* requires interpretation and there is potential for misunderstanding and miscommunication.

The applicability and scalability of CA to smallholdings have been questioned, especially in developing countries (Giller et al. 2009; Stevenson et al. 2014). However, some case studies show remarkable social-ecological outcomes. Collectively, recent evidence shows that the adoption of CA has led to multiplicative increases in food production along with cost-saving or income-boosting effects including reduced soil erosion, increased resilience to climate-related shocks, increased soil carbon, improved water productivity, reduced debt, livelihood diversification, and improved household-level food security (Marongwe et al. 2011; Owenya et al. 2011; Silici et al. 2011; Farooq and Siddique 2015; Kassam et al. 2018; Schwarzer 2019). The complexity of CA systems highlights the need for involvement of farmer-leadership throughout the innovation process: on-farm research, evaluation, ultimate implementation combined with the dissemination and communication of the information to other farmers and, finally, identifying further problems and opportunities for another cycle of innovation.

Carbon Management

The importance of carbon in CA systems has been reviewed recently by Reicosky and Janzen (2018), Mitchell et al. (2019), Reicosky (2019), and Schwarzer (2019). Several long-term, incremental and economic benefits of CA have emerged (Fig. 3.2); the most important have been attributed to the accumulation of SOM at the soil surface for erosion protection, enhanced water infiltration, and storage, and efficient nutrient cycling. Conservation Agriculture with enhanced carbon management is also being

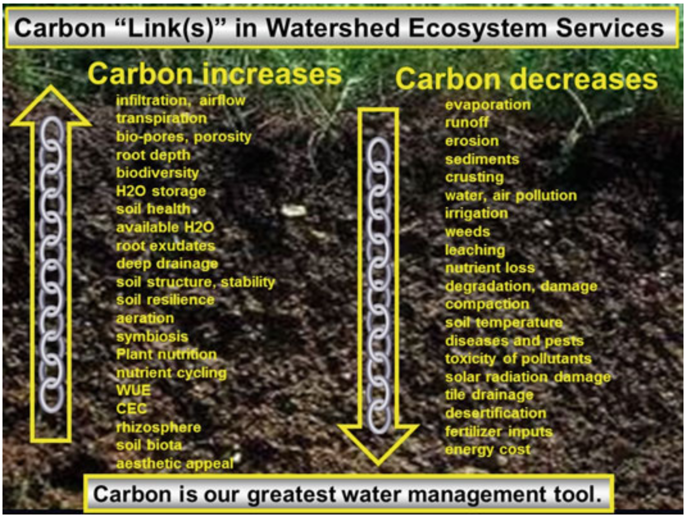


Fig. 3.2 Carbon benefits and hydrologic management in CA watersheds

called *regenerative agriculture*. The synergistic simplicity of CA (minimizes carbon and soil loss) and the use of diverse rotations and cover crop mixes (maximizes soil coverage and carbon input) allows for protection of soil biodiversity and regeneration. With less intensive tillage, greater environmental benefits accrue with lower input costs.

Farmers have tilled the soil for 10,000 years (Lal et al. 2007). Tillage brings benefits but, also, serious problems—notably the resulting soil degradation and erosion. Soil organic matter responds dynamically to changes in soil management, primary tillage and carbon inputs. More than a century of field experiments in Illinois and Missouri show that, regardless of the cropping system, continually cultivated plots continuously lose soil organic matter (Odell et al. 1984; Wagner 1989). Reicosky and Lindstrom (1993) demonstrated immediate and serious impacts of tillage on emissions of carbon dioxide and soil degradation as carbon loss by placing a portable gas-measuring chamber directly on the soil surface immediately after the passage of different tillage implements during autumn ploughing of wheat stubble: the mouldboard plough and four other implements that penetrated to different depths but didn't turn over the furrow slice. No-till was simulated by a single pass of the tractor wheels. CO_2 was measured once per second for 60 s, every 3–5 min for 5 h, then less frequently for 14 days, in triplicate (Fig. 3.3).

Following the mouldboard plough that cut a 25 cm furrow and turned over the whole surface of the field, the initial release of CO_2 was 29.1 ± 2.4 $g/m^2/h$; the cumulative amount over 5 h was 59.8 gCO_2/m^2; and 150.7 gCO_2/m^2 over 24 h. The various tillage implements that didn't break up the entire soil surface or turn the furrow released between 3.4 and 31.4 gCO_2/m^2 over 5 h and 15.4–66.2 gCO_2/m^2

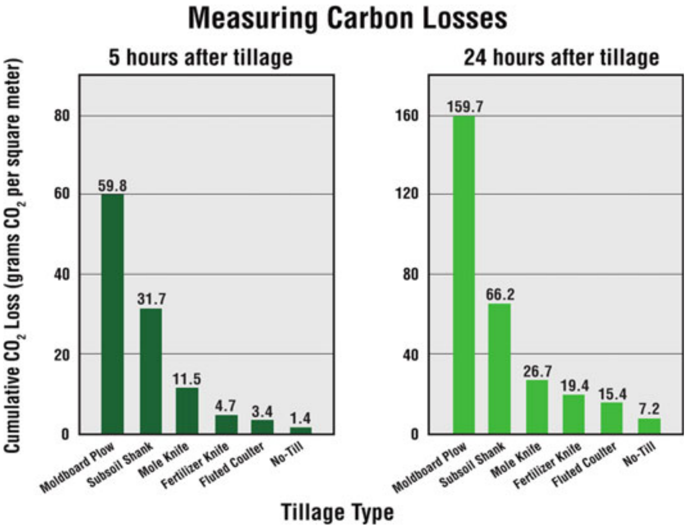


Fig. 3.3 Release of CO_2 from tillage of Hamerly clay loam *(Aeric calciaquoll/Calcic chernozem)*, Morris MN, USA, 4 Sept 1997 after Crummet (2019)

over 24 h, depending on the depth of penetration. No-till released 1.4 gCO_2/m^2 over 5 h and 7 gCO_2/m^2 over 24 h. These relative differences were still apparent 14 days after tillage. We may attribute the immediate release of CO_2 simply to soil disturbance, like bursting a balloon. An invisible cloud of CO_2 erupted behind every tillage implement; the volume of gas was directly proportional to the volume of soil displaced and continued long after the tillage operation. Over the longer term, we may envisage greater oxygenation of the soil and accelerated mineralization of soil organic carbon from the pulverized soil crumbs.

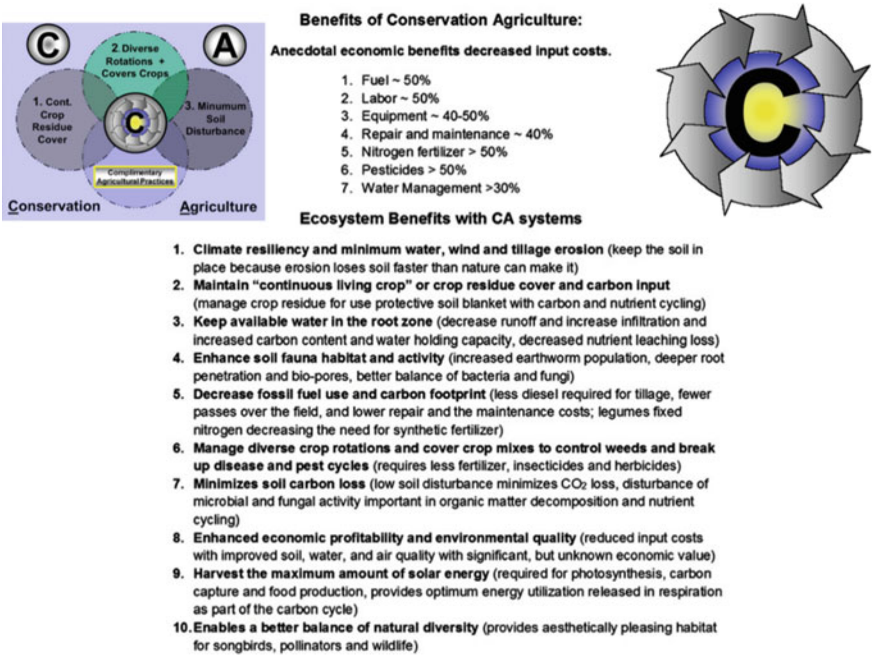
Ecosystem Services

Enhanced carbon management is critical for providing ecosystem services. In CA, good crop residue management arrests wind and water erosion by attenuating runoff and evaporation, and by improving soil health and resilience (Lindwall and Sonntag 2010; Jat et al. 2013). Basche et al. (2016) found soil water improvements under long-term cover crops; the cover crop increased water retention at field capacity by 10–11% as well as increasing plant-available water by 21–22%. Ranaivoson et al. (2017) studied the relative effects of surface crop residues on ecological functions in CA systems compared with NT bare soils. They found that 8 t/ha of residues decreased soil water evaporation by about 30% compared to bare soil; and to achieve a significant improvement of infiltration, runoff, and soil-loss control, required at least 2 t/ha of crop residues over the soil surface. The average annual SOC gain increased with increasing amounts of residues; with 4–5 t/ha of residues, a mean annual increase of 0.38 tC/ha was achieved. Assuming the C content of the residues was about 45%, little more than 8% of the crop-residue carbon remained in the soil after one year. These estimates are in line with other analyses showing hydrologic impacts with long-term use of cover crops (Basche et al. 2016; Basche and DeLonge 2017; Basche and Edelson 2017).

Schipanski et al. (2014) demonstrated that cover crops can provide a suite of ecosystem services beyond nutrient retention and erosion control. In a 3-field crop rotation, relative to the system without cover crops, cover crops increased biomass production, N supply, soil C storage, NO_3 retention, erosion control, weed suppression, mycorrhizal colonization and conservation of beneficial insects; insect pest suppression was unchanged; emissions of N_2O increased. In simulations, a cover crop of red clover provided enough N to the following crop of corn to achieve yields equivalent to fertilization with 168 kgN/ha; and yields for all the main cash crops were equivalent between cropping systems with and without cover crops. Palm et al. (2014) in a comprehensive review of the impact of CA on ecosystem services, acknowledge that CA cuts erosion and runoff and improves water quality compared to conventional practices, and influences many other soil properties and processes in critical ecosystem services. They suggest that inconsistent results from location to location may be due to soil type, topographic position, climate, and their combination, all interacting with management. An additional factor, already alluded to, may be the lack of clarity in the tillage terminology used in research studies (Eagle et al. 2012; Reicosky 2015). Experiments for testing CA are complex and, compared with conventional practices like tillage, residue removal, or incorporation, don't necessarily have the design and controls needed to separate the synchronized individual and combined effects of the different CA practices. More work is certainly needed to assess the feasibility of restoring degraded soils and increasing yields in tropical smallholder farming systems by CA; the biggest obstacle to improving soils in these situations is the need for enhanced management of crop residues in the face of competing claims from other uses of these assets.

Table 3.1 lists the economic benefits provided by conversion from conventional tillage to CA. Many can only be demonstrated qualitatively; individual differences in farm operations, soil types, the rate of transition to CA, and a host of other factors contribute to this challenge. Economic benefits include reduced use of fossil fuels, fertilizers and pesticides; less wear-and-tear on equipment; and less soil erosion. A few farmers are finding environmental and economic benefits go hand-in-hand. By using cover crops and diverse crop rotations in CA, some farmers are finding that their soil actually has more available water for their cash crops when those crops really need it, which means more and better food. Some farmers expressed concern over the expense of new seeding equipment and the cost of cover crop mixes. However, the early adopters of CA with innovative skills have made management decisions that create economic savings; anecdotal evidence from a few early adopters suggest

Table 3.1 Summary of economic and ecosystem benefits of Conservation Agriculture systems



Benefits of Conservation Agriculture:

Anecdotal economic benefits decreased input costs.

1. Fuel ~ 50%
2. Labor ~ 50%
3. Equipment ~ 40-50%
4. Repair and maintenance ~ 40%
5. Nitrogen fertilizer > 50%
6. Pesticides > 50%
7. Water Management >30%

Ecosystem Benefits with CA systems

1. **Climate resiliency and minimum water, wind and tillage erosion** (keep the soil in place because erosion loses soil faster than nature can make it)
2. **Maintain "continuous living crop" or crop residue cover and carbon input** (manage crop residue for use protective soil blanket with carbon and nutrient cycling)
3. **Keep available water in the root zone** (decrease runoff and increase infiltration and increased carbon content and water holding capacity, decreased nutrient leaching loss)
4. **Enhance soil fauna habitat and activity** (increased earthworm population, deeper root penetration and bio-pores, better balance of bacteria and fungi)
5. **Decrease fossil fuel use and carbon footprint** (less diesel required for tillage, fewer passes over the field, and lower repair and the maintenance costs; legumes fixed nitrogen decreasing the need for synthetic fertilizer)
6. **Manage diverse crop rotations and cover crop mixes to control weeds and break up disease and pest cycles** (requires less fertilizer, insecticides and herbicides)
7. **Minimizes soil carbon loss** (low soil disturbance minimizes CO_2 loss, disturbance of microbial and fungal activity important in organic matter decomposition and nutrient cycling)
8. **Enhanced economic profitability and environmental quality** (reduced input costs with improved soil, water, and air quality with significant, but unknown economic value)
9. **Harvest the maximum amount of solar energy** (required for photosynthesis, carbon capture and food production, provides optimum energy utilization released in respiration as part of the carbon cycle)
10. **Enables a better balance of natural diversity** (provides aesthetically pleasing habitat for songbirds, pollinators and wildlife)

annual input savings ranging from $245 to $500/ha (Mitchell et al. 2012), depending on the farm and many personal assumptions involved.

Multiple economic benefits listed in Table 3.1 accrue from reductions in consumption of diesel fuel, size of equipment required, equipment maintenance, and labour. Incorporating biodiversity principles reduces pesticide and insecticide costs but may pose chemical management challenges in the transition from conventional agriculture to CA. The savings associated with reduced use of synthetic N fertilizer are substantial and contribute to shrinking the carbon footprint of farming. The economic incentives associated with soil carbon storage in the form of carbon credits, offsets, and/or taxes are still being evaluated. The economics of soil health is the subject of definition, measurement, research and education, and policy programs (Schwarzer 2019).

Cover crops make major contributions to the environmental benefits of CA systems by decreasing erosion; increasing water-use efficiency, nutrient capture and cycling; as well as enhanced carbon cycling that decreases carbon loss. Cover crop biomass stimulates soil biological activity and both surface cover and soil organic matter improve soil physical properties resulting in greater water infiltration through the direct effects of the residue coverage and better soil aggregation or tilth. This results in better nutrient and moisture management; less surface sealing because residue intercepts raindrops—reducing the dispersal of clay particles during rainfall or irrigation; and greater soil porosity—due to macropores formed as roots grow, die, and decompose (Calegari et al. 2008, 2013a, b; Schwarzer 2019).

Improvements in soil physical properties depend on soil type, crops grown and residue management, as well as temperature and rainfall. Grasses and brassicas are better than legumes at reducing N leaching (Dabney et al. 2001; Kremen and Weil 2006; Meisinger 1991); winter rye is very effective at reducing N leaching because it tolerates cold, grows rapidly, and produces a lot of biomass (Delgado 1998). Winter annual weeds do not effectively reduce N losses. However, regardless of soil type, tillage will very quickly negate any cover crop benefits associated with increased soil organic matter. Simply put, any tillage breaks down soil organic matter much faster than NT, hence the need for continuous minimum soil disturbance.

Summary and Conclusions

We as a society must agree that productive agriculture and the environment can and must coexist! The challenge is to balance economic development and protection of nature. Soil care and protection should be everyone's concern. Everyone has a responsibility to take an interest in how farm soils are used—or abused; everyone's food supply and the environment are at risk. Politicians, policy-makers, and planners have particular responsibility to protect of good agricultural soils.

Farmers can contribute to regenerative soil management by adopting conservation practices that enhance soil health without sacrificing profit. The solution lies in CA that brings together innovation, new technology, and systems concepts. However, a universally acceptable definition of CA needs to be developed for clear communication and understanding before real progress can be made with its acceptance and adoption worldwide.

Conservation Agriculture offers the opportunity to create a legacy of healthy farms and healthy, living soils that will support food security. Although the action must come primarily from the farming community, it must be underpinned by the scientific, rural, and urban sectors, and supported by Society at large. There must be a strong partnership between these sectors to promote adoption and success of the CA approaches. We owe it to future generations.

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Chapter 4
Resilient Cropping Systems in a Mediterranean Climate

Johann Strauss

Abstract In water-scarce South Africa, conventional rainfed arable, especially continuous wheat, is under increasing economic and ecological stress. With business, as usual, regional food security cannot be maintained. There is an alternative: Conservation Agriculture (CA) built on the three principles of no-till, continuous ground cover by crops or crop residues, and diverse crop rotations. But while 40% of farmers in South Africa have adopted at least one of these practices, only 14% employ all three simultaneously. Long-term field experiments demonstrate that, with crop rotation, better yields enable two-thirds of the present total wheat production to be grown with only half the cropped area under the main crop, and with better gross margins—dramatically better with integrated cropping and livestock. Benefits of adoption of the whole CA package include much-improved infiltration of rainfall and, so, arrest of soil erosion and better rain-use efficiency; better nitrogen-use efficiency; a steady reduction in the use of fertilizers and pesticides; carbon capture; and greater resilience of the farming system against drought and economic shocks.

Keywords Conservation agriculture · Drylands · Crop diversity · Livestock · Gross margin

The Western Cape Perspective

Rainfed agriculture in southern South Africa has been based on winter cereals since the 1700s. The expansionist policies of the colonial powers initially encouraged wheat monoculture (Anon 2000). Government subsidies, the region's inherent potential for wheat production, the availability of commercial fertilizers, and effective chemical weed and pest control kept it that way, even though other options were available. These same drivers also encouraged expansion of grain production into marginal areas (Arkcoll 1998). However, the sustainability of this mode of production is now challenged by the increasing costs of industrial inputs, competitive world

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market prices since the introduction of a free market in 1994, and increasingly uncertain home production because of land degradation and capricious rainfall. These apply not only in the Western Cape but across the continent.

Southern South Africa has a Mediterranean climate with cold, rainy winters and hot, dry summers. Annual rainfall varies between 150 and 550 mm. About 80% of the rain falls during the April–September growing season, which constrains production to one crop per year, sown in April and harvested in November, with a summer fallow. The soils, mainly derived from shale, are mostly shallow and stony.

Worldwide, continual tillage has proved ruinous. Depletion of soil organic matter has made a significant contribution to the current high levels of CO_2 in the atmosphere; and loss of microbial life, soil structure, and water-holding capacity has much reduced the world's capacity to produce food (World Resources Institute 2000). Under business as usual, a point will be reached where food security cannot be maintained; that point may be reached soon in South Africa and, indeed, across the continent (Swanepoel et al. 2017).

Why Conservation Agriculture?

Conservation agriculture (CA) is a philosophy and a set of practices aimed at lessening or remedying the ravages of conventional agriculture. It has been promoted by FAO as a resource-efficient crop production system based on an all-inclusive combination of soil, water, and biological assets and external inputs. It is built on three strategic principles: *continuous cover on top of the soil* in the form of crops or crop residues, *continuous minimum soil disturbance* (no-till), and *diversity through crop rotations*. Integration of cropping and livestock wasn't part of the initial concept but the inclusion of pastures, in particular legume pastures, has brought further benefits including greater diversification and, therefore, resilience; greater financial and income stability; and, even, greater profits.

In a water-scarce country, CA production systems are essential to maintain food security. The dire need for change in our local cropping systems is underscored by the findings of Le Roux et al. (2008) that indicate a loss of 3 tons of fertile topsoil for every ton of maize produced. Over the past 15 years the rate of adoption of CA in southern South Africa has increased fast—although the three principles of CA has been embraced to varying degrees. This has happened in the absence of any policy support (Knott et al. 2017). It has been driven by need. A handful of local pioneers adopted zero tillage and took it from there. In South Africa, the highest rate of adoption has been in the Western Cape, followed closely by KwaZulu-Natal, while small pockets of CA farmers have established themselves in other provinces. Across South Africa, the adoption rate of each of the three CA principles is better than 40%, even though only 14% of farmers have adopted all three principles simultaneously (Findlater et al. 2019).

Results from Long-Term Trials

CA systems research started in 1996 with zero tillage and, in 2002, converted to full CA embracing minimal soil disturbance, retention of crop residues and crop rotation. Since then, five more such trials have been established throughout the province. The flagship CA trial conducted by the Western Cape Department Agriculture compares several crop and crop/annual legume pasture rotation systems to determine the potential implications of CA practices in systems with and without livestock. The trial was established in 1996 on the Langgewens Research farm near Moorreesburg, about 100 km north of Cape Town (3°17′0.78″ S, 18°42′28.09″ E, Fig. 4.1) and is now entering the 25th year of production.

The topography of the area consists of, mostly, rolling hills to flat sandy areas. The dominant soil forms are Swartland, Oakleaf, and Glenrosa (Soil Classification Working Group 1991), mainly derived from Malmesbury shale, shallow and stony. The maximum working depth of the soil ranges from 30 to 60 cm, coarse fragments make up 40–60%, texture is sandy loam with 5–15% clay and the range of carbon content 0.5–2.0% (Cooper 2016).

From 1996 to 2001, minimum tillage (scarifier and adapted seed drill) was used in all systems. From 2002 onwards, full CA production practices (no-till, crop rotation, and residue retention) were implemented for all crops in the experiment. All actions have been undertaken using normal-size farm implements. No-till seeding utilized a knifepoint opener (since 2016, a double-disc drill). All crops in each of the eight

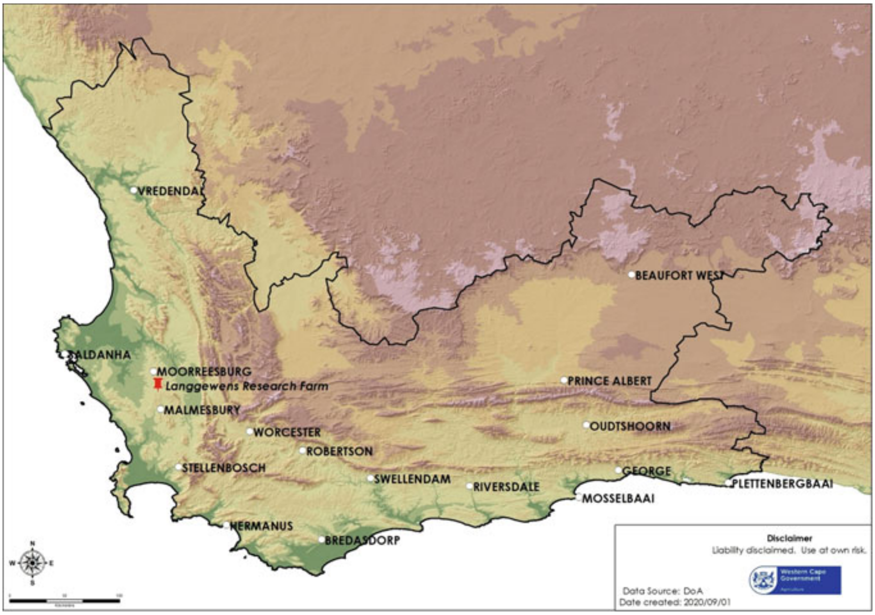

Fig. 4.1 Location of the long-term trials site in Western Cape Province

Table 4.1 Composition of the eight systems included in the Langgewens long-term crop rotation trial

System code	Rotation system	Letter sequence of each system
A	Wheat–Wheat–Wheat–Wheat	WWWW
B	Wheat–Wheat–Wheat–Canola	WWWC
C	Wheat–Canola–Wheat–Lupin	WCWL
D	Wheat–Wheat–Lupin–Canola	WWLC
E	Wheat–Medic–Wheat–Medic	WM^{g}WM^{g}
F	Wheat–Medic + Clover–Wheat–Medic + Clover	WMc^{g}WMc^{g}
G	Wheat–Medic–Canola–Medic	WM^{g}CM^{g}
H	Wheat-Medic + Clover–Wheat–Medic + Clover	WMc^{sg}WMcs^{g}

Note ^{g}Crop phases grazed by sheep; ^{s}With saltbush pastures to rest medic+/clover pastures

rotation systems were present on the field every year to allow comparisons between the various systems. Wheat, canola and lupin represent pure cash crops. Clover and annual medic are grazed by sheep at a stocking rate of four sheep per ha. Sheep are moved onto the forage crops when the medic and clover pastures self-regenerate in April or May (they are sprayed off in cash crops) but, in system H, sheep are kept off to forage on saltbush (*Atriplex nummularia*) for about 6 weeks until the annual medic/clover mix has reached at least 90% ground cover. Sheep also graze crop residues over the summer in systems E-H. Occasionally, to make planting easier, they are used in the ungrazed systems for a few days at the end of summer fallow that carries a lot of crop residue. All rotations are managed according to local best practices and industry recommendations.

No-till continuous wheat serves as the control. Wheat yield and system gross margin data from the 2002 to 2018 seasons are included in the following discussion. Eight 4-field crop rotations with a randomized block design are compared (Table 4.1). Crop species included are wheat (*Triticum aestivum*), canola (*Brassica napus*), lupin (*Lupinus angustifolius*), annual medic (*Medicago truncatula* and *M. polymorpha*) and white clover (*Trifolium repens*). Gross margins (including all direct allocatable costs) and yields of all crops were determined.

Yield

The yield data discussed here were obtained over 17 years following full CA implementation in 2002. Figure 4.2 depicts the average wheat yield for each system. On average, the systems that included a legume pasture and livestock out-yielded continuous wheat by 961 kg/ha (including droughts in 2015 and 2017 and big losses to wind damage in 2018). These crop-pasture systems also yielded 304 kg/ha more

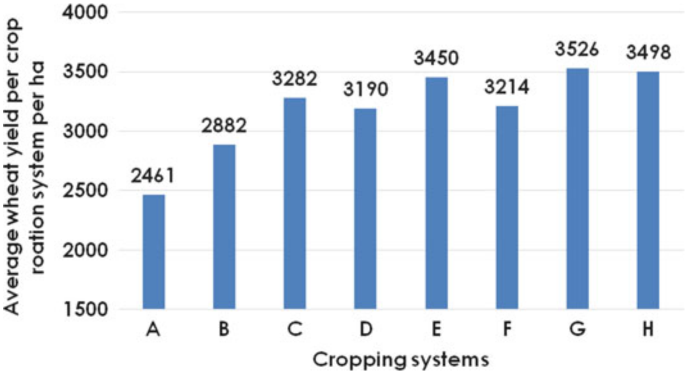

Fig. 4.2 Average wheat yield for each of the eight crop rotations from 2002 to 2018

on average than the three pure cash-crop rotations that included wheat, canola and lupin, which themselves yielded an average of 657 kg/ha more than continuous wheat. These might not seem big differences but, when the other crops and income from livestock are also brought into the picture, the economics changes dramatically.

Figure 4.3 compares improvements per system taking the average yield of continuous wheat as 100%. Substituting a single wheat crop in a 4-year rotation with a broadleaf cash crop increases the average wheat yield by 17% compared with continuous wheat; inclusion of two broadleaf cash crops resulted in an increase of 31% and inclusion of the annual legume pasture increased the average wheat yield by another 8%. Systems that included a single legume crop, over a 4-year period, increased average wheat yield by 31.5 and 39% in the systems where a legume pasture made up half of the rotation.

Figure 4.4 depicts the effect of crop rotation and the opposite effect of planting wheat on wheat. The reduction in the average wheat yield from two consecutive

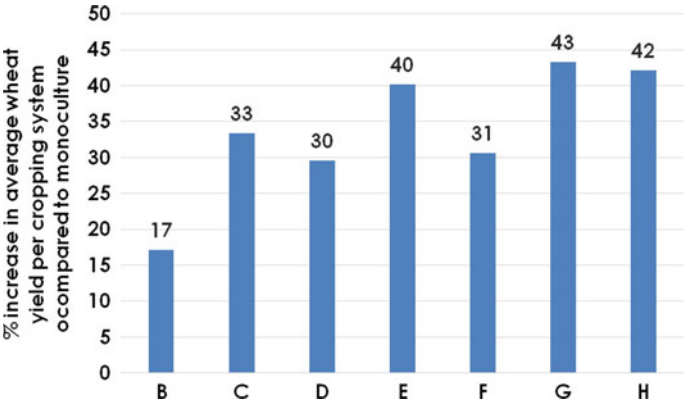

Fig. 4.3 Wheat yield improvement in different cropping systems compared to continuous wheat

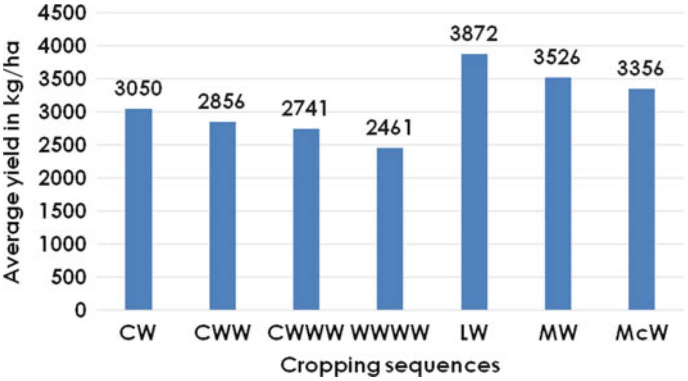

Fig. 4.4 Mean wheat yield after different predecessors: W = wheat, C = canola, L = lupin, M = medic, Mc = medic/clover

wheat crops is 282 kg/ha, exacerbated by a further 239 kg/ha for a third consecutive wheat crop, and a further 357 kg/ha for the fourth consecutive wheat crop. These yield losses may be attributed to increased weed and disease pressure year-on-year that is controlled by crop rotation in canola, lupin and wheat systems (Lamprecht et al. 2006, 2011). An integrated approach to management helps ensure the sustainability of CA cropping systems: seedbank data from the long-term CA trial has shown that effective control of weeds in a CA system lies in integration of cropping and livestock and management diversity (MacLaren et al. 2018). Herbicides and grazing apply contrasting selection pressures on weeds and this combination is more effective in reducing weed pressure than increasing herbicide quantities or mode-of-action diversity.

Hard-nosed farmers want to know why they should practise crop rotation as part of a conservation strategy when, if they bring in other crops, they will produce less wheat. Table 4.2 illustrates the reality if we take the average wheat yield per system, as discussed earlier, and convert it to total wheat production on a farm with 800 ha arable land. Systems are ranked for total wheat production and an indication of total production differences compared to continuous wheat.

System A, continuous wheat, produces the most wheat. Wheat in system C is planted on 75% of the available production area; in systems C, D, E, F, and H wheat occupies only 50% of the arable; in system G wheat is planted to only 25% of the cropping area. However, systems E, F, G, and H also have an animal component that contributes to their gross margins. The proportion of land allocated to wheat thus plays a significant role in the production ranking but, with the exception of systems B and G, all systems that produce wheat on only half of the production area only lose one-third of total wheat production compared with continuous wheat; in system H, the reduction is only 29%. Based on this ranking alone, our hard-nosed farmer would probably dismiss system G but, stepping back and looking at profitability, the picture changes dramatically.

Table 4.2 Total wheat production on an average wheat farm in different system scenarios

System code	Systems	Average wheat yield (kg/ha)	Total wheat production (kg)	Production ranking	Cut in total production compared to monoculture (%)
A	WWWW	2461	1,968,800	1	
B	WWWC	2882	1,729,200	2	12
C	WCWL	3282	1,312,800	5	33
D	WWLC	3190	1,276,000	7	35
E	WMWM	3450	1,380,000	4	30
F	WMcWMc	3214	1,285,600	6	35
G	WMCM	3526	705,200	8	64
H	WMcWMc + s	3498	1,399,200	3	29

Economic Comparisons for Whole Systems

The average gross margin per system depends on all its different components. In system B, gross margin is determined by the wheat and canola; in systems C and D wheat, canola and lupin contribute. Most of the pasture/crop systems have a wheat and a livestock component (wool and meat), while system G adds canola to the mix as well. Gross margins were calculated by subtracting direct allocatable production costs from the gross income for each system. All cash-crop systems were left ungrazed at the end of the season. The legume pastures were grazed during the production season, after which the residues of both the wheat and pastures in these systems were grazed during the summer months. Grazing was managed so that at least half of the crop residues were left on the field before the next planting season so as to meet the minimum soil-cover target of 30%. In Table 4.3, systems are ranked for gross income and an indication of total gross income differences compared with continuous wheat. The data used only cover the period up to 2015, after which lupin was replaced with a predominantly legume cover crop; the economics of the last three years are still under scrutiny.

The average gross margin of continuous wheat (System A) was the lowest while system H has the best. The cash-crop rotation systems (B, C, and D) show a 17% increase compared to continuous wheat; while the pasture/crop systems (E to H) record a 42.5% increase. The gross margins of systems C and D might have been higher but for the poor performance of the lupin crop: its average yield was only 1000 kg/ha and a low commodity price over several seasons resulted in a negative gross margin for this crop, which resulted in a lower system gross margin. The configuration of system D also contributed to somewhat lower gross margins: two years cereal followed by two broadleaf years with crops that share similar diseases contributed to lower average wheat and canola yields that cut the gross margin compared with systems C and B. The outstanding performance of system H can,

Table 4.3 Example summary of gross income on an average wheat farm in different system scenarios

System code	Systems	Average gross margin (R/ha)	Increase in gross income compared to monoculture (%)	Total gross income (Rand)	Gross income ranking
A	WWWW	2281		1,824,554	8
B	WWWC	2765	21	2,211,825	5
C	WCWL	2712	19	2,169,306	6
D	WWLC	2557	12	2,045,751	7
E	WMWM	3359	47	2,687,105	2
F	WMcWMc	3052	34	2,441,596	3
G	WMCM	2909	28	2,327,127	4
H	WMcWMc + s	3670	61	2,936,208	1

again, be attributed to the setup of the system: with the added saltbush pasture planted on marginal land, the sheep could be withheld from the legume pasture at the start of the growing season until a 90% cover was attained, which enabled a higher stocking rate compared to the other pasture/crop systems (Basson 2017).

When we look at the rankings of the different systems in terms of their gross margins (Table 4.3) we see a dramatic difference compared with their ranking by total wheat production in Table 4.2. Continuous wheat falls from first position to last. System B, the second-highest in total wheat production, falls from 2nd to 5th. System H outperformed all the other systems.

Input costs such as diesel, pest and disease control, and fertilizers are lower in the crop + pasture systems than in the cash-crop systems. This has a significant effect on the economic performance. If we also take account of the lower carbon footprint and the ecological benefit of the more diverse management strategies in systems E to H (MacLaren et al. 2018), the sustainability of these systems is clear. The benefit of integrating cropping and livestock is abundantly clear when we compare the average gross margin of all the cash-crop systems with the average of the crop + pasture systems (Fig. 4.4). Chatterton and Chatterton (1996) made the same point in their development work with annual medic pastures in the comparable environments of South Australia and the Maghreb (Fig. 4.5).

It's All About Creating Resilience

In 2003, one year after implementing CA, the average wheat yield was only 524 kg/ha. This was a consequence of only 210 mm of rain during the April–September growing season (well below the long-term average) and very little rain during the first

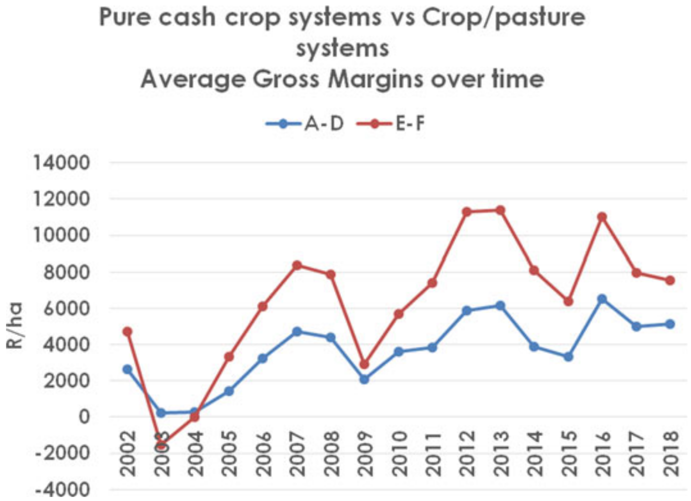

Fig. 4.5 Economic comparison of cropping and integrated systems based on gross margins

4 months. Only the rotation systems that included medic and medic-clover pastures managed to sustain the wheat until August and September when most of the season's 210 mm arrived. The 2015 season recorded even lower rainfall: 169 mm (the second driest year in the area since 1900) but the benefits of surface cover by crop residues and better soil structure under CA brought better infiltration and a greater water holding capacity that supported an average yield of 2000 kg/ha. The average yield over all seasons and rotations (except the two drought years) was 3500 kg/ha on 351 mm of rainfall in the growing season. The CA effects were even more striking in 2017 and 2019 (data not included in other figures): in 2017, wheat yielded an average of 2488 kg/ha on 175 mm of in-season rainfall, while in 2019 the average was 3658 kg/ha on 210 mm rainfall, even though only 28 mm fell during the grain-filling stage.

Projections of global heating point to an increase of between 1.5 and 3 °C over the next 30 years. In South Africa, this will likely mean heat waves and greater occurrence of drought; possibly, rains will be less frequent but more intense. Overall, the prediction is that our climate will become more unpredictable (Midgley et al. 2016). The synergy of no-till (minimum loss of soil and soil carbon) and the use of diverse rotations and cover crop mixes (maximum soil coverage and carbon input) delivers not only soil regeneration through carbon capture but, also, the potential for drought proofing the landscape, a must in the current climate-change scenario (Rosenzweig et al. 2002).

Effectiveness of the System in Reducing Inputs

The benefits of CA lie not only in better yields and gross margins but, also, reduced inputs. There is a perception that no-till systems depend on the application of copious herbicide and insecticide. In fact, insecticide use has declined to the point that it is hardly ever necessary to spray. Moreover, a seed bank study over 12 years of the trial revealed that the crop + pasture systems were more effective in weed control than the pure cash-crop systems. The more diverse the system, the fewer the weeds—and these systems also used lower inputs of herbicides and fertilizer (MacLaren et al. 2018).

The efficiency of the systems is most easily illustrated in terms of the yield per mm of rain received and per kilogram of nitrogen applied. Systems that included at least one legume, be it cash crop or legume pasture, were 26% more effective than the monoculture in kilograms of wheat produced per millimeter of rain received. System B that included a single alternative crop, canola, was 11% more effective in its water use. Systems based on legume pastures used applied nitrogen 89% more effectively than the control. The two systems that included a single lupin crop was 35% more effective in nitrogen use; even system B was 9% more effective. When it comes to the amount of nitrogen applied per ha, the average application rate dropped by 53% from 1997 to 2002. From 2002 to 2018 the reduction was 57%, and another 4% from 2018 to 2019. From the start of the trial until the end of 2019, the nitrogen application rate has dropped from an average of 129 kg per ha to 46 kg per ha. If we take account of the carbon footprint of manufacturing nitrogen fertilizer, this is much more environmentally friendly. Carbon capture increased over the time span of the trial: the average increase over all the systems since 2002 has been 32%. Increase has been slow because of the prevailing climatic conditions; in the Western Cape, the winters are cold and the summers are dry. Soil carbon builds up much faster in warm, wet climates.

What Next?

The long-term sustainability of agriculture depends on natural resources and, thus, the conservation of these resources. The necessary change in the farming system needs support at every level from central government to investor and consumer choice. Conservation Agriculture practices strive for acceptable profits hand-in-hand with sustainable production and, at the same time, conserving the environment. In the Western Cape, CA enables the small farmer and the big farmer to keep farming. Some of the Province's leading producers have adopted it and the system has evolved—not least on the Research Farm.

The principles of CA are mutually supportive. They need to be practised as a comprehensive whole to realize their full potential. The inclusion of even more diversity through the use of cover crops is currently under scrutiny; the results so far are very positive, especially where the cover crops are used as part of the fodder flow on the farm. Current research efforts include the identification of bacteria and fungi associated, in particular, with wheat in various systems—with the idea that if we know what functional groups are associated with the wheat plant, we shall be able to advise a farmer what he or she needs to do to enhance beneficial microbial life.

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Chapter 5
Soil Degradation Problems and Foreseen Solutions in Uzbekistan

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Abstract Soil erosion and salinity are long-standing afflictions of Uzbekistan. Regional climate change, already evident, is likely to exacerbate droughts and high summer temperatures; the future rainfall regime is unknown. All these hazards will increase the risk of land degradation. The Aral Sea has been declared a *zone of environmental innovation and technology* but, beyond sowing halophytes in its dry bed, we are a long way from restoration. New and different ways have to be found to combat these challenges including science-based crop rotation taking into account soil characteristics; sustainable farming systems adapted to the harsh landscape; widespread adoption of agro-ecotechnology, biotechnology and information technology in soil conservation and land use planning; and effective ways to combat salinization, erosion, depletion of soil organic matter, and compaction. All need a sound theoretical base. Innovations under trial include soil improvement with a range of vegetable crops and legumes, application of various composts including worm compost from household waste and biogas production residue, microbiological preparations, and systematic reclamation of gypsum soils.

Keywords Climate change · Soil erosion · Salinity · Aral Sea · Policy and technical responses

Introduction

Uzbekistan is one of the big states of Central Asia with more than 33 million people, extensive irrigated agriculture and developing industries. The diverse landscape ranges from high mountains, foothills, and plains, to depressions. The plains include the Ustyurt Plateau and the Aral lowland in the northwest, most of the Kyzyl Kum

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Desert and the adjoining steppes that grade into the foothills. In the east are mountain ranges enfolding the valleys of Ferghana, Zerafshan, Kitab-Shakhrisabz, and Sherabad-Surkhandarya. The continental climate is characterized by big daily and seasonal temperature fluctuations; hot, dry summers; rains in autumn; and unstable winter weather. Except in the mountains and foothills, it is arid so there are relict salt deposits as well as modern salt accumulations—and both of these have often been remobilized by irrigation (Juliev et al. 2017). Frost, heavy rains, hail, and strong winds can occur everywhere. The average wind speed across the plains is 3–4 m/s but gusts of 6–10 m/s raise dust storms on 10–30 days a year on flat land, up to 50 days on the Karshi Steppe and lower reaches of the Amu Darya, and up to 64 days in the Muynak steppe-desert in the Aral Sea region; winds in excess of 15 m/s that prevent sheep grazing occur up to 11 days a year. Local east winds in the foothills are known as *Bekabad* and *Kokand*; and hot, dry winds from the mountains, known as the *Garmsil* and *Afghan*, bring dust and sand storms (Belolipov et al. 2013).

Land Degradation

Geography makes the country vulnerable to land degradation that threatens the whole economy, agriculture in particular, and the living standards of the people. Land degradation is of long standing. It takes many forms: waterlogging and secondary salinization of irrigated land, pasture degradation and deflation in rangelands, deforestation and erosion by water in the mountains and foothills, compaction and depletion of soil organic matter in cultivated land everywhere, pollution by agrochemicals and industrial emissions, and the disastrous desertification of the Aral Sea (Aw-Hassan et al. 2016; Dubovyk et al. 2013; Egamberdiyeva et al. 2007; Gintzburger 2003; Nurbekov et al. 2016; Shaumarov et al. 2012; Shirokova and Morozov 2006; Strikeleva et al. 2018).

The many faces of land degradation are a consequence of interactions of physical, biological, political, social, cultural, and economic factors; some predetermined by nature but all of them exacerbated by failures of policy and planning, irrational management, and a lack of awareness and involvement of society at large (Nurbekov et al. 2016). Natural hazards include drought and floods, forest and steppe fires, and winds that exploit any weakness in the soil cover to bring deflation, dust, and salt storms. Long slopes promote water erosion, mudflows, and landslides (Juliev et al. 2019); depressions harbour waterlogging and salinization (Vogel et al. 2018); topography drives local winds; attributes of the parent rock determine subsidence and karst phenomena, soil texture, crusting, salinity, and predisposition to wind erosion; and the degree of buffering determines resistance to various toxic substances (Merritt et al. 2003). But there can be no dispute that mismanagement has played its part in the loss of soil organic matter and nutrients; soil contamination with pesticides; violation of stocking limits leading to bare ground and destruction of the soil structure that opens the door to deflation and sand encroachment over fertile land; deforestation leaving mountain slopes open to erosion (Gintzburger 2003; Mueller et al. 2014);

irrigation with inadequate drainage causing waterlogging and salinity, and reliance on big doses of mineral fertilizers and pesticides on cotton fields contaminates both land and water (Durán Zuazo and Rodríguez Pleguezuelo 2008).

The hazard of soil erosion is common to drylands everywhere. In Uzbekistan, out of the total area of 26 million ha of farmland, less than 6% *is not* subject to erosion. More than 4.7 million ha suffers from erosion by water (Strikeleva et al. 2018). Of the 3.7 million ha of irrigated land, 2.9 million ha (75%) is eroded to some degree, annual soil removal can reach 100–500 t/ha, and the annual loss of humus 500–800 kg/ha is equivalent to 100–120 kgN and 75–100 kgP/ha (Nurbekov et al. 2016; Shaumarov et al. 2012). Salinity affects 65% of irrigated soils and increased groundwater discharge brings secondary salinization, commonly with the formation of gypsum soils (Krasilnikov et al. 2016).

The Aral Sea

The Aral Sea is a glaring example of reckless exploitation of land and water resources. It was one of the world's largest enclosed water bodies, covering 68.9 km^2, with a volume of 1083 km^3 and maximum depth of 68 m, receiving an average annual input of 50–55 km^3 from the Syr Darya and Amu Darya rivers (Micklin 2014a, b). It moderated the regional climate, the wellbeing of the population, agricultural production, and regional ecology (White 2014), and it supported a valuable fishery. Large-scale construction of irrigation canals began in Central Asia in the 1930s and intensified in the 1950s. The irrigated area increased from 4.5 million ha in 1960 to 9.1 million ha, and annual water demand increased from 60 to 120 km^3, of which 90% was consumed by irrigation. In less than half a century, the inflow to the Aral Sea decreased four or five-fold; the volume of water in the sea decreased 15-fold, and its salinity has increased to 125–300 g/l—more than 10 times the average salinity of the oceans (Xenarios et al. 2019).

The dry sea bed, the Aralkum Desert, now comprises more than 5.5 million ha of salt flats subject to frequent dust storms that annually spread 100 million tons of dust and salt over a distance of 300 km or more (Krivinogov 2014). The number of days with temperatures above 40 °C has doubled and wintertime temperatures are now often below −30 °C. The catastrophe engulfed more than half of the gene pool; the biological productivity of the whole region decreased ten-fold. From the Red Book, the Turanian tiger, Asian cheetah, Ustyurt sheep, and striped hyena are lost; the saigak was on the verge of extinction; and the Red Book has been supplemented by 11 species of fish, 12 mammals, 26 species of birds, and 11 species of plants (Matsui et al. 2017).

In response, however belated, the Aral Sea has been declared a *zone of environmental innovation and technology*. It remains a focus of attention for international organizations, politicians, and experts from around the world (Wheeler 2018). A state program to improve conditions and quality of life in the Aral Sea region from 2017 to 2021 was approved with a budget of 8.4 trillion sum ($US 81 billion). At the same time, Uzbekistan initiated a multi-partner trust fund for human security for the Aral Sea region, which received UN support. The Government has promulgated a National Environmental Health Action Plan, National Strategy and Action Plan for the Conservation of Biological Diversity, and National Action Program to Combat Drought and Desertification (Yang 2011). In the period 2013–2017, more than 500 projects have been undertaken—in particular, aerial seeding of 350 thousand ha on the dry seabed with saxaul *(Haloxylon ammodendron)* and other salt-tolerant plants to stabilize the soil. A related program has improved 2.2 million ha of irrigated land, reducing by 10% the area of land with critical groundwater levels.

Climate Change

Climate change isn't a problem for the future: *it is a problem now*. And agricultural strategy should take account of it (Lioubimtseva and Henebry 2009). Three-quarters of the country is desert occupied by hard-to-manage grey-brown soils, takyrs, sand, and salt marsh. The remaining quarter, in the high-altitude zone of dark grey and brown soils, meadow steppe and hydromorphic soils is now at greater risk of frosts and drought as the snow melts sooner year on year. In the face increasing aridity, soil and water resources are limited and their current condition is alarming; over the past 30–50 years, the soil organic matter and nutrient content has declined; salinity, soil erosion, and pollution by heavy metals, fluorides, and agrochemicals have all worsened (Mustaeva and Kartayeva 2019).

Across Central Asia, regional climate change means more extreme weather events, changes in the rainfall regime, and further land degradation. By 2050, depending on the predictive model, the region may experience an increase in mean annual temperature of 1.9–2.4 °C with the greatest warming in winter and spring; and mean annual rainfall may increase by 15–18%, mostly through summer rains, or it may not. What is certain is more risk for agriculture with its dependence on already insufficient water resources, most particularly in the Aral Sea Basin where the water deficit will increase from 2 km^3 (in 2005) to 11–13 km^3 in 2050. By way of compensation, a longer growing season may make it possible to grow new crops (Haag et al. 2019; Reyer et al. 2017).

Priorities for Land Use and Soil Science

Urgent and far-reaching action is needed to combat land degradation and establish more sustainable land use across the country. What is missing? What else do we need to know? These are good questions and our answer is Plenty, both practical and theoretical. Necessary practical improvements in agronomy, soil science, and technology include:

- Effective methods to combat salinization, erosion, depletion of humus, and compaction
- Sustainable farming systems adapted to our harsh landscape
- Introduction of science-based crop rotations according to the best predecessors for each individual crop, taking into account soil characteristics
- Widespread adoption of agro-ecotechnology, biotechnology and information technology in land use planning and soil protection.

All these need to be underpinned by better theory, so we also need:

- Investigation of the processes of transfer of substances and energy in the upper layers of the soil
- Theoretical foundations and effective technologies for reclamation of dryland, saline, gypsum and eroded soils
- Improved soil classification
- Inclusion of agricultural science in the training for the agricultural sector, and integration of higher education, agricultural science, and production
- Promotion of soil science, drawing public attention to the problems of soil and land use and protection, and international cooperation to broaden and deepen our knowledge.

Innovative Methods and Technologies on the Test Bed

- *Improving the fertility of degraded soils by growing vegetables and legumes.* The standard forms of soya, chickpea, and asparagus beans (*Vigna unguiculata* ssp. *sesquipedalis*), used as the main crop or as a cover crop, improve the soil's chemical and physical properties, and increase its biological activity. Winter legumes, in particular, enrich the soil with nitrogen, other nutrients, and biologically active substances, increase microbiological and enzymatic activity, and improve soil permeability and the wet strength of soil aggregates.
- *Improving the fertility of degraded soils by enriching them with organic matter.* Soil fertility is enhanced by diverse crop rotations including perennials and cover crops, combined with 15–20 t/ha composted crop residues applied at the time of autumn ploughing. Biogas-production digestate is first-class organic fertilizer that greatly reduces the need for mineral fertilizers.
- *Increasing the fertility of degraded rangeland.* Seed germination and plant survival, soil health and pasture productivity have been improved by a suite of agro-eco-biotechnologies: microbiological fertilizers, hydrogels, nano-adapters, pelleting, and electrical treatment of plants with high forage value.
- *Improving the fertility of rainfed croplands.* The use of hydrogels, biological preparations, composts, new types of mineral fertilizers, and foliar feeding of grain crops improve grain quality and increasing productivity by optimum use of soil moisture.

- *Improving fertility and preventing secondary salinization on slightly saline irrigated lands.* Measures include autumn soil leaching, increased rates of organic fertilizers and the use of plant residues, crop diversification including legumes. The need for soil flushing is much reduced and the accumulation of organic matter makes for fertile, well-structured soils.
- *Reclamation of desert soils contaminated with oil and oil products* by bioremediation and phytomeliorants over 5–7 years, followed by restoration of fertility.
- *Reclamation of infertile soils with organic and mineral fertilizers based on secondary resources.* Less-costly organic and natural mineral fertilizers derived from glauconite, bentonite, and low-grade phosphorites by vermicomposting with manure, as well as bio-humus with mineral additives.
- *Vermicompost from solid household waste (SHW).* Composting organic waste and other materials using local lines of earthworms to obtain an economical organic fertilizer containing the basic nutrients and microelements. Bio-organic fertilizer enriches the soil with organic matter, macro- and micro-nutrients, increases biological activity, and improves soil's water-holding properties.
- *Phytomelioration: Liquorice (Glycyrrhiza glabra L)* grows for more than ten years and, at the end of the rotation, the rhizomes are harvested and the field is prepared for another crop. It enriches the soil with organic matter and increases water-resistant aggregates by 70–80%, reduces bulk density to optimum values of 1.3–1.4 g/cm^3 and its roots, penetrating to a depth of 3.5–4 m, lower the saline groundwater. *Indigo (Indigofera tinctoria)* is in demand in the world market. Studies under the ZEF/UNESCO project Bonn/Urgench State University have shown that it can be grown successfully on saline degraded land. Symbiotic root-nodulating bacteria fix nitrogen from the air and enrich the soil; as well as yielding the natural dye *indigo*, the crop makes good green fertilizer.
- *Nano-irrigation and drainage techniques* improving the ecological resistance of plants to extreme environmental conditions using small-volume biological preparations that increase germination energy and biological productivity of crops.
- *Management of saline and gypsum soils*. Measures include deep soil loosening, maintenance of collector drains, flushing the root zone, balanced plant nutrition; crop rotation of cotton (April–October)—winter wheat (October–June)—legumes (July–October)—grass under cover crops (October–March), soil enrichment with plant residues after harvest, timely inter-row cultivation; and biological methods of plant protection, fertilizers, and adaptogens.
- *Issuance of an agro-reclamation soil passport* of a farmer's field that includes complete information about soil, reclamation, and climatic conditions (topography, nutrients, salinization, basic soil properties, etc.) and which supports decision-making on effective agricultural practices.

Conclusion

The priorities for soil science in the context of adaptation of agriculture to climate change are:

- Optimizing the biological activity of soils under various soil and climatic conditions and farming systems, including further development and adoption of agro-eco-technologies
- Theoretical foundations and effective ways to combat salinization, erosion, humus decline, crusting, and pollution with heavy metals, fluorides, and agrochemicals
- Interaction between fertilizer efficiency, environmental factors, the specific needs of individual crops, and ways of applying fertilizer
- Science-based crop rotation, alternation, and placement of crops
- Environmentally-friendly farming systems adapted to particular landscapes
- Carbon balance in soils and agro-landscapes
- GIS technologies in rational use and protection of soil resources
- Water-saving technologies
- Rational use of forest resources and forest reclamation
- International collaboration on the management of the dry bed of the Aral Sea.

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Chapter 6
The Relevance of Black Soils for Sustainable Development

Luca Montanarella, Panos Panagos, and Simone Scarpa

Abstract *Black Soils* have attracted renewed attention from policy-makers and the public thanks to strong interest from China; an International Network on Black Soils was launched in 2017 and the first plenary meeting held in Harbin in 2018. The *Chernozem* originally defined by Dokuchaev in 1883 is the central concept of Black Soils but, more than 140 years on, these soils have been much changed by human intervention and there is a need for a new definition—including Chernozem but, also, other soils with similar properties. The term *Black Soils* is taken to encompass *Chernozem*, *Kastanozem* and *Phaeozem*—all characterized by thick, dark-coloured, humus-rich topsoil originally developed under grassland. Chernozems, in particular, are known for their granular structure, optimal bulk density, and goodly stock of plant nutrients; however, all these favorable properties are only present in soils within virgin ecosystems that are now rare. Black Soils make up only 7% of the land surface but they are of fundamental importance to food security; UN Sustainable Development Goal 2—to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture by 2030—will only be achieved if we introduce a mandatory framework for their sustainable management. Sustainable management means arrest of soil erosion, compaction, salinity, sodicity, pollution and soil sealing; maintenance of protective cover, a stable stock of soil organic matter both as a store of plant nutrients and as a carbon sink; maintenance of capacity to infiltrate and hold rainfall and irrigation water but drain any excess to streams and groundwater; and conservation of biodiversity to maintain essential soil functions.

Keywords *Chernozem* · *Kastanozem* · *Phaeozem* · Sustainable soil management · Soil organic matter

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Introduction

Black Soils are characterized by thick, black, humus-rich topsoil. Recently, they have attracted renewed attention from policy makers and the public led by strong interest from China—where they are highly significant for food production, especially in Heilongjiang Province. At the initiative of the Heilongjiang Academy of Agricultural Sciences, an International Network on Black Soils was officially launched in the wings of the Global Symposium on Soil Organic Carbon (21–23 March 2017) at FAO headquarters in Rome (Global Soil Partnership 2017). A plenary meeting, hosted in Harbin by the Heilongjiang Academy of Agricultural Sciences, the Soil Science Society of China, and Soil Fertilizer Society of Heilongjiang Province in 2018, resulted in the Harbin Declaration on the International Network of Black Soils.

This interest stems from recognition that they are the most productive soils in the world; they grow a lot of the world's food and play a big role in the international grain trade (Liu et al. 2012). They occupy an estimated 1.85 million km^2 worldwide (Fig. 6.1): as a continuous belt of steppe and forest-steppe landscapes from Ukraine through Russia and northern Kazakhstan to Central Asia and northern China, and more locally in Central Europe (Fig. 6.2); in the Great Plains of the United States and Prairie Provinces of Canada (Fig. 6.3), and in South America (Fig. 6.4). The central concept of Black Soils is the *Chernozem* (Black Earth in Russian) first described by Dokuchaev (1883). According to the World Reference Base (IUSS Working Group WRB 2015), Chernozem are characterized by a very dark topsoil *(mollic horizon)*

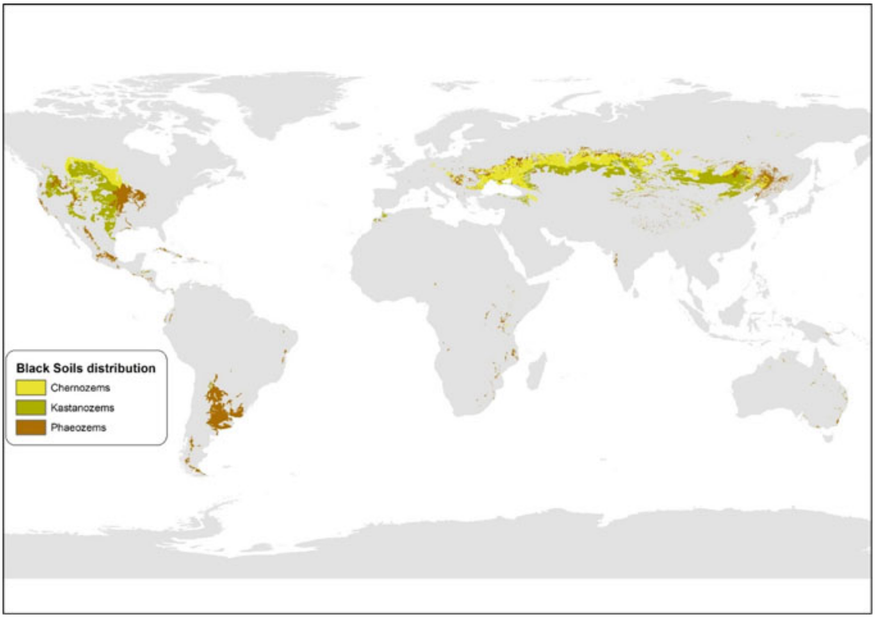

Fig. 6.1 Global distribution of Black Soils (HWSD 2012)

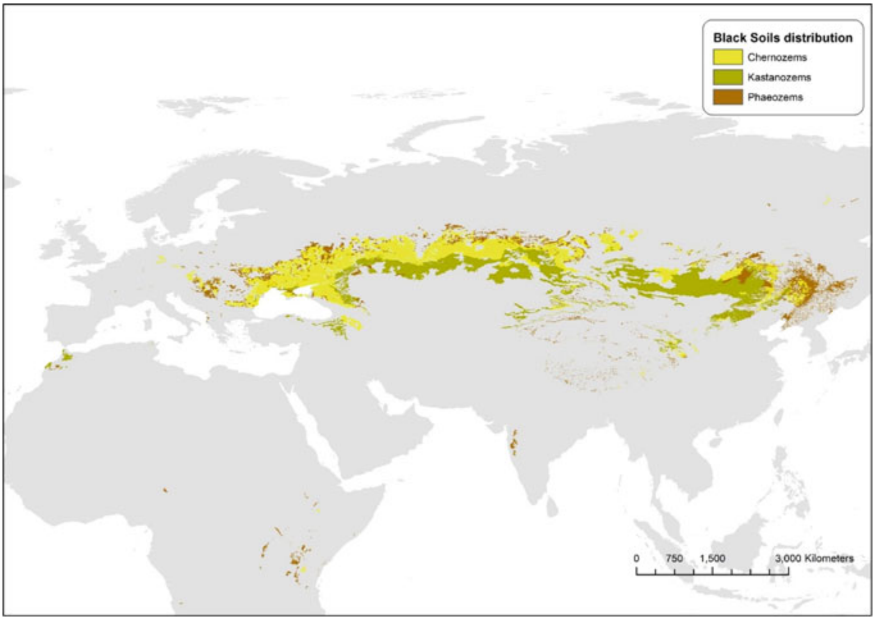

Fig. 6.2 Distribution of Black Soils in Eurasia and Africa (HWSD 2012)

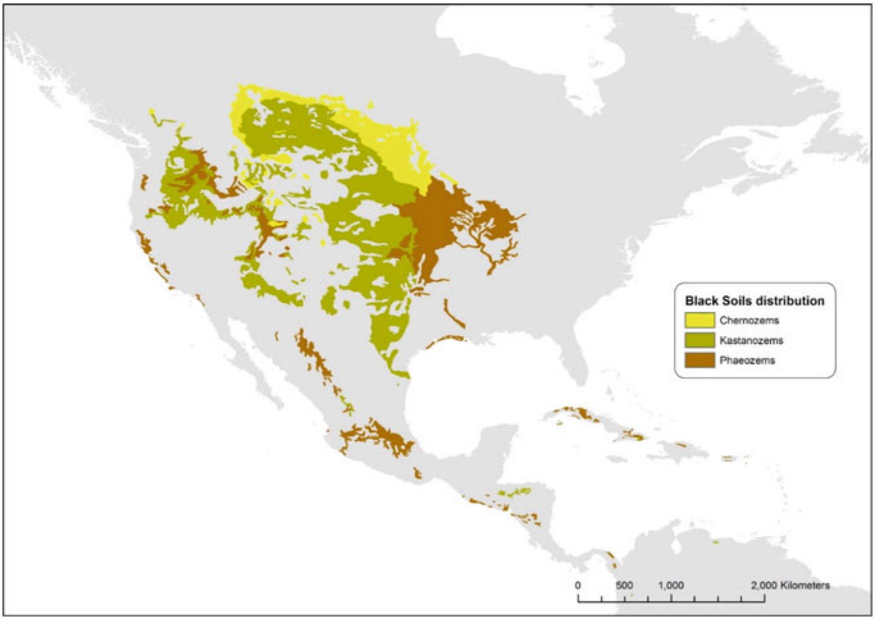

Fig. 6.3 Distribution of Black Soils in North and Central America (HWSD 2012)

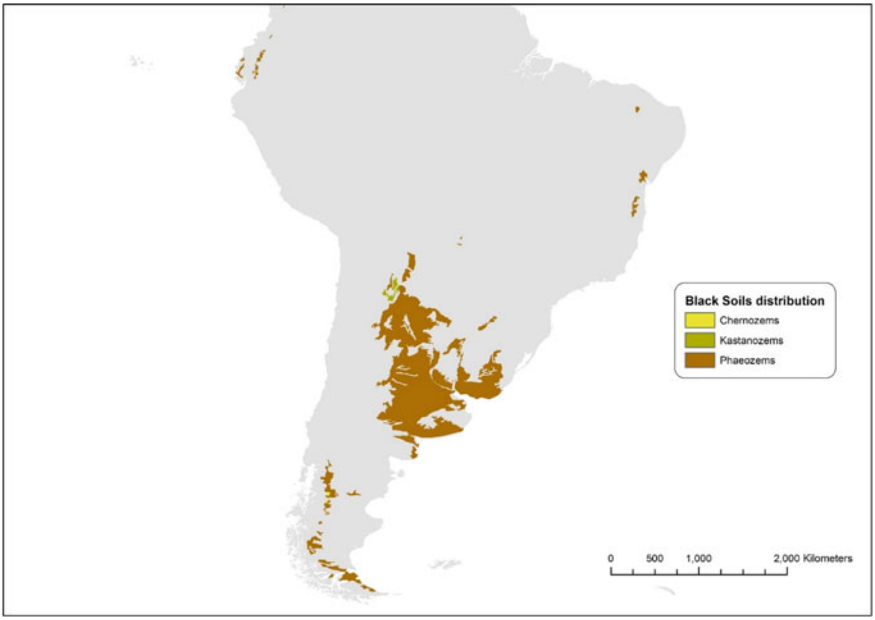

Fig. 6.4 Distribution of Black Soils in South America (HWSD 2012)

rich in organic matter (10–16%) and with a neutral reaction, saturated with bases, and by a concentration of carbonates in the subsoil. As highlighted in the Status of World's Soil Resources report (FAO and ITPS 2015), Chernozem are renowned for their unique structure and inherent fertility: the humus-rich topsoil may be a metre thick, distinguished by water-stable, fine granular structure, optimal bulk density, and a goodly stock of nutrients. However, all of these favourable attributes are only present in soils within virgin ecosystems that are now rare (Krupenikov et al. 2011). Most Chernozem are nowadays much changed by human intervention; being highly productive, they are almost entirely under intensive agriculture. Wheat, barley, and maize are the principal crops alongside oilseeds and forage for livestock.

Extending the Definition of Black Soils

Black Earth (Chernozem) as originally defined by Dokuchaev may be considered a valid historical definition of these soils but, more than 140 years on, these soils have been much changed by human interventions. There is a need for a new definition, including the Chernozem but, also, other Black Soils with similar properties.

Obviously, the first criterion for defining Black Soils is colour. Black soils are characterized by a black or blackish surface horizon, typically in crushed samples a Munsell colour value ≤ 3 moist, and ≤ 5 dry, and a chroma ≤ 2 moist. Typically, this corresponds with the *mollic horizon*, as described in the WRB or, with >2.5% SOC and strong granular structure, a *chernic* horizon. Other WRB horizons could also be included, like *fulvic* and *melanic* horizons, or the *plaggic* and *pretic* horizons resulting from human activities leading to the *Plaggen* soils in Germany and the Low Countries and the *Terra Preta do Indio* in South America. Many WRB soil groups could be included by only using the criterion of colour for defining Black Soils: Anthrosols, Chernozems, and Vertisols are typically black in their surface horizons so, obviously, using only colour to define Black Soils is not enough and may even be confusing.

Dokuchaev adopted the local Russian name Chernozem (black earth) in 1883 to denote the typical soils of the tall-grass steppe. Worldwide, Chernozems extend across an estimated 1.85 million ha, mainly across the mid-latitude steppes of Eurasia and prairies of North America. South of this zone in Eurasia, the *Kastanozem* of the short-grass steppe have a similar profile but their topsoil is thinner and not so dark as that of the Chernozem, and they exhibit more prominent accumulation of secondary carbonates in the subsoil. *Phaeozem* are much like Chernozem; they have a dark, humus-rich surface horizon, not so base-rich as in Chernozem, and are either free of secondary carbonates or have them only at greater depths. Kastanozem cover around 1.8 million km^2 and Phaeozem cover 7.25 million km^2 worldwide (Table 6.1). All three soils have strong accumulation of soil organic matter and high base saturation in the upper metre of the profile. All three should be included within the definition of Black Soils since they feature similar use and management and are distributed in similar environments. In total, the three groups of Black Soils cover around 10.9 million km^2 which is about the 7.34% of total land surface.

Umbrisols are, in many ways, similar to Black Soils. They exhibit with a *chernic* or *mollic* horizon and, often, a high base saturation. They have a significant accumulation of organic matter in the topsoil; many are under a natural or near-natural vegetation cover; but Umbrisols occur in cool to temperate humid regions, mostly mountainous and with little or no soil moisture deficit. They present completely different management and use compared to the previous groups.

In conclusion, while keeping Chernozem as the central concept of Black Soils, we might also include Kastanozem, Phaeozem, Umbrisols, Anthrosols, and Vertisols within a broader definition of black soils mainly based on soil colour. Nevertheless, the original idea for establishing a network of interested institutions for the sustainable management of Black Soils was the need to protect the highly productive soils of the mid-latitude Steppes and Prairies of Eurasia and North America. This means

Table 6.1 Distribution of Black Soils and their global coverage

	Surface (million km^2)	% of total land surface
Phaeozem	7.25	4.88
Kastanozem	1.8	1.21
Chernozem	1.85	1.25
Total Black Soils	10.9	7.34

essentially the sustainable management of Chernozem, Kastanozem and Phaeozem. All the other WRB reference groups that might also be considered Black Soils based on their colour should be excluded since they require very different approaches for their sustainable management and protection.

Sustainable Management of Black Soils

The main aim of establishing an International Network on Black Soils is to promote their sustainable management and protection for future generations. As the most fertile soils in the world and providing much of our food, we need to ensure their protection as a common good. The proposal to declare the *Typical Chernozem* in Moldova, first described by Dokuchaev, as a UNESCO World Heritage Site[1] was based on this universal recognition of the value of these soils for all of us.

The fundamental principles of sustainable soil management (SSM) have been endorsed by the FAO Members in 2016 (FAO 2017). In these guidelines, SSM is defined according to Principle 3 in the revised World Soil Charter:

> Soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing either the soil functions that enable those services or biodiversity. The balance between the supporting and provisioning services for plant production and the regulating services the soil provides for water quality and availability and for atmospheric greenhouse gas composition is a particular concern.

SSM is associated with the following attributes:

1. Minimal rates of soil erosion by wind and water
2. The soil structure is not degraded (e.g. no soil compaction) and provides a stable physical environment for the movement of air, water, and heat, as well as for root growth
3. There is sufficient surface cover (e.g. from growing plants or plant residues) to protect the soil from the elements
4. The store of soil organic matter is stable or increasing and, ideally, near-optimal for the local environment
5. Availability and flows of nutrients are enough to maintain or improve soil fertility and to constrain losses to the environment
6. Soil salinity and sodicity are minimal
7. Water (e.g. from precipitation and irrigation) infiltrates efficiently, is stored to meet the requirements of plants but any excess drains readily to streams and groundwater
8. Contaminants are below toxic levels (i.e. those that would cause harm to plants, animals, humans, and the environment)
9. Soil biodiversity provides the full range of biological functions

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[1] https://whc.unesco.org/en/tentativelists/5647/.

10. Soil management systems for producing food, feed, fuel, timber, and fibre rely on optimized and safe use of inputs
11. Soil sealing is minimized through responsible land use planning.

All these requirements for SSM are perfectly applicable to Black Soils.

Soil Erosion

Black Soils are subject to extensive erosion by wind and water (Fig. 6.5). The best-documented event is the Dust Bowl of the 1930s, in the USA, that drove mass migration and widespread hunger and poverty (Worster 2004). In response, the US Congress passed the Soil Conservation Act in 1935 and the Soil Conservation and Domestic Allotment Act in 1936 that included the establishment of the USDA Soil Conservation Service. This may be considered the best example of successful legislation reversing severe land degradation at a national scale. Thanks to the erosion control measures put in place, today's erosion rates in North America (Fig. 6.6) are much less than during the Dust Bowl event (Borrelli et al. 2017).

Of course, erosion of fertile soils has economic and social consequences because it reduces crop yields and has substantial and widespread off-site effects (Panagos et al. 2018). Sartori et al. (2019) estimate the annual loss of ~$8 billion to global

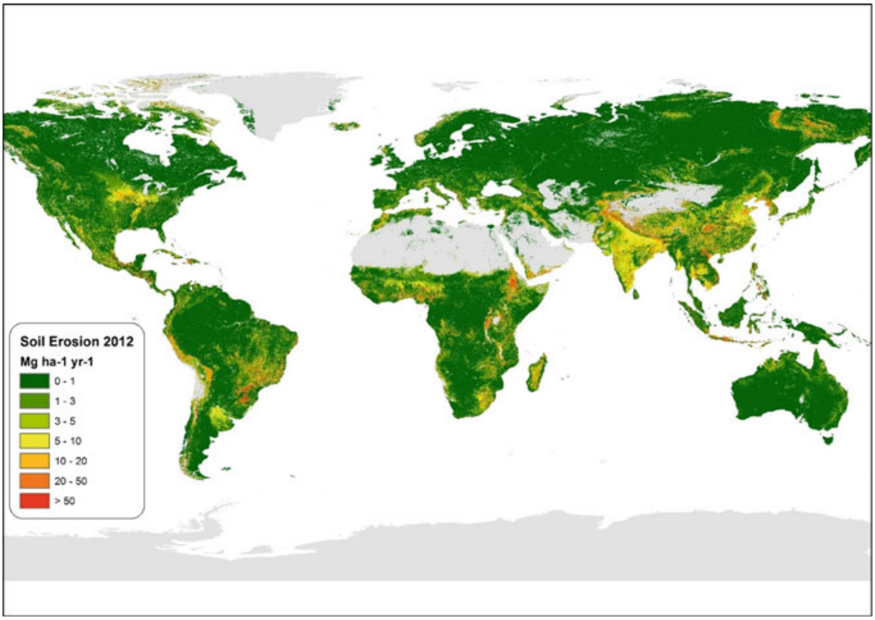

Fig. 6.5 Global soil erosion. Data from ESDAC, Borrelli et al. (2017)

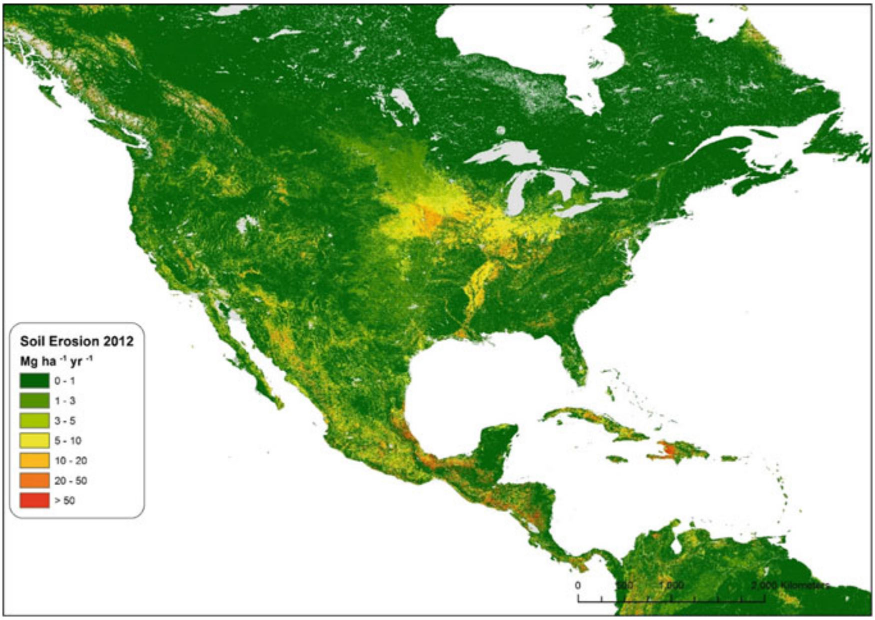

Fig. 6.6 Soil erosion in North and Central America. Data from ESDAC, Borrelli et al. (2017)

GDP from reducing yields by 33.7 million tonne and increasing water abstraction by 48 billion m^3. Nevertheless, other soil groups are experiencing more severe erosion than Black Soils (Fig. 6.7) and they too need attention.

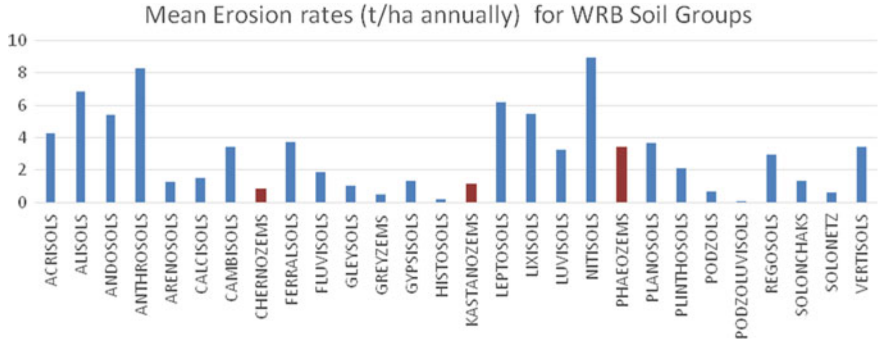

Fig. 6.7 Mean erosion rates in the major WRB soil groups globally

Loss of Soil Structure (Compaction)

Black Soils of Eurasia (Chernozem and Kastanozem) have suffered severe soil compaction through intensive agricultural use (Zhukov and Gadorozhnaya 2016). In particular, the use of heavy machinery under wet soil conditions has severely degraded soil structure in many areas of Ukraine and Russia (Medvedev et al. 2006). Chernozem are vulnerable to mechanical deformation because of their low bulk density and wetness at the time of spring tillage, compounded by low mechanical strength of the swelling smectite minerals that make up most of their clay fraction (Teich-McGoldrick et al. 2015). A shift to reduced tillage and Conservation Agriculture has substantially improved the situation in recent years (Medvedev 2012).

Contamination

A major threat to soils in general, and especially to Black Soils, is their exposure to contaminants. Heavy industry, urban expansion, mining, industrial and military activities have greatly affected soils of many parts of Eurasia and Northern America. Especially in Europe, a long history of industrial activities has bequeathed some 2.5 million contaminated sites (Lysychenko et al. 2017; Panagos et al. 2013) that may release contaminants into the food chain and, thus, threaten human health.

Conclusions

- Black Soils—defined as Chernozem, Kastanozem and Phaeozem—are an important, non-renewable natural resource but they are threatened by several degradation processes.
- As the most productive soils, they are of fundamental importance for sustainable development. UN Sustainable Development Goal (SDG) 2 which aims to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture by 2030, will only be achieved if we introduce a mandatory framework for the sustainable management of Black Soils.
- The priority in the areas holding substantial areas of Black Soils should be SDG target 2.4: *to ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality*.

- National authorities of these countries need to be aware of the global importance of this resource. And they need to be supported in the sustainable management of these soils. This should be the goal of the International Network on Black Soils and its tangible benefit for the international community.

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Chapter 7
Managing Chernozem for Reducing Global Warming

Rattan Lal

Abstract Chernozems or Black Earth in Russian (Mollisols in the USDA taxonomy), cover a total of 916 million ha or 7% of the world's ice-free land: 485 Mha in Eurasia, 290 Mha in North America and 102 Mha in South America. On the occasion of the first World Soil Day, 5th December 2005, the Chernozem was proclaimed *Soil of the Year* because of its environmental, economic and societal significance. Chernozems are formed under grassland across the Steppes of Eastern Europe, Russia and Central Asia, the Prairies in North America and on the Pampas in South America, under a wide range of climate with mean annual temperatures of 5–20 °C and annual rainfall of 500–1500 mm. Their thick, humus-rich topsoil contains 4–16% organic matter or 2–8% soil organic carbon (SOC) which creates a favourable structure, high water retention capacity and large plant nutrient reserves; and their subsoils exhibit a concentration of primary and secondary carbonates. Land misuse and soil mismanagement have accelerated soil erosion, undermined their productivity and depleted SOC with associated emissions of CO_2, CH_4 and N_2O. Fifty years or more of continual cultivation has depleted SOC down to depths of 120–130 cm with losses of 38–43% from the top 0–10 cm layer. Restoring degraded Chernozems is a win-win-win strategy with agronomic, environmental, economic and societal benefits including advancing the UN Sustainable Development Goals (SDGs). Restoration would sustain and enhance crop yields, use-efficiency of inputs and advance SDG2 (Zero Hunger). It would reduce gaseous emissions and sequester carbon while reducing risks of accelerated soil erosion and non-point-source pollution, advancing SDGs 6 (Clean Water) and 13 (Climate Action). It would improve farm income and profitability and advance SDG1 (No Poverty). And it would improve societal wellbeing and advance SDG3 (Good Health and Wellbeing). An important global benefit of restoring degraded Chernozems would be adaptation and mitigation of climate change by offsetting anthropogenic emissions; SOC sequestration with improved management can be 0.7–1.5 MgC/ha/y.

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Introduction

Chernozem or Black Earth is the common name of the soil of the Russian Steppes; in Soil Taxonomy they are called *Mollisols* (Buol et al. 2011). The Chernozem was vividly described by Dokuchaev (1883) as 'The Tsar of soils'. Together with minerals, plants and animals, Dokuchaev considered soils 'the fourth kingdom of nature' and, because of its importance in agriculture and human wellbeing, especially in Eastern Europe, 'Chernozem for soil science is comparable with the frog in physiology or calcite in mineralogy' (Shcherbakov and Vasenev 1999; Chendev et al. 2015a, b). Chernozems of Eastern Europe are of aeolian origin, formed from thick, calcareous loess (Gerasimov 1973). The black colour is due to the high concentration of soil organic matter (SOM) and *Typical Chernozem* has a SOM content of 5–6% in the surface layer.

Globally, Chernozems along with their dryland cousins the *Kastanozems* and non-calcareous *Phaeozems* cover a total of 916 million hectares (Mha) or 7% of the world's ice-free land area (Table 7.1). Of this, 485 Mha are in Eurasia, 290 Mha in North America and 102 Mha in South America (Liu et al. 2012; Montanarella et al. 2021). Thus, sustainable management of Chernozems has local, regional and global implications for our habitat, economy and society.

Environmentally, the big soil carbon pool in Chernozems has a significant role in the global carbon cycle (Mikhailova and Post 2006). It has two distinct but related components: soil organic carbon (SOC) and soil inorganic carbon (SIC). The SOC pool is derived from decomposition of the remains of plants and animals, live biomass and microbial by-products; it makes up approximately 50% of soil organic matter (SOM) or humus which is primarily composed of carbon, hydrogen and oxygen; it has a large surface area, high charge density (both positive and negative) and is a reservoir of essential plant nutrients (N, P, K, Ca, Mg, Fe, Zn, Mo etc.). As much as 90% of the SOC pool may be located in the upper 50 cm layer; under natural conditions, Chernozems can have 500 MgC/ha; 224 MgC/ha in the top 20 cm and another 211 MgC/ha

Table 7.1 Global land area under Chernozems (adapted from Liu et al. 2012)

Country/region	Area of Chernozems (million ha)
USA	200
Canada	40
Mexico	50
Eurasia	450
South America	102
China	35
World	916 (7% of the ice-free land)

in the 20–50 cm layer (Eremin 2016). However, cultivated soils commonly lose 20–30% of their native SOC; the rate of depletion of 1.0–1.4 MgC/ha/y is exacerbated by ploughing and extractive farming methods. Ploughing accompanied by increased soil erosion can lead to 38–43% losses from the SOC pool in the top 10 cm layer and measurable losses up to 60 cm depth have been observed in a 50-year continuous fallow (Mikhailova et al. 2000).

Chernozems also have a large SIC pool at >1 m depth composed of primary or lithogenic carbonates derived from the parent material, and secondary or pedogenic carbonates derived from dissolution of CO_2 in soil air to form carbonic acid, its reaction with Ca^{2+} or Mg^{2+}, and precipitation as carbonates (Lal et al. 2000). Leaching of bicarbonates is another mechanism of SIC sequestration, especially in irrigated lands (Monger et al. 2015; Bughio et al. 2016). The SIC pool in Chernozem may range from 100 to 200 MgC/ha (Mikhailova and Post 2006). The Chernozem of the northern Caucasus region is characterized by hard carbonate nodules that vary in size, internal porosity and recrystallisation, increasing with increase with the age in the chronosequence (Khokhlova et al. 2000).

Because of their economic, social and environmental importance, Chernozems were proclaimed Soil of the Year on 5th December in 2005, on the occasion of the first World Soil Day (Altermann et al. 2005). This proclamation was aimed at enhancing awareness of the importance of soil to policy makers and the general public. In contrast to plants and animals, the multiple functions and importance of soils in general, and Chernozems in particular, to ecosystem services are not readily discernible. The sequestration of SOC is also important to advance the UN Sustainable Development Goals (Groshans et al. 2018). Therefore, the objective of this chapter is to elaborate the processes, factors and practices of SOC sequestration for sustainable management of Chernozems.

Mechanisms of Sequestration of Soil Organic Carbon in Chernozems

The general principle of SOC sequestration is to create a positive soil C budget. Thus, the inputs of biomass-C (C_I) must exceed the amount of C taken out (C_O) from the soil (Eqs. 7.1 and 7.2):

$$\text{Soil C Sequestration} = C_I > C_O \tag{7.1}$$

$$\text{Soil C Depletion} = C_O > C_I \tag{7.2}$$

where C_I or inputs of carbon come from roots, straw, compost, manure and deposition (aerial, alluvial) and C_O or outputs of carbon comprise harvest (grain, straw, animal products), decomposition, erosion and leaching.

Quantification of the site-specific inputs and outputs is essential to developing the soil C budget and identifying appropriate land use and soil/crop management practices that sequester SOC, restore soil functions and provide essential ecosystem services. Once the SOC pool is being progressively improved through adoption of recommended management practices (RMP), it is essential that the sequestered C remains in the soil and is not emitted back into the atmosphere. In other words, the mean residence time (MRT) of SOC must be prolonged to the centennial and millennial-scale.

The principal determinants and control of MRT, or the mean rate of carbon renewal, are soil characteristics that: (i) enhance formation and stabilisation of micro-aggregates, (ii) reduce soil erodibility and decrease risks of accelerated soil erosion, (iii) increase translocation of SOC deep into the subsoil, (iv) moderate soil temperature and moisture regimes that affect decomposition and (v) maintain air-filled porosity at about half of the total porosity to moderate methanogenesis, nitrification and denitrification. Larionova et al. (2008) determined the rates of SOC sequestration by using natural ^{13}C abundance in Chernozem (in a 40-year corn monoculture with residue retention) and in a Grey Forest Soil. The MRT in Chernozem reached 1271–1498 years compared with 19–63 years in the Grey Forest Soil. Furthermore, the rate of renewal in Chernozem was 697 years in the upper horizons compared with 2742 years in the 40–60 cm layer and increased with a decrease in particle size.

The literature indicates several concepts in accord with the principles of increasing MRT: (1) with increase in stable micro-aggregates (Kuznetsova 1998); (2) decrease in particle size (Larionova et al. 2008); (3) increase in clay content (Bezuglova and Yudina 2006); (4) increase in input of root residues which decompose slower than the above-ground residues (Lazarev and Maisyamova 2006); and (5) with increase in the fossil humus content. In general, MRT is longer in closed (that is to say, natural) ecosystems (Ivanov et al. 2009). Herein lies the basis of sustainable management—or the principles of regenerative agriculture.

Recommended Management Practices of SOC Sequestration in Chernozems

RMPs for creating a positive soil C budget and prolonging MRT involve: (1) integrating crops with trees and livestock to create complex crop rotations and diverse farming systems, (2) adopting a system-based Conservation Agriculture (CA) featuring no-till (Lal 2015) and (3) using systems of integrated nutrient management that focus on CNPK rather than on NPK. A systems-based CA has four basic components: (i) elimination of mechanical seedbed preparation (tillage), (ii) retention of crop residues or mulch on the soil surface, (iii) use of complex crop rotations including incorporation of a cover crop in the cycle and (iv) adoption of integrated nutrient management systems with a judicious combination of organic and synthetic materials and discriminate use of supplementary chemical fertilizers based on soil testing and the desired crop yield. On the basis of data from long-term soil management experiments on some Canadian Chernozems (Dumanski et al. 1998; Bremer et al. 2008; Zavalin et al. 2018), the following RMPs are proposed: (i) elimination or reduction of summer fallow, (ii) conversion of fallow to hay or cereals, (iii) balanced application of plant nutrients, (iv) adoption of effective measures for soil and water conservation and (v) use direct seeding methods. In the case of Canada, adoption of these RMPs could sequester 50–75% of total agricultural emissions of CO_2 for the 30-year period from 1998 to 2028 (Dumanski et al. 1998; Zavalin et al. 2018).

Protection/Restoration of Chernozems in Eastern Europe and the US Great Plains

In Eastern Europe, extractive farming and unsustainable management of the Chernozems reduced their productivity and severely depleted of their SOC pool by the mid-nineteenth century. Accelerated erosion by wind and water was the principal cause (Chendev et al. 2015a, b). A program to restore degraded Chernozems, generally known as Stalin's Plan for the Transformation of Nature, was approved in October, 1948. It involved establishing windbreaks and constructing ponds to increase water storage on about 120 Mha of degraded Chernozems, and irrigation across three major river basins, the Dnieper, Don and Volga covering a distance of 1000 km (Altermann et al. 2005). Understanding the historical evolution of soil/landscape processes and properties is pertinent to assessing the effectiveness of such a restorative program. Over time, these shelter belts enhanced build-up of SOC; similar accumulation of SOM in the 0–30 cm layer with the establishment of shelterbelts was observed on the Great Plains. Over the 55-year period since the establishment of shelterbelts in Russia, the average rate of SOC sequestration was 0.7–1.5 MgC/ha/y. In comparison, the rate of SOC sequestration in South Dakota was 1.9 MgC/ha/y (Chendev et al. 2015a, b).

SOC Dynamics in Chernozems

Formation of stable micro-aggregates protects and stabilizes SOC. The protected SOC pool encapsulated within stable micro-aggregates can be enriched in otherwise labile fractions of SOC (Rodionov et al. 2001). On the contrary, cultivation breaks down water-stable aggregates, increases mineralization of SOM, and decreases biological activity (Kuznetsova 1998; Rusanov 1998). After harvest, during the period from September to May, decomposition of stubble is more rapid than that during the summer. Further, the decomposition of root residues is slower than that of the shoot residues (Lazarev and Maisyamova 2006). Ploughing may deplete the SOC pool of Chernozems at the rate of ~1 MgC/ha/y (Eremin 2016). Ploughing and use of chemical fertilizers can alter biological activity, and some of these changes may be irreversible (Devyatova and Shcherbakov 2006).

Managing the SOC Pool in Chernozems

Since the 1980s, there has been an increasing interest in the sustainable management of Chernozems and, specifically, the amelioration/restoration of their properties (Shcherbakov and Vasenev 1999). There are also growing concerns regarding transformation and mineralization of the SOM, severe agronomic degradation and depletion of soil fertility, and accelerated rates of erosion of Chernozems including a progressive formation of gullies and severe dissection of the landscape. With business as usual, the degradation of Chernozems may be exacerbated by climate change. Thus, restoration and sustainable management of Chernozems is an imperative. Furthermore, 23 Mha of Eurasian steppe grassland converted into cropland in northern Kazakhstan from 1954 to 1963 (the so-called Virgin Lands Scheme) and abandoned with the collapse of Soviet Union must also be restored (Kraemer et al. 2015). However, technological options to re-cultivate the abandoned croplands in Russia, Ukraine and Kazakhstan (Meyfroidt et al. 2016) should be objectively and critically evaluated.

It is widely accepted that fallow aggravates the depletion of SOC pool (Janzen 1987). Potentially mineralizable SOC in a ploughed soil may be 1.9–3.9 times lower than that in soils under natural vegetation (Semenov et al. 2008); annual inputs of plant residues in a less frequently fallowed system would enhance potentially mineralizable carbon and restore soil quality. Karbozova-Saljnikov et al. (2004) observed that potentially mineralizable SOC was inversely proportional to the frequency of fallow; frequent fallows deplete the SOC pool through accelerated mineralization.

Increasing SOC sequestration, decreasing emissions and protecting the existing C pool in Chernozems are also appropriate strategies to mitigate climate change. Semenov et al. (2008) observed that the highest soil C sink capacity may follow the following order: *Leached Chernozem* > *Dark chestnut soil* > *Chestnut soil* > *Tundra soil* > *Grey forest soil* > *Sod-podzolic soil*. Dumanski et al. (1998) observed that the greatest potential for SOC sequestration in Canada is in Chernozems. In general, conversion of conventional ploughing to no-till enhances SOC sequestration; the RMPs for SOC sequestration in Chernozems are adoption of CA in conjunction with the replacement of summer fallow by hay or cereals. These technological options have the potential to offset a large proportion of emissions from agricultural operations. SOC sequestration can also happen through self-restoration when farmland is abandoned. Kalinina et al. (2011) evaluated the SOC pool after 8, 19, 37 and 59 years of cultivation abandonment and self-restoration in Chernozems in Russia. Naturally, the vegetation was transformed towards virgin steppe and the soils towards natural Chernozems; the SOC content increased from 38.9 to 54.5 g/kg in the 0–10 cm layer; the SOC sequestration rate for the 59 years of self-restoration was 520 kg/ha/y and the SOC stocks increased to 91% of that of Chernozems under natural vegetation.

Sequestration of Soil Inorganic Carbon in Chernozems

Carbonate accumulation in Chernozems, as in other soils of dry climates has pedological and climatological significance (Lal 2019). Pedologically, understanding the carbonate profile is an important tool for paleo-environmental reconstruction. Forms of carbonate concentrations in Chernozems are related to past environmental conditions. In the northern Caucasus region, Khokhlova et al. (2001) compared the carbonate profile of Chernozems under irrigated and natural moisture regimes for soils buried under archaeological mounds of 1600–1700 to >5000 years BP. Analysis of the carbonate profile showed that climate of the region during the second half of the Holocene (>5000 years BP) changed from dry and warm to more humid and cooler in 5000–4000 BP and the present era. Recent changes in carbonate profile due to agricultural activities are shown by the migration of carbonates by leaching and accumulation driven by the increased wetness of the upper 3 m solum between 1973 and 2006 (Ovechkin and Bazykina 2011). The SIC pool is also affected by land use. Mikhailova and Post (2006) reported that, in the Kursk region of Russia, the SIC pools in the top 2 m were 107 MgC/ha for native grassland, 91 MgC/ha for the yearly-cut hay field, 242 MgC/ha for the continuously cropped field, and 196 MgC/ha for the 50-year continuous fallow. Most of the SIC pool was as carbonates and stored below 1 m depth.

Cultivation of Chernozems can also affect the rate of sequestration of SIC. A comparative study of the Mollisols of the U.S. Northern Great Plains and the Russian Chernozems (Mikhailova et al. 2009) showed that cultivation of these fertile, Ca-rich soils of temperate grassland ecosystems decreased SOC but increased the SIC pool (Table 7.2); cultivation increased the ratio of SIC:SOC pools.

Mollisols contain both lithogenic and pedogenic carbonates, and the increase in SIC upon cultivation may be due to formation of pedogenic carbonates. Further, most of the carbonate formation in Mollisols occurs below the root zone and, therefore, below the zone of most biological activity (Mikhailova and Post 2006; Cihacek et al. 2002). Formation of pedogenic carbonates in cultivated Chernozems also happened due to changes in soil moisture regime and deep drying of the subsoil (Lebedeva 2002).

Table 7.2 Increase in SIC pool at 0–1 m in Mollisols in the U.S. and of Chernozems in Russia (adapted and recalculated from Mikhailova et al. 2009)

Country	Soil series	SIC pool (MgC/ha)		Ratio of SIC:SOC pool	
		Grassland	Cultivated	Grassland	Cultivated
USA	Amor	77	80	0.54	0.74
USA	Shambo	78	105	0.67	0.93
USA	Stady	4	24	0.0067	0.175
Russia	Kursk	9	35	0.026	0.200

Management Effects on Soil Physical and Hydrological Properties of Chernozems

Cultivation-induced changes in the SOC pool can strongly modify soil physical, mechanical and hydrological properties. Indeed, SOC content and soil physical properties are inter-related. Bezuglova and Yudina (2006) reported that the SOC content is closely correlated with soil texture and, especially, with the clay content; changes in clay content under intensive agriculture, caused by erosion and illuviation, may also impact aggregation and the proportion of aggregated clay. Furthermore, cultivation transforms the bonded humus fraction into a more active (labile) form that can be rapidly mineralized. In the Central Russian province of the forest-steppe zone, Kuznetsova (2013) assessed the impacts of agro-technology, agro-economy and agro-ecology during 1964–2002 on physical properties of *Typical and Leached Chernozems*: mechanisation, increased use of mineral fertilizers and decreased inputs of organics exacerbated the problem of soil compaction and soil physical quality (Table 7.3).

Land use can also impact rheological characteristics as Khaidapova et al. found in *Typical Chernozem* in the country around Kursk (Table 7.4). Soils under oak forest are more resistant to changes in rheological properties under loading, and these differ from those under ploughland and fallow.

Soil water storage in cultivated versus uncultivated (virgin) Chernozem differs between wet and dry years (Table 7.5). Decline in soil water storage during the dry year is an indication of the aridization of cultivated Chernozems. On the contrary, the

Table 7.3 Cultivation effects on physical properties of *Typical and Leached Chernozem* for 0–30 cm depth (adapted from Kuznetsova 2013)

Parameter	Natural soil	Cultivated soil
Bulk density (Mg/m^3)	0.93–0.95	1.05–1.20
Total porosity (%)	60–65	55–60
Water-stable aggregates (%)	72–86	43–60
Infiltration rate (mm/h)	170–312	60–180
Field capacity (%)	34–38	32–35

Table 7.4 Effect of land use on rheological properties (adapted from Khaidapova et al. 2016)

Land use	Total C (%)	Swelling (%)	Specific surface area (m^2/g)	Moisture content (%)	
				At maximum swelling	At liquid limit
Oak forest	6.5	30.4	114.0	72.9	49.8
Ploughland	3.3	16.5	98.8	63.6	39.9
Long-term fallow	3.0	17.2	86.6	56.5	35.7

Table 7.5 Soil water storage (mm of water) in cultivated and virgin Chernozems to 2 m depth (adapted from Lebedeva 2004)

Moisture regime	Summer		Autumn	
	Steppe	Cultivated	Steppe	Cultivated
Dry	100	88	112	83
Wet	100	112	101	125

supply of water in spring may exceed the evapotranspiration and, thus, lead to increase in water storage (Table 7.4). Such differences in hydrological regimes can also lead to changes in the migrational form of pedogenic carbonates. Aridization of cultivated Chernozems leads to ascending moisture flows and the attendant development of a carbonate-accumulative horizon due to the formation of pedogenic carbonates. Rapid drying of Chernozems even in subsoil layers enhances formation of secondary carbonates (Lebedeva 2002).

Soil physical properties and moisture regimes are also affected by fertilizer use, tillage and crop rotation. Borontov et al. (2005) reported that application of organic and chemical fertilizers enhanced soil water uptake by sugar beet. Further, sugar beet in rotation with clover increased soil water consumption coefficient more than alternation with fallow. Water supply and productivity of sugar beet were greater with mouldboard ploughing and manuring than with reduced or zero tillage and chemical fertilizers.

Management Effects on Soil Erosion

Pulverization of soil by tillage is the primary cause of accelerated erosion of Chernozems. Bulygin (1993) reported that Chernozems in the steppe zone of Ukraine are severely eroded and black storms caused by wind erosion are common. Soil erosion is also widespread in ploughed croplands of Western Siberia; Tanasienko and Chumbaev (2010) reported that the water content in the surface layer exceeds field capacity in the late fall. During winter, an ice barrier is formed in the humus horizon and, being impermeable to snowmelt, such barriers increase runoff and aggravate erosion. However, Gusarov et al. (2018) report that adoption of effective conservation measures is leading to a decreasing trend of erosion of arable *Southern Chernozems* across the south-eastern boundary of Russia with Asia.

Conclusions and Researchable Priorities

Synthesis of the literature presented above supports the following conclusions:

- Cultivation of Chernozems can decrease SOC content of the surface layer by ~30% and the depletion of SOC can extend beyond 50 cm depth. The magnitude of depletion is exacerbated by ploughing and accelerated erosion by water and wind. Black dust storms are common in ploughland.
- Cultivation also degrades physical, rheological and hydrological properties of Chernozems.
- Chernozems sequester atmospheric CO_2 in the form of SOC and SIC. Whereas cultivation may decrease the SOC, it increases SIC through the formation of secondary/pedogenic carbonates. Changes in soil moisture regime also enhance the formation of pedogenic carbonates.
- Protection, restoration and sustainable management of Chernozems is a high priority because of their high soil C pool and soil C sink capacity.

Researchable priorities for management of Chernozems include:

(i) Improving quantitative estimates of the ecological state of Chernozems
(ii) Understanding the temporal changes in soil quality of abandoned cultivated Chernozems
(iii) Assessing and understanding the temporal changes in soil quality, soil properties and, in particular, SOC and SIC pools when cultivated land reverts to nature
(iv) Evaluating the potential and achievable rates of SOC and SIC sequestration in Chernozems worldwide
(v) Evaluating the cause-and-effect relationship in SOC content and crop yield on degraded Chernozems.

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Chapter 8
Climate-Change Policy for Agriculture Offsets in Alberta, Canada

Tom Goddard

Abstract The number of countries with carbon pricing has increased five-fold over the last 12 years. Carbon markets that constrain big emitters and allow offset purchasing and trading are also increasing. Agriculture is recognized as an emitter of greenhouse gases (GHGs) as well as an economic sector that can store or sequester carbon. The Canadian province of Alberta is both the country's largest source of all GHGs and agricultural emissions as a consequence of its big industrial and agriculture sectors. It was the first province with a climate-change policy, and with amendments to that policy in 2007 to include GHG offsets, it became the first jurisdiction to implement agricultural offsets. The conservation cropping protocol is used by aggregator companies to assemble large projects to attract the big final emitters. This voluntary market rewards farmers for no-till practice if they comply with the protocol requirements including a third-party audit. Since 2007, about 14 million tonnes of offset valued at 143 million Euros have been supplied to market by this one protocol.

Keywords Greenhouse gas offsets · Voluntary markets · No-till

Background

Interest in greenhouse gas (GHG) offsets has been around since governments and industries started measuring emissions and seeking ways to reduce them, whether by voluntary or regulated systems. The most recent carbon pricing report from the World Bank (2019) reveals a growing assemblage of carbon pricing policies; much of that growth is in Canada and the Americas. Only 20% of global emissions have a price on their head but the proportion in Canada is much higher at 80%, the EU and Australia with 50% and China with 33%. The World Bank carbon pricing dashboard (2020) displays 58 carbon pricing initiatives in place in 2019, compared with 10 in 2007 when Alberta was the only listed jurisdiction outside Europe. The current mixture of sub-national, national and regional initiatives indicates a willingness of

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policy makers to try a range of tools to incentivize reduction of GHG emissions. The World Bank's review of compliance systems reveals a range of carbon prices from zero to \$US125/tCO_2, most within a range of \$20–30/t. However, Hamrick and Goldstein (2016) reported pricing in voluntary markets in a range of \$3–6/t, so offsets in a voluntary market need a very low transaction cost in order to interest suppliers.

Agriculture has been recognized as a big contributor to global GHG emissions (IPCC 2019) as well as a potential contributor to their mitigation (Smith et al. 2008). Mitigation can be achieved by changes to cropping, forestry and land management and various livestock management practices. In nearly all cases, GHG mitigation is accompanied by other ecosystem benefits such as improved soil and water conservation and biodiversity; in many cases, there are economic improvements and resilience in the face of extreme weather events. Carbon capture can be achieved through a range of strategies from restoration of degraded landscapes to agronomic management and no-till planting (Lal 2008, 2021).

Canada has created climate-consciousness, certainly since the Canadian chairmanship of the Rio Conference and Declaration in 1992 and, subsequently, following various paths and activities at international, national and provincial levels considering the issues of GHGs, climate change and the policies to elicit desired actions (Swallow and Goddard 2016). Over several decades, awareness and concern about GHG emissions have prompted investments in research into industrial as well as agricultural impacts and into measurement and management and of GHGs. The province of Alberta is responsible for the biggest share of Canada's GHG emissions (Table 8.1) as well as supporting a vibrant agricultural sector supported by research and expertise that is fully engaged in policy and science development at every level which enabled it to develop agricultural protocols for an emergent GHG offset system in 2007.

Local Context

Since World War II, Alberta's developing energy economy and agriculture have accounted for both the largest proportion of national total emissions (37%) as well as the largest proportion of national agricultural emissions (32%); the former from coal-fired power stations as well as an oil and gas production and processing industry, the latter because Alberta has nearly one-third of Canada's agricultural land and a large ruminant population. Alberta needed to give a lead in GHG policy development to make a difference to national emission inventories and trajectories and, in 2002, became the first province with a climate-change policy. Amongst other things, this directed big emitters to record and report GHG emissions. At that time, some other provinces and the national government were moving in similar policy directions—the national government was considering emission offsets and protocol

Table 8.1 Greenhouse gas emissions from all sources and the agricultural sector, by province, expressed as a percentage of total Canada inventory, 2015

Province	Total	Top 5 rank	Agric	Top 5 rank
Newfoundland/Labrador	1		0	
PEI	0		1	
Nova Scotia	3		1	
New Brunswick	2		1	
Quebec	11	3	13	4
Ontario	24	2	17	3
Manitoba	3		11	5
Saskatchewan	10	4	22	2
Alberta	37	1	32	1
British Columbia	9	5	4	
Yukon	0			
NW Territories	0			
Nunavut	0			
Canada	100		100	

development—but a change of national government in 2006 brought national climate policy development to an abrupt halt.

Alberta, however, forged ahead and amended the Climate Change and Emissions Management Act in 2007 to require big final emitters to reduce their emissions. As of 2007, facilities emitting more than 100,000 tonnes of CO_2 equivalent per year had to reduce their emissions by 12% below their baseline, which was the three-year average established since 2002. If they failed to meet their target at the annual reconciliation period, they could make use of any combination of three options to comply:

1. Purchase others' or use their own emission performance credits (EPCs) from any facility that reduced more than the required emissions
2. Purchase emission offsets produced within Alberta using government-approved protocols
3. Pay into a Tech Fund at a set rate, initially \$C15/t (increased to \$C30/t in 2018). The fund is largely used for investment in research into technologies that reduce GHG emissions in any sector.

The stage was set for more than one hundred regulated facilities either to reduce their emissions or to purchase compliance tools.

Offsets

Since the offset system arises from an Act of Parliament that has fiduciary implications for the provincial budget, the Alberta Auditor General followed these developments keenly and has audited the process and products several times; the Alberta agricultural offset protocol and projects may be the only ones in the world to have undergone such scrutiny. A positive result is that the guidance documents have been revised in the light of the auditor's requests: the negative side is a burden of transaction costs that diminish the revenues available to the farmer or offset originator. Even so, a science-based and policy-sensitive approach to developing protocols and projects provides transparency and assurance of real, measurable and verifiable reductions in emissions.

The general procedure for developing a protocol begins with a proposal to government, which reviews the initial proposal and offers advice (Fig. 8.1). If successful at this stage, the protocol goes through development of a draft that is submitted for a technical review and a government departmental review. Once that is completed, the protocol is posted for a public review, and if it passes scrutiny, it can be approved and posted for use. Involving technical experts, government staff and the public

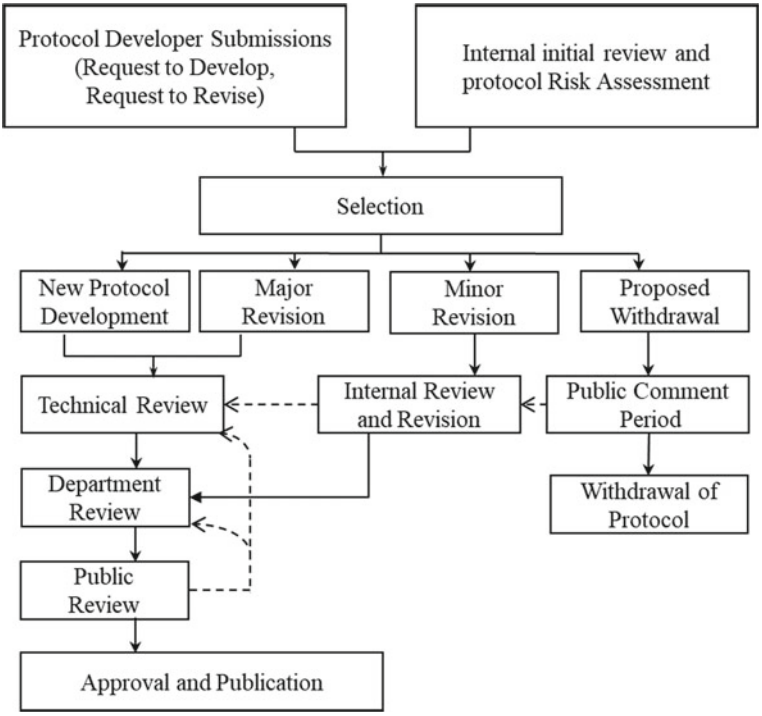

Fig. 8.1 Alberta protocol development and revision process (Alberta 2020)

assures that the science is sound; the protocol supports, is aligned with policy, and is pragmatic and sensible from the public perspective.

The most popular protocol, especially in the early days, has been for no-till annual cropping (part of the protocol development process is a review every five years so the no-till protocol has been revised and is now called the Conservation Cropping Protocol—CCP). The prohibitive cost of measuring changes in fields across the province, and verifying those measures and practices, was apparent at the outset. So, to keep down costs and allow all farmers to participate if they wanted to, a modelling approach was adopted to develop a pooled *coefficient of carbon storage*. The model developed for the national GHG inventory for the IPCC was applied to representative crop rotations for all major soil landscape mapping units (soil × climate polygons) in both conventional and no-till planting scenarios. It is anchored in several ways, including testing against tillage experiments conducted across the region (VandenBygaart et al. 2008, 2010), and it averages out soil extremes, inter-annual climate variability and crop varieties, as well as accounting for net changes in emissions of both carbon dioxide and nitrous oxide emissions through farm practice. Paustian et al. (2019) have reviewed approaches to quantifying carbon changes at scales appropriate for applications such as offset programs; the Alberta protocol is one example provided.

For simplicity, the province was divided into two zones—the dry prairie and parkland. The dry zone has *Brown chernozem* soils, and the parkland has *Black chernozem*. The polygon coefficients were aggregated to provide one coefficient each for the dry prairie and the moist parkland regions. Depending upon which side of the delineation line a field is located, the appropriate coefficient is applied. In the dry zone, the current sequestration rate for soil carbon when switching from full tillage to no-till is 0.41 $tCO_2e/ha/yr$[1], and 0.59 for the moist zone. The full range of coefficients can be found in Table 11 of the conservation cropping protocol (Alberta Government 2012). The coefficients have been reduced from the initial protocol of 2007 to reflect the change in the carbon pool from adoption of the practice over time.

The farm must also comply with annual cropping practices and utilize low disturbance planting equipment (there is a geometric calculation test of the ratio of opener to shank spacing that must be satisfied). Protocol requirements also include ownership so proof of land ownership is required or a rental agreement that allows the operator (renter) to transact on the changes in soil carbon.

Implementation of the CCP depends on *Aggregators*. These are intermediaries that work with many farmers to assemble individual contributions into one project that provides enough offset-tonnes to interest a buyer. Large facilities may need to purchase 100,000 tonnes of CO_2 offsets for compliance: They are not interested in many small-volume purchases. Aggregators may be a division or special service of an agriculture consultant, or a new company established for the sole purpose of aggregating offsets. They raise interest amongst farmers, explain the requirements, provide data support, and inject innovation and streamlining—all with the goals of holding down transaction costs, keeping farmer-clients happy, and providing a robust project to the verifiers. All projects must be third-party verified and submitted to the offset project registry (currently operated by the Canadian Standards Association) where each tonne is serialized. In addition to the third-party verification, the government may ask for an independent audit.

Results

Industries and government entities in Alberta now have more than a decade of experience in developing offsets in a regulated GHG emissions environment. Currently, there are 19 approved protocols that have been deployed to varying degrees (Alberta 2020 and Fig. 8.2). Although regulated facilities were not limited as to how much of each of the three compliance options they utilized, they have always made use of all three to varying degrees. Offsets grew from 20% of compliance obligations in 2007 to 51% in 2011. Since then, they have dropped back to 25% or less. The cumulative total tonnage in projects from July 2007 to March 2019 is 51.4 million tCO_2e, of which 75% is retired or pending retired status; and the remainder is active (available for transacting). The Conservation Cropping protocol has supplied just over 14 million tonnes.

Assuming a value of $C15/tonne that amounts to $C210 million or about 143 million Euros (since 2017 Alberta has doubled the set price to $C30/tonne). And

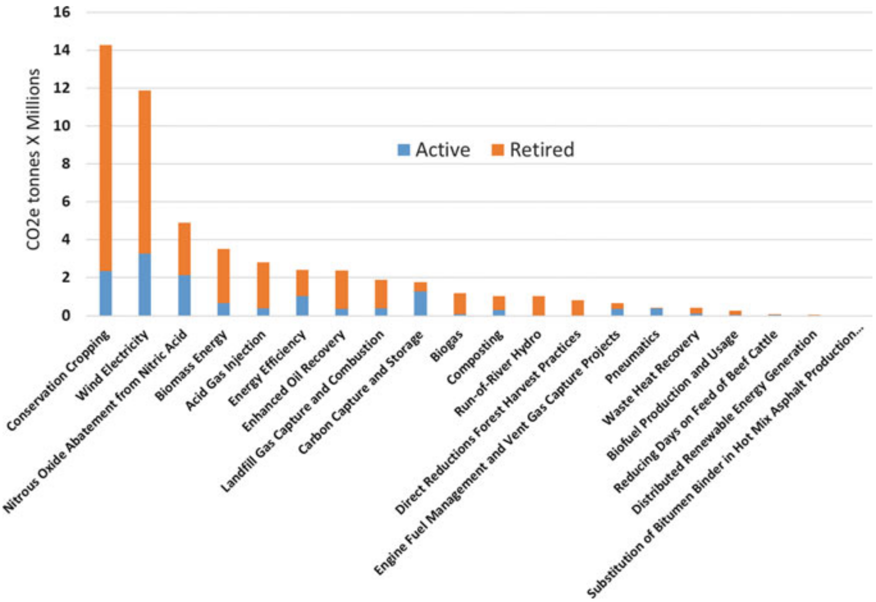

Fig. 8.2 Alberta active and retired (used) offsets as of March 2019

what appeals to government is that the money comes directly from the regulated industry to other entities providing offsets (e.g. farmers); government involvement is only needed for oversight of the system.

A downside to offsets is they incentivize change of practice only for a minority of the emission reductions that are possible. The concept of *additionality* limits the utility of offset policy to somewhere in the order of 10–40% adoption; the argument being that beyond a certain level, the practice will have overcome all barriers to adoption. In effect, it will have become common practice so incentives are no longer required. In Alberta, the CCP is nearing the additionality threshold, and the protocol will be retired (withdrawn).

Discussion

Alberta has learnt several lessons from over a decade of experience with GHG offsets. Here are a few:

- We need to move from reductionist science to integrative or systems science
- National inventory or other efforts for GHG accounting should be utilised
- Plot results need to be scaled up to regions and longer periods
- Operational policy is needed for protocols. Science is not enough
- Implementation needs more than a protocol: It needs a registry, verification, oversight, private sector involvement, new business models, and understanding
- Verification methodology that is practical and cost effective is needed for non-metered, biological systems
- There are many useful outcomes of ministries working together: the ease of moving beyond sustainability metrics (footprints), and new directions for research supported by government and industry.

In 2007, Alberta was one of the early jurisdictions to adopt carbon pricing along with an offset system for regulated facilities. Recent developments confirm that Alberta had developed sound policy 13 years ago. The national government has now developed nationwide carbon pricing with a proposed framework for GHG offsets that, for the most part, mirrors Alberta's (ECCC 2019); guidance for protocol development is expected sometime in 2020. There can be many points of debate that may encourage more players in society and business to get involved and reduce emissions. A few additional items deserve mentioned along with some elaboration of points that have already been mentioned briefly.

Additionality: Two kinds of additionality need to be considered. One is *emissions additionality*: the determination of both a baseline and a project emission value. The CCP used an adjusted baseline technique that accounted for soil carbon sequestered up to the present. Payments have been made only on subsequent incremental carbon capture. Other sources of reference material for standardized baselines are the International Emissions Trading Association (IETA) in Geneva, and the Greenhouse Gas

Management Institute in Washington DC. *Additionality of the practice or the technology* refers to its prevalence where an offset market does not exist. Alberta has developed technical guidance with a decision tree or test methodology for developers to review and assess additionality (Alberta 2020). Policy tries to find a balance between relaxed regulations that pay for offsets that would have occurred anyway under business as usual, and regulations that might be too stringent, discourage offset markets and not reduce emissions.

Conservativeness: This principle is guided by prudence—or cautiousness; that one should err on the conservative side of the ledger or transaction. If the principle is applied throughout the development of a protocol as well as a project, many tonnes of saved emissions are left unrecognized, unaccounted and not valued. Where errors are likely to be equally distributed around an estimated value, then an average value may be more correct and appropriate.

Indigenous peoples: Alberta created legal agreements between the national government and indigenous settlements to allocate carbon rights to their administrative body so that offsets could be transacted. This was a first in Canada. No issues or harms have been filed and indigenous tribal nations appreciate the responsibility of the custody of soil carbon resources.

Looking Ahead

The world is rich in international conventions and public or corporate initiatives aimed at enhancing or conserving natural resources. Very often, soil quality and soil carbon are at their core. With that focus, you might think that farmers, foresters and land managers would be in mind when policies are being developed. Unfortunately, that is not always the case. Good policy development needs to have bottom-up as well as top-down traits. Swanson et al. (2009) list traits of adaptive policy including decentralized decision making, multi-stakeholder deliberation, formal review and continuous learning. In Alberta, involvement of a wide range of scientists along with policy makers and industry representatives has been proven to yield robust protocols. Annual review meetings with the industry have also been invaluable in maintaining communications and fixing issues before they become problems. However, though it is honourable to examine the needs in detail, provide all available science-based information, and deliberate over policy, we will not get everything right. Adaptations or changes will be required. The main point is to start, as Alberta did more than 12 years ago. Governments change; opportunities emerge and recede; and policy and science specialists need to look ahead.

International conventions that support soil carbon and quality enhancements include:

- COP21: The Paris Accord called on countries to file Nationally Determined Contributions (NDCs) or actions at a national level that would mitigate GHGs

and recognize sinks including soil carbon. NDCs could include both market and non-market actions; France championed the *4 per mille* soil carbon initiative.
- UN Sustainable Development Goals: The 2030 Agenda, adopted in 2015, has 17 goals with actionable targets, several of which emphasize natural resource management including soils (directly or indirectly).
- The UN Convention to Combat Desertification has various initiatives including tree planting and a sustainable land management program.
- The International Convention on Biological Diversity, recognizing the need to go far beyond the percentage of protected areas (parks) to achieve its targets, is developing a new strategic plan this year. There is more interest now in 'Other Effective Area-based Conservation Measures' which could include recognition of the contributions of sustainable land management and support for the same.

The corporate sector is also becoming more carbon conscious. Corporations of all sizes have targets to reduce emissions or become net-zero by some future date; and their staffs are supportive of recycling and energy-saving initiatives. The term *sustainability* has become acceptable again and is used by many corporations and NGOs in strategies and initiatives. Retailers of consumer goods are branding, labelling and certifying sustainable production and procurement along supply chains. The public is becoming sensitized, carbon conscious and supportive of responsible use and conservation of natural resources.

The planets are aligning for soil carbon programs and initiatives to attract public, private and government attention. Governments have the opportunity to develop agriculture policies to protect soil carbon with the full support of society at large. Agriculture should benefit from initiatives to increase soil carbon and move to more sustainable cropping systems. International conventions, corporate strategies, and public support all highlight the compelling arguments for public policy development to incentivize and accelerate changes in farm practice that can accomplish greenhouse gas mitigation, climate-smart agriculture, biodiversity, food security and farm sustainability.

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Chapter 9
School Meals Programs: Connecting with Local Farmers to Provide Good, Sustainable Nutrition in School—And a Lever for Change

Kathryn Wilson

Abstract Food sustainability and environmental impact are urgent matters that depend on collaborative efforts throughout the entire food chain—producer to consumer. Engaging governments and public and private sectors will be necessary to improve food production while strengthening rural economies. The government of the US spends billions of dollars annually in procuring food for schoolchildren. The effort to encourage schools to engage directly with local farmers, ranchers, fishers, and other food producers has many benefits including: strengthening agricultural communities, providing healthier food choices, reducing costs and creating a more sustainable school meals program by serving local food that children like. Sharing best practices for leveraging the power of collective procurement and influencing food and food production by increasing local sourcing and sustainable farm practice brings benefits for both student acceptance of healthier foods and a more sustainable food system. When school meals programs and local producers form an alliance, everyone wins.

Keywords School meals · Farm to School · Healthy eating · Sustainability

Context

Since the early 1800s, charity groups and those overseeing children's education in the US have been aware of the important connection between feeding children at school and success in the classroom. The first documented school meal was in New York City in 1835, where a few women's groups and teachers were providing meals in school. The science connecting nutrition to learning had not then been fully realized but health professionals and educators observed that students attended school more often, stayed alert, and retained information when they were fed during the school day. Appreciation of the national economic impact of providing meals in school grew when Congress saw a need to purchase surplus agricultural products off the US

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market to help the country's struggling farmers during the 1930s. The commodities program was established in 1935 and offered schools, prisons, food banks, and other federally subsidized institutions the opportunity to access wholesome food produced by American farmers and ranchers. With this partnership, American farmers were assisted financially, citizens realized the value the farmer brings to the community, and a variety of products became available to public institutions at a very low cost.

Even though the practice of providing meals to children in school continued to expand throughout the country, it was not until 1946 that child nutrition, specifically, and American-produced products became permanently connected. At the end of World War II, it was discovered that thousands of young men were not fit for the military due to malnutrition. Coming out of the great depression, many did not have enough, or good enough, food for normal growth and development. With hunger and malnutrition evident across the country, schools seemed to be the reasonable place to reach most children. So Congress established the National School Lunch Program signed into law by President Harry S. Truman. It was, and still is, the intent of the school meals program to 'safeguard the health and well-being of America's children' (Public Law 79-396, 1946).

Almost 75 years have gone by with the National School Lunch Program and the Commodities Program (now called USDA Foods Program) working together to provide children with healthy, affordable meals at school using American produce. Regular access to healthy food addresses both issues of hunger and poor nutrition. It is clear that hunger and poor nutrition interfere with children's ability to take full advantage of their educational opportunities because they are listless in class, get sick more often, and miss school more frequently than children that are well-fed (Alaimo et al. 2001). We hear: 'A hungry child cannot learn' many times and from many different sources. Healthy school meals are a safety net for all children, regardless of income level, family situation, or ethnic identity. In school, a child receives a nutritious meal and has time to eat it.

As we celebrate the success of a national school lunch program, we are also acutely aware that children today are developing diseases previously seen only in adults. Obesity, Type 2 diabetes, hypertension, and other chronic conditions are diagnosed in children at an alarming rate, and the connection to health and academic performance has drawn the attention of researchers. It has been found that children who are overweight or obese are more likely to suffer low self-esteem, higher rates of anxiety, depression, and other psychopathology that may affect academic performance (Hollar et al. 2010; Zametkin et al. 2004; Taras and Potts-Datema 2005). Because obesity and related chronic disease risk factors are relatively stable characteristics that track from childhood into adulthood, finding interventions that work to assist children to make smarter food choices is an imperative.

Children spend a large part of their time each day in a school environment and over 33 million children get at least one school meal every school day across the US (some as many as three meals per day). Therefore, once again, schools provide an excellent opportunity to help develop healthy habits. Many school-based interventions have attempted to influence children's eating behaviour. Although these efforts may be improving children's general health, it is unknown what intervention component is effective at promoting the desired changes (Hersch et al. 2014). Change takes time, innovation, and education. Many stakeholders, including the schoolchildren themselves, need to be introduced to a new way of looking at food; and healthy offerings can only improve a child's health when they are consumed. Farm to School is a program in the US through which schools buy and feature locally produced, farm-fresh foods such as dairy, fruits, vegetables, eggs, honey, meat, and beans. Schools also incorporate a nutrition-based curriculum and provide students with experiential learning opportunities such as farm visits, school garden-based learning, and environmental conservation programs (Farm to School Network Fact Sheet 2020). As a result, students have access to fresh, local foods, and farmers have access to new markets through school sales. Farmers also participate in educating students about food and agriculture.

Farm to School has revitalized not only the partnership between school meals and American farmers but also energized a healthy food movement known as Know Your Farmer, Know Your Food. This is a US Department of Agriculture (USDA) effort to strengthen local and regional farm systems and reconnect consumers to healthy, locally grown foods. Introducing the program in 2015, the USDA leads the conversation about food and agriculture between consumers and farmers, with Farm to School a top priority of the initiative (USDA.gov/Know Your Farmer, Know Your Food).

Health

Farm to School is a community-based strategy that focuses on creating a healthy school environment with activities that help develop healthy eating habits for children while boosting the quality of school meals (Green et al. 2013; Turner and Chaloupka 2010; Keener et al. 2009). Multiple studies support the claim that children who grow their own food are more likely to eat fresh fruit and vegetables (Canaris 1995; Hermann et al. 2006; Libman 2007; McAleese and Rankin 2007; Pothukuchi 2004) or express a preference for these foods (Lineberger and Zajicke 2000; Morris and Zidenberg-Cherr 2002; Ratcliffe et al. 2011; Greer et al. 2017). Rather than promote the health outcomes of consuming fresher, less processed food, Farm to School programs focus on hands-on experience where children engage in growing food, cooking the food, and meeting the farmer that produces food. Once children develop a relationship with where food comes from, they are more likely to consume that food, consume it in a healthier form, and reduce the impact on the environment.

These concepts were identified in a comprehensive study completed by the PEW Charitable Trust in 2016. When schools offered school gardens, 44% of students ate more fruit and vegetables; and when schools served and promoted local food, 33% of students ate more fruit and vegetables. Additional health impacts of Farm to School Programs are discussed by Hughes (2007) who found improvement in overall student health behaviour including choosing healthier options at school meals, consuming more fruit and vegetables at school and at home (up to an additional 1.3 servings per day), consuming less calorie-dense foods and carbonated beverages, and increasing physical activity.

Economic Impact for Farmers and Communities

Farm to School Programs can offer a significant financial opportunity for farmers, fishers, ranchers, food processors, and manufacturers by opening doors to an institutional marketplace worth billions of dollars. In 2014, more than $US789 million was used to purchase local foods in 42,587 schools across the country, and the program continues to grow (Farm to School Network 2020). Support for farms and producers also increases opportunities for local employment and income.

Farmers can engage with this nationwide program in various ways. First, when school districts partner with local and regional farmers, they can commit to purchasing large quantities of produce before it is even produced. Advanced planning informs the farmers what to produce and guarantees them a fair price for their produce. This helps a farmer or producer plan expenditure and income appropriately and adds to other community-based business when these families have more income to spend. Secondly, farmers can belong to co-operatives where someone tracks the quantity of products available, which enables school meal planners to purchase the quantities of products needed from a variety of small and medium farmers and producers. These co-ops allow even the smallest of producers to participate and benefit from the Farm to School Program. And finally, because of the demand for more local and regional products, processors and food distributors have begun to purchase products from local and regional farmers. This is a trending tool to market their business with the institutions they serve, and it is an *added value* to many customers. For instance, if carrots from a local farmer can be purchased, cleaned, and cut into usable sizes by the processor, the school district is more likely to use that processor or distributer. This opportunity was strengthened in the 2008 Farm Bill when Congress added: ‘institutions receiving funds through Child Nutrition Programs may apply an optional geographic preference in the procurement of locally grown or locally raised agricultural products.’ The Farm Bill (2008) and others since then have also included millions of dollars in Farm to School Grants for schools to implement of these ideas.

As schools begin to understand that they have a stake in supporting the local economy and community, things begin to improve for farmers and producers. Many evaluations of these programs have noted that: ‘farms that sold direct to institutions had higher gross sales than those that did not’ (CT DoAg 2012) and ‘farms that sold to institutions expanded an average of three acres from 2012 to 2015 while those that did not sell to institutions remained the same size’ (Farm to Institution 2017). Farm to Schools Programs benefit everyone, providing opportunities to build engagement and creating new jobs and stronger local economies.

Environmental Impact

Finally, it is impossible to overstate the environmental impact of the food system (Allan and Dent 2021), and there is a lot of room for improvement in farm practices in general. Engaging students in agricultural practices help them get excited about and connected to their food. USDA data show school cafeterias waste less food if they participate in Farm to School activities (USDA Office of Communications 2015). Along with cutting food waste, reducing transport reduces emissions of pollutants and greenhouse gases (National Resource Defense Council 2017) and reduces cost of the food to the institution. The power of collective procurement also supports all sizes of farm operations and might easily drive more sustainable farm practice to create a sustainable and socially just food system.

Conclusion

This paper is a snapshot of the impact that US Farm to School Programs have had on children's health: influencing academic outcomes and life-long healthy habits; influencing long-term quality of life and lower health care costs. In the US, October is National Farm to School Month. It is a time to celebrate the connections between schools, farmers, and local and regionally produced foods—all advancing local economies. School meal providers, cooks, farmers, parents, teachers, food distributors, and government policy developers all play a part in making the Farm to School Program a success. Sharing best practices for leveraging the power of collective procurement and influencing food and food production by increasing local sourcing and sustainable land management brings benefits for both sustainable nutrition and student acceptance of healthier foods. The program also promotes stability and fairness in the food system; it can be a lever for transition toward sustainability. When school meals programs and local producers form an alliance, everyone wins.

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Part III
What's Missing?

For according to the measure of his understanding
and according to his leisure,
Every man must say what he says and do what he does.
Alfred the Great c 890

Chapter 10
Diverse Perennial Vegetation is Missing!

Timothy E. Crews

Abstract The thick black topsoil of the Chernozem developed under diverse, perennial grassland. Of the five soil forming factors identified by Dokuchaev, we have most significantly modified the *organism* factor, which includes vegetation, to create the row-crop agro-ecosystem. This agro-ecosystem cannot make or, even, maintain a Chernozem, so we are drawing on capital inherited from the native grassland. In replacing diverse perennial vegetation with a few species of annual grains, we have come to depend on a poorly functioning ecosystem that is vulnerable to pests and diseases and that loses soil organic matter, nutrients, and the soil itself. Why Neolithic farmers chose to domesticate annual grasses and legumes, rather than perennial species, is open to speculation but our predecessors may have been steered towards annuals by the time and energy needed to terminate stands so as to accomplish cycles of sexual recombination and selection in their chosen crops. Now, given unprecedented human demands on the planet, it is imperative that we transform how we grow food—from a way that degrades the soil to one that builds it up again. Today, we have the capability to breed perennial grain crops and learn how to grow them in ecologically functional mixtures. Through re-inventing grain growing to resemble the structure and function of natural ecosystems, humanity has the potential to greatly improve the sustainability of agriculture and our own long-term prospects.

Keywords Perennial grains · Native vegetation · Row crops · Soil formation · Soil erosion · Soil organic matter

Altering the *Organism* Soil Forming Factor

Many elements of the ecosphere combine to create a soil. Russian geologist and geographer Vasily Dokuchaev identified five *factors of soil formation* that interact to determine the kind of soil that develops in a particular place: parent material, climate, topography, organisms, and the age of the landscape (Dokuchaev 1880).

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His concept inspired Hans Jenny who further developed the state factor approach to understanding how soils form and, also, how ecosystems develop (Jenny 1941; Amundson and Jenny 1997; Vitousek 2004). The state factor model treats each of the soil forming factors as independent, not because they do not interact and co-vary in the real world but because they can vary, and exert unique influence on soil formation, independently.

Since the dawn of agriculture, humans have been a driving force, interacting with and influencing other soil forming factors and thus soil formation as a whole. Amundson and Jenny (1997) and others argue that *Homo sapiens* might be considered a unique factor of soil formation, apart from the influence of other organisms. Indeed, we have modified topography by making terraces, water availability by tapping water for irrigation, temperature by mulching fields, and even parent material through activities like managing fire for the accumulation of biochar in the *Terra Preta do Indio* in Amazonia (Sombroek et al. 1993). Our capacities leapt dramatically with the exploitation of energy from fossil fuels: laser-levelling fields, covering them with plastic, and applying synthetic fertilizers are just a few examples of high-energy modification of soil forming factors. But I propose that none of these, pre- or post-fossil fuels, comes close to the global impact that Neolithic farmers have had on soil development with the selection of annual grasses to undergo what we now call domestication. Harlan (1995) famously said: ‘Farming is plant breeding.’ In selecting annual species of grasses, legumes, composites (Asteraceae), and other crops, early farmer/plant breeders unknowingly set us on a trajectory of inevitable soil destruction. Arguably, the need to clear vegetation every year so as to provide the proper habitat for annual crop seedlings to thrive has made vegetation a factor of soil retrogression rather than formation (Crews et al. 2016).

Why Annuals?

The question of why Neolithic people set annual species, and not perennials, on the path to domestication remains highly speculative. It was not for lack of perennial candidates—7821 of the 11,313 grass species are perennial. In a recent study of the legume family, 18,018 of the 19,694 taxon with growth-habit data were perennial, and 6644 were herbaceous perennials (Ciotir et al. 2018). It may be tempting to think that because Neolithic people only domesticated annual grains, it proves that *only* annuals can be domesticated. Such an argument presupposes that early farmers tried to domesticate both annuals and perennials and, at some point, chose annuals as superior. There are good reasons to suspect that no such comparisons were ever made: annuals were likely chosen for reasons that superseded seed characteristics.

Van Tassel et al. (2010) advanced several hypotheses to explain why herbaceous annuals were favoured over perennials in the domestication of grains. These range from trade-offs that plants might experience under artificial selection, genetic mechanisms that may have disfavoured perennials, to experiences Early Neolithic farmers may have had trying to grow herbaceous plants. The researchers comment: ‘If there ever were attempts to grow perennial species through yearly sowing, the slow-to-establish, often relatively unproductive first-year perennial plants would not have been at all attractive'. Possibly an even more critical factor that has been overlooked is the arduous work required to terminate stands of perennials so as to accomplish repeated cycles of sexual selection: some perennial species may be slower to establish than annuals, but they are much slower to die. The challenge of terminating perennials without iron tools may have been too great, given the restricted caloric budget of early farmers (Pimentel and Pimentel 2008).

Why is stand termination an issue? There is a suite of plant traits that consistently changed through inadvertent selection by farmers simply growing out generation after generation of the progenitors of wheat, barley, rice, corn, and other proto-grains: traits like non-shattering, synchronicity of seed maturation, increase in seed size, and loss of dormancy are favoured when farmers grow a crop, allow it to undergo genetic recombination through pollination, and then gather the seed (Harlan 1995). Given that these selective changes are slow—a minimum of 60 generations may have been needed to achieve non-shattering wheat (Zohary 2004)—the farmers were probably unaware that cycles of sowing, collecting seeds, re-sowing, etc., were essential for future crop improvement. Thus, even though there were seed-producing herbaceous perennials in places where crops were domesticated, it is hard to imagine farmers deciding to kill and re-sow perennials when there was no apparent reason to do so. Just the opposite is likely true; there was a compelling reason *not* to kill perennials given (1) the amount of work required to terminate such deep-rooted, re-sprouting plants, and (2) the observation that they re-grow on their own over several years. It is conceivable that farmers did not try to terminate perennial proto-crops but simply sowed new stand after new stand, adding to the land area covered by the species. Had this approach been taken, the problem of gene flow through cross-pollination between the different generational stands could greatly reduce progress in selection for the important domestication traits (Fehr 1991). Annuals, by definition, die every year so no labour is needed to terminate them; and they do not experience gene flow with subsequent generations.

This multi-faceted logic of why Neolithic farmers worked with annual species to develop grain helps to understand how we got to where we are now. If the labour of stand termination played a role in steering farmers towards annuals, it is ironic that the route of domestication that demanded far less labour locked humanity into vegetation-clearing agricultural practices that are extraordinarily labour intensive. In many if not most indigenous farming systems, the labour involved in clearing vegetation and then weeding out invasive vegetation is unmatched by any other agricultural activity (Pimentel and Pimentel 2008). Moreover, arresting agro-ecosystems in the early stages of secondary succession through frequent disturbance (e.g. tillage) diminished ecosystem functions like nutrient and carbon retention and water infiltration (Crews et al. 2018). Loss of these functions relative to natural ecosystems characterized by diverse perennial vegetation means that farmers have to expend ever more energy to compensate for reduced ecosystem integrity. In other words, more work is required per unit of food obtained from a degraded soil compared to one that is well maintained and fertile.

We can only speculate why Neolithic farmers advanced annual grains through the process of domestication, but we know, with certainty, that the global food situation we face today was shaped by the shift of the organism state factor away from the perennial vegetation that dominated the preceding natural systems. The following discussion looks at some of the consequences of this shift and the opportunity for a course correction, 10,000 years into our dependence on disturbance-based, early succession agro-ecosystems.

Soil Degradation and Regeneration

In the last decade, many reports have highlighted the soil degradation that constrains the productivity and sustainability of agro-ecosystems around the world (FAO 2015; Olsson and Barbosa 2019). The FAO report acknowledges many examples of improved soil management and conservation but warns that, overall, soils are being degraded at an alarming rate, both in more- and less-developed countries. The recent IPCC report on *land and climate change* (2019) asserts that even herbicide-based no-till agriculture loses soil at 10–20 times the rate at which soil is formed; and when tillage is employed to control weeds, soil loss is another order of magnitude greater. These values are within an order of magnitude of Montgomery's (2007) estimate that global median soil loss from no-till is 16 times the rate of soil formation, and soil loss under tillage is 360 times the rate of soil formation. Indeed, according to Nearing et al. (2017), farmers in the corn belt of the Midwest USA lose more than a kilogram of soil for every kilogram of grain produced; and Strauss (2021) reports a figure of three tons of soil lost per ton of wheat grown in South Africa.

The persistent downward spiral of degradation affecting croplands cannot be explained by a lack of farmer interest, scientific investigation, or social investment to curb soil erosion. What does appear to consistently explain this spiral is the inherent inability of the annual grain ecosystem to protect and build soil (Pimentel 2006; Olsson and Barbosa 2019). Our food-production ecosystem, based on one or more cycles of vegetation clearing per year to reduce competition with annual crops, has no analogue in nature. There are various non-agricultural, terrestrial ecosystems dominated by annual vegetation—for instance, annually inundated floodplains (Mazoyer and Roudart 2006)—but these are open systems in which losses of sediment are balanced by annual deposits. In contrast, rates of soil formation on most landscapes are orders of magnitude less than rates of erosion from cropland.

Soil degradation ranks with climate change amongst bio-geochemical disruptions that put humanity at odds with critical Earth processes. Ultimately, rates of soil formation have to balance soil loss, just as the rate of carbon dioxide removal from the atmosphere must balance carbon dioxide emissions. Agricultural ecosystems featuring perennial roots that ramify to the depths achieved by native vegetation would not disrupt soils so often, and would help rectify the carbon imbalance that threatens the planet's ability to host life as we know it. Arguably, erosion is the most consequential form of soil degradation. However, the lack of perennial roots in arable systems also disrupts nutrient retention; Rockström et al. (2009) and Steffen et al. (2015) argue that contemporary flows of nitrogen and phosphorus through terrestrial and aquatic ecosystems critically exceed what the ecosphere can process. The consequences of exceeding these planetary boundaries include: eutrophication of freshwater and marine ecosystems (Sharpley and Rekolainen 1997; Elser et al. 2007), the formation of more than 400 hypoxic (dead) zones in seas around the world (Diaz and Rosenberg 2008), increased emission of the potent greenhouse gas nitrous oxide, fertilization of downwind ecosystems, and acidification of agricultural soils (Helyar and Porter 1989; Galloway et al. 2004).

Tracing back the nitrates and phosphates responsible for these impacts to where they originated, we find that annual croplands are by far the most important source—although there are other hotspots such as animal feedlots (Mallin and Cahoon 2003). To understand why this is the case, it helps to consider annual croplands in a continuum of ecosystems at different stages of development that have predictable behaviours. Ecologists have long recognized the dynamics of nutrient retention and losses that occur at different stages of ecosystem succession (Gorham et al. 1979). In ecology, succession describes changes in the composition of biological communities and their ecosystem processes through time (Odum 1969). Primary succession is the development of an ecosystem starting from the beginning—the colonization of newly exposed rock or newly deposited sediment by plants, microbes, and other organisms. Secondary succession occurs following disturbance to an already existing ecosystem—by fire, flood, or any other force that disrupts or eliminates the dominant plant/organism community (Whittaker 1975). Farmers actively manage a number of agents to set back farmlands to early stages of secondary succession, that is, to say freshly tilled fields ready for planting. With the harnessing of draught animals and then fossil fuels, the plough and, more recently, herbicides have become the agents of choice to arrest farmlands in a perpetual stage of early secondary succession (Crews et al. 2016; Smil 2018).

Vitousek and Reiners (1975) developed a conceptual model describing the biological regulation of nutrient retention at different stages of ecosystem succession; it predicts that, when an ecosystem is disturbed to start secondary succession, there is potential for temporary, rapid losses of nutrients that were stored in detritus and soil organic matter that may decompose rapidly in bare soil. Their prediction has been supported by many studies, including one at the Hubbard Brook Experimental Forest in New Hampshire in which the vegetation of a mid-successional hardwood forest was killed by herbicides, resulting in large exports from the catchment of bases, nitrogen, and other nutrients (Likens et al. 1970). This breakdown of biological control over nutrient retention following severe soil and ecosystem disturbance is exactly what we see in annual cropping. Using tillage or herbicides, we reset ecosystems to early stages of secondary succession (Fig. 10.1).

When native ecosystems were cleared for agriculture, the net mineralisation of soil organic matter yielded a predictable flush of nutrients. Over years or decades, some fraction of these flushes was captured by crops but, eventually, the soil organic matter pool approaches equilibrium between biomass production and respiration, and the flush of free nutrients comes to an end. Today, since in most cases, the flush

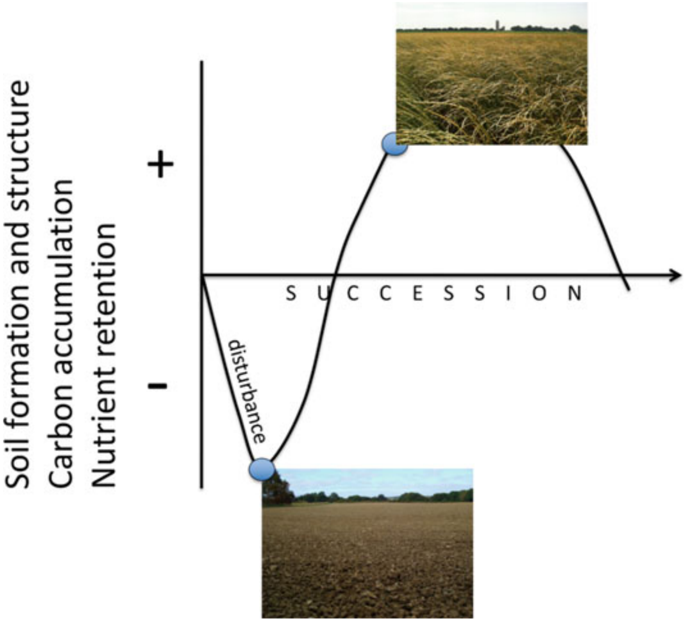

Fig. 10.1 Conceptual model of improvement in ecosystem functions as an agro-ecosystem moves along the successional gradient from early to middle secondary succession. Early succession is characterized by disturbance to remove all competition for annual crops, and mid-succession is characterized by perennial grain species with year-round ground cover and root proliferation

of nutrients ended long ago, inorganic and organic fertilizers are used to support crop growth—but they are applied at a stage of ecosystem development that affords minimal biological control over nutrient retention so it is not uncommon to lose 50% of the nitrogen applied (Ladha et al. 2005).

What would an agro-ecosystem look like that occupied a later phase of succession that can exert stricter biological control over nutrient fluxes? Perhaps, like the experimental crops illustrated in Figs. 10.2 and 10.3. One particular attribute of natural vegetation that offers potential to improve nutrient regulation is *perenniality*. The new perennial grain Kernza®, which is being developed from the forage plant intermediate wheatgrass or IWG (*Thinopyrum intermedium*) is proving useful for initial evaluation of what might be expected if annual grains were replaced with perennials. Studies in Minnesota and Michigan compared nitrate leaching under IWG with annual grains (Table 10.1); they show that, at low and high N application rates, 86–99% reduction of nitrate leaching in the IWG stands relative to maize or wheat (Culman et al. 2013; Jungers et al. 2019). In the Minnesota study, switchgrass (*Panicum virgatum*), a perennial bio-fuel crop, is also demonstrated 83 and 91% reduction in nitrate leaching compared to maize under high and low fertilizer rates, respectively. The only measurement that showed N losses under IWG comparable to those under an annual grain was in the establishment year in Michigan—because, in

Fig. 10.2 Kernza® intercropped with lucerne, a perennial forage legume. The two species have very different rooting habits: Kernza's prolific fine roots abstract water mainly from the top metre of soil; lucerne's deep tap roots access water down to 3 m and host biological nitrogen fixation that, in the short term, reduces competition with Kernza for soil nitrogen and, ultimately, meets the cereal's nitrogen requirements

Fig. 10.3 New dawn. Experimental cropping system at the Land Institute in Salina, Kansas. Kernza® planted in single-species plots at 38 or 76 cm row spacing and fertilized with 0, 75, or 150 kgN/ha/yr. In other plots, Kernza is intercropped with lucerne. The two species seem to partition water resources so that competition is minimized and nitrogen from lucerne improves Kernza productivity after three years of intercropping

Table 10.1 Nitrate leaching comparisons of annual and perennial crops in the Upper Midwest USA

Location/soil N sampling approach	Soil order/texture	Crop	kg N ha^{-1} Applied[a]	kg ha^{-1} NO_3-N Leached	Reduction in N leached as % of annual crop	Study
Minnesota USA (3 sites over 3 years) Suction lysimeter (50 cm) + DNDC model	Mollisol 1 loam, 1 clay-loam 1 silty-clay-loam	Maize	80			Jungers et al. (2019)
		Switchgrass	40		91	
		IWG	40		96	
		Maize	160			
		Switchgrass	160, 120[b]		83	
		IWG	160, 120[b]		99	
Michigan USA (2 years[c]) Suction lysimeter (135 cm) + SALUS model	Alfisol Fine loamy and coarse loamy	Wheat (year 1)	90 (organic)	11.3		Culman et al. (2013)
		IWG (year 1)	90 (organic)	11.6	(2)	
		Wheat (year 1)	100	9.8		
		IWG (year 1)	100	12.7	(30)	
		Wheat (year 1)	140	24.3		
		IWG (year 1)	140	17.7	28	
		Wheat (year 2)	90 (organic)	17.7		
		IWG (year 2)	90 (organic)	0.1	>99	
		Wheat (year 2)	100	27.5		
		IWG (year 2)	100	0.5	98	
		Wheat (year 2)	140	69.8		
		IWG (year 2)	140	9.9	86	

[a] All N applied as urea fertilizer except in treatments labelled organic which was chicken manure

[b] Fertilization rate in year 1 was 160 kg ha^{-1}, was 120 kg ha^{-1} in years 2, and 3

[c] Year 1 in Michigan was an establishment year in which the root system of perennial IWG was not significantly different from that of annual wheat

the first half year of development, a perennial growing from seed is quite similar to an annual. Over time, the persistence and more extensive proliferation of perennial roots improve nutrient retention and other ecosystem functions. Current IWG varieties yield annually only one-third to one-sixth of the grain of modern wheat, which is only to be expected given that wheat has a head start of 10,000 years breeding and selection. A positive attribute of IWG is that it produces large amounts of high-quality forage in addition to grain. This dual-use makes the crop more attractive to many growers.

The temporal and spatial reduction of roots also drives the insidious decline in soil organic matter under annual grains—because annual crops contribute much less organic matter to the soil and they sustain higher rates of mineralization from microbial respiration (Crews and Rumsey 2017; Reicosky and Janzen 2019). Being predominantly perennial, the vegetation of natural ecosystems allocates some 50–68% of net primary productivity (NPP) below ground (Saugier et al. 2001). In contrast, the below-ground allocation of NPP in annual crops is between 15 and 25% (Goudriaan et al. 2001; Whalen and Sampedro 2009). Moreover, recent research suggests that roots play a greater role in the formation of soil organic matter than above-ground residues. Jackson and his colleagues (2017) reviewed 16 studies using primarily isotopic approaches to compare contributions to soil organic matter from above-ground and below-ground inputs; they found that the mean and median below-ground inputs retained as soil organic matter were 45 and 39%, respectively, compared with 8.3 and 6.6% retained above-ground inputs.

Replacement of perennial vegetation that maintains deep roots year-round with transient, less-prolific annual roots has certainly compromised soil quality and function. Replacement of high root diversity with low root diversity has also played a role. Recent studies have found that the accumulation of organic carbon in soils planted with diverse, perennial vegetation far exceeds that accumulated in lower diversity or single-species plantings (Cong et al. 2014; Hungate et al. 2017; Chen et al. 2018). Yang et al. (2019) reported a diversity study involving 1–16 herbaceous perennial species over 22 years in Minnesota, USA. Compared to plots with single species, soil carbon concentrations in the top 20 cm doubled in assemblages with 2–4 species, and increased fourfold in assemblages of 16 species; and carbon in roots increased from approximately 2.5 to 5.5 tC/ha as the species diversity increased from 1 to 16. It is rarely made clear whether the increase in soil organic carbon with plant diversity reflects greater *particulate organic matter* or *mineral-stabilized organic matter* associated with efficient microbial decomposition. That said, there is growing theoretical and empirical evidence that a more diverse plant community than, for example, a cereal monocrop, may accumulate greater pools of stable soil organic matter. Intercropped species such as legumes generally have higher-quality tissues that can result in stable SOM formation (Schmidt et al. 2011; Cotrufo et al. 2015).

Conclusion

Approximately, 11% of the land surface has been converted from plant communities dominated by perennials to croplands, and approximately 85% of croplands are planted to annual species (Monfreda et al. 2008). Interpreted through the lens of Dokuchaev's soil forming factors, this substitution of annual plants for perennials, initiated at least 10 millennia ago, has turned out to have unexpectedly destructive consequences for the ecosystems that feed us. Scholars have adduced many reasons why we took the path of domesticating annuals, but few compelling arguments suggest that annuals were chosen because they had higher yield potential. It is likely that our ancestors committed to the path for entirely other reasons, involving genetic and life history attributes of perennials and annuals, as well as the energetics of crop breeding itself.

Modern plant breeding coupled with molecular tools, such as marker-assisted and genomic selection, provides an opportunity for a course correction. Re-establishing perennial roots from diverse species could make grain agriculture truly regenerative—a farming system that re-builds soil carbon, retains nutrients, and holds erosion below the rate of soil formation. Efforts are underway to develop many new perennial grain crop species, either through *de novo* domestication of wild perennial species, or wide hybridization between an extant annual grain crop and a perennial relative (Crews and Cattani 2018). However, if a transition to a diverse perennial agriculture is going to happen, many more crop-perennialization projects will be needed (Fig. 10.4). To this end, a global inventory of potential perennial candidates in the legume, grass, and sunflower families has been established (Ciotir et al. 2016).

Fig. 10.4 *Silphium integrifolium*, a deep-rooted, drought-tolerant species in the sunflower family undergoing *de novo* domestication at The Land Institute in Salina, Kansas. This species is native to the grasslands of central USA and is bred as an oilseed crop that could replace annual sunflower or soybean

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Chapter 11
A Biological Way to Intensify Agriculture

Sergei Lukin and Vladislav Minin

Abstract Long-term field experiments demonstrate the effectiveness of biological ways to increase soil fertility on *Sod-podzolic soils* of the central and north-western regions of the Russia. Biological intensification of agriculture may be accomplished by increasing the share of legumes in crop rotations; the use of organic fertilizers, green manure and plant residues, including precise application of fertilizers into the root zone; and the use of microbiological drugs. Raising the share of legumes in crop rotations to 40% achieves a positive nitrogen balance, without applying fertilizer, and increases the productivity of the whole rotation by more than 50%. Perennial legumes in rotation fixed from 153 to 264 kgN/ha/year, annual legumes 104–139 kgN/ha/year. Microbiological preparations activate rhizosphere activity and increase crop yields, in the case of potatoes by more than 35%. Lessons from organic farming practice and possible future directions are discussed.

Keywords Sustainability · Crop rotation · Legumes · Organic fertilizers · Microbiological drugs

Biologisation of Agriculture

‘*Transition to a highly productive and environmentally friendly agriculture and aquaculture, implementation of systems of rational use of chemical and biological protection of crops and animals and development of high-quality, functional, food products* …’ is a priority of the strategy for scientific and technological development of the Russian Federation (Govt Russian Federation 2016). Sustainable agriculture

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that meets society’s needs for food and raw materials depends on making better use of biological potential; biologisation of agriculture, as a system of inter-related measures (Eskov et al. 2005), intensifies production of food, stock feed and raw materials by:

- Better cycling of organic matter and nutrients
- Crop rotations with the maximum proportion of highly productive crops
- Incorporating the carbon and nutrients of crop residues and green manure in the biological and economic cycle
- Environmentally safe use of organic and mineral fertilizers and biological preparations
- Increasing the biological activity of soils
- Rational soil tillage
- Biological and physical methods of controlling weeds, pests and diseases.

Biological regeneration of soil fertility makes efficient and economical use of material and technical resources, cuts the cost of production and improves its quality. This does not mean a return to low-yielding farming systems that depend only on natural soil fertility. Rather, it makes the best use of biological resources in combination with mineral and organic fertilizers, crop protection products, etc. (Novikov et al. 2007; Lukin and Rusakova 2018).

The Role of Biological Nitrogen

The most important source of nitrogen in agriculture is symbiotic fixation from the atmosphere. Nitrogen budget calculations and studies using the ^{15}N isotope show that legumes acquire 60–70% of their nitrogen supply by symbiotic fixation, depending on the level of soil fertility. The proportion can be even higher in coarse-textured soils where mineral nitrogen is in short supply (Lukin 2018a). The results of 42 field experiments on sandy and coarse loamy *Sod-podzolic soils* (Albic luvisols) at the Verkhnevolzsky Federal Agrarian Scientific Centre (VNIIOU) demonstrate the potential of legumes as a biological source of nitrogen. The greatest yield of nitrogen is achieved by perennial legumes: clover, yellow melilot (*Melilot officinalis*) and lupin. The total biomass of these crops amounted to 11.7–18.5 tonne dry matter/ha, of which 40–56% was roots; on average, root residues contributed 6.3 t dry matter/ha/yr and 131 kgN/ha/yr. Annual legumes are less productive. Annual lupin yielded 9.4 t dry matter/ha, of which 4.7 t dry matter/ha and 88 kgN/ha was left in the soil as crop and root residues but on average, the root residues of annual legumes contained only 29% of the nitrogen accumulated in the total biomass, compared with 48% in perennial legumes; so, the intake of nitrogen with the roots of annual legumes was 2.6 times less.

The performance of the studied crops in order of the amount of nitrogen fixed (kgN/ha/yr) was as follows: red clover with timothy over two years—168; red clover over one year—163; white clover—153; perennial lupin—139; peas for green fodder—138; serradella (*Omithopus sativus*)—118; lucerne over one year—114; peas for grain—106; fodder beans—104; vetch and oats—70; peas and oats—53 (Lukin 2018a). Of the annual legumes, the largest amount of nitrogen was fixed by annual yellow lupin but, even so, only half that fixed by clover. According to Kokorina and Kozhemyakova (2010), the potential nitrogen fixation by legumes can reach 550 kgN/ha/yr and the coefficient of nitrogen fixation (the share of N fixed from the atmosphere in the total N uptake by the crop) 91% (Table 11.1).

In the non-Chernozem zone of Russia, legumes are cultivated as cash crops, forage and green manure. Generalization of the results of the institute's long-term field experiments reveals that increasing the share of legumes in the crop rotation to 40% will increase the yield of the rotation as a whole by 1.6 times compared with the unfertilized variant and by 1.5 times that of the variant receiving manure, although the benefit of legumes decreases under intensive fertilizer application (Table 11.2).

Table 11.1 Nitrogen fixation by legumes

Cultures	Potential nitrogen fixation, kgN/ha/yr	Coefficient of nitrogen fixation, %	Average nitrogen fixation, kgN/ha/yr
Pea	140	66	40–60
Vetch	160	70	40–70
Chickpea	210	75	40–80
Soybean	390	88	60–90
Lupin	220	81	80–120
Clover	310	87	120–180
Sainfoin	270	80	110–160
Lucerne	550	88	140–210
Fodder galega	510	91	140–240

Table 11.2 Productivity of crop rotations on *Sod-podzolic* sandy loam depending on the share of legumes, tonne grain-equivalent/ha

Share of legumes in crop rotation, %	Number of crop rotation	Kind of fertilization		
		None	Manure	Manure + NPK
0	6	1.77	2.68	4.73
25	13	2.58	3.48	4.25
40	2	2.75	4.09	4.23
100	1	2.42	2.64	3.51

Table 11.3 Nitrogen balance in unfertilized crop rotations, kgN/ha/yr

Crop rotation	Share of legumes, %	Main sources of nitrogen			N uptake by yield, kgN/ha/yr	N balance
		Seeds and precipitation	Symbiotic N fixation	Total		
Grain–root	0	10.5	0	10.5	40.0	−29.5
Grain–root with seeded fallow	12	10.3	10.4	20.7	46.3	−25.6
Grain–root with annual lupin	25	11.0	26.0	37.0	48.3	−11.3
Grain–grass–root	33	9.7	37.8	47.5	63.7	−16.2
Grain–grass	33	9.2	89.7	98.9	103.7	−4.8

Structure of Land Use

The structure of land use across the landscape should ensure productive use of the arable with an optimal combination of economic and environmental objectives. The optimum is determined, on the one hand, by soil and climate and, on the other hand, by the capability of the farmer and the demands of the market. Assessment of the nitrogen balance in unfertilized control variants of field experiments with different crop rotations shows that with an increase in the share of legumes in the rotation, the nitrogen uptake by the crop increases sharply and the nitrogen balance improves (Table 11.3).

Mixed crops of legumes with cereals and other crops make very efficient use of heat, light, water and nutrients. A positive nitrogen balance in a grain-grass rotation requires a 40% share of legumes in the crop rotation. Where farmyard manure is not available, the proportion of perennial legumes needs to be at least 30% to maintain the soil organic matter and nitrogen status; ploughing-in clover in the autumn provides the same amount of organic matter and nitrogen as 30–35 t of manure.

VNIIOU scientists have evaluated the agro-biological features of different species and varieties of crops of high fertilizing value and promising crops suitable for local conditions (melilot, soya, perennial lupin). In cooperation with colleagues from Russia, Mexico, Kazakhstan and Belarus, they have created *Meshchersky 99* white sweet clover, *Sudogodsky* yellow sweet clover, *Grenadier* perennial lupin, *Amigo*, *Norman*, *Carmen* and *Rossika* varieties of spring triticale and other soil-improving varieties that have been approved for use in many regions of the Russian Federation.

Organic Fertilizers

Optimizing the structure of the cultivated area includes using green manure and soil-improving crops to increase soil fertility and to provide a sustainable foundation for rearing livestock. However, sole reliance on biological methods, without the use of

Table 11.4 Effects of different fertilizer systems on the productivity of crop rotation on coarse loamy *Sod-podzolic* soil, VNIIOU 1968–2014

Variant	Crop rotation productivity including by-products, t grain units/ha/y	Additional yield	
		t grain units/ha/y	%
Without fertilizer	2.27	–	–
Manure 10 t/ha	3.07	0.80	35
Manure 5 t/ha + $N_{25}P_{12}K_{30}$	3.48	1.21	54
$N_{50}P_{25}K_{60}$	3.56	1.29	57
Manure 20 t/ha	3.45	1.18	52
Manure 10 t/ha + $N_{50}P_{25}K_{60}$	4.08	1.81	80
$N_{100}P_{50}K_{120}$	3.96	1.69	74
Manure 10 t/ha + $N_{100}P_{50}K_{120}$	4.22	1.95	86
$LSD_{0.05}$	*0.14*		

fertilizers, does not compensate for the removal of nutrients in the crops so a system of fertilization is crucial. A comparison of different fertilizer systems was conducted in the long-term field experiment which begun in 1968 on *Sod-podzolic* sandy loam soil. Organic, organo-mineral and mineral fertilizer systems were aligned in the amount of nutrients, equivalent to 10 and 20 t farmyard manure/ha/y. On average over 46 years, organic fertilizer was 39% less efficient than the organo-mineral system and 34% less efficient than mineral fertilizers (Lukin et al. 2018). The total productivity of the crop rotation under the organic fertilizer system was 12–15% lower and, accordingly, a shortfall equivalent to 0.49–0.63 t grain/ha/y (Table 11.4).

Different crops react differently to changes in mineral nutrition. Whereas there was no significant difference in yield between fertilizer systems in the case of annual lupin, the shortfall of winter wheat under an organic fertilizer system reached 9%, for potatoes 14% and for barley 22–27%. These differences arise from the mismatch between crops' nutrient demands and mineralization of the manure; for winter wheat, the most intensive consumption of N and K is between 20th May and 10th June; for barley from the beginning to 20th June; whereas the maximum decomposition of organic fertilizers is in mid-summer. Lupin hardly responds to fertilizer because it makes use of up to 200 kg/ha symbiotically fixed N, and its deep roots can absorb nutrients from the lower soil layers. So organic farmers must pay special attention to optimizing the crops' mineral nutrition; for cereals, organic fertilizers rich in mineral nitrogen should be used, including manure, peat and poultry manure, litter-free liquid manure, slurry and rapidly decomposing green manure with a narrow C:N ratio (Table 11.5).

For root crops, the availability of nutrients from organic fertilizers can be increased by 30–40% by placing the manure directly into the root zone; this is especially effective with peat-manure compost, green manure and farmyard manure that have a lesser share of nutrients in mineral form. It also reduces consumption by weeds and combination in unavailable forms. In field experiments, local application of organic

Table 11.5 Content of mineral and organically bound nitrogen in organic fertilizers (generalization VNIIOU)

Organic fertilizer	N content, % of the raw material	N content, % of total amount	
		N mineral	N organic
Manure with litter	0.51	20	80
Manure without litter, semi-liquid	0.31	40	60
Liquid manure without litter	0.23	50	50
Slurry	0.23	90	10
Poultry manure with litter	1.28	25	75
Poultry manure without litter	1.07	50	50
Peat-manure compost	0.53	10	90
Sapropel	0.80	–	100
Sewage sludge	1.30	5	95
Green manure	0.7	–	100
Straw	0.80	–	100

fertilizers eliminated the deficit of mineral nitrogen during the first half of the growing season and increased the yield of corn, compared with broadcast application, by 4.6 t/ha (18%) and of potatoes by 40–47% (Lukin 2018b) (Tables 11.6 and 11.7).

Where manure is not available, soil fertility can be raised by crop residues and green manure. The efficiency of organo-mineral and biological fertilizer systems was compared in the field experiment with a grass–root crop rotation. In the organo-mineral system, the harvest of primary and secondary products was removed, mineral fertilizer was applied annually, and cattle manure was applied for potatoes. Regeneration of soil fertility in the biological system made use of straw and a decoction of

Table 11.6 Influence of application method of organic fertilizers on corn yield (tonne green mass/ha)

Kind of fertilizer	Method of fertilizer application		Effect of localization, t/ha
	Pre-ploughing	Local	
Without fertilizer	21.4	21.4	
Peat-manure compost 50 t/ha	25.1	29.7	+4.6
Peat-poultry dung compost 40 t/ha	24.6	25.0	+0.4
Poultry manure 20 t/ha	21.2	26.2	+5.0
$LSD_{0.05}$			2.9

Table 11.7 Influence of application method of organic fertilizers on the yield of potatoes, t/ha

Kind of fertilizer	Method of fertilizer application		Effect of localization, t/ha
	Pre-ploughing	Local	
Without fertilizer	7.4	7.4	
Peat-manure compost, 50 t/ha	7.8	11.8	+4.0
Peat-poultry manure compost, 40 t/ha	9.5	13.7	+4.2
Poultry manure, 20 t/ha	8.9	13.6	+4.7
$LSD_{0.05}$		2.9	1.6

perennial grasses in combination with modest doses of mineral fertilizer. The efficiency of the organo-mineral and biological systems was much the same: the rotation yielded 4.11 t grain units/ha under the organo-mineral system and 3.99 t/ha under the biological system (Novikov et al. 2007).

Biological Preparations to Optimize Crop Nutrition

Nitrogen reserves in agricultural soils can be significantly increased by preparations of non-symbiotic N-fixing microorganisms that stimulate plant growth. More recently, strains of microorganisms have been identified that can suppress the development of pathogenic microorganisms. In VNIIOU studies, application of microbial preparations together with peat-manure compost enhanced the chitting of potatoes: in variants with added microbial preparations, chitting was 88% while in the variants without preparations, it did not exceed 83%; and the bacterial preparations increased the yield by 1.8–3.6 t/ha. The highest potato yield for most preparations was obtained with the biggest supplement; combination of 30 t/ha of peat-manure compost with Extrasol CO and C-218 at 4.75 kg/ha increased potato yield by 5.5 t/ha (43%); the yield increase from bacterial preparations on variants with organic fertilizers was 3.6 t/ha (25%) (Lukin and Marchuk 2011). Bacterial preparations are most effective with organic fertilizers that contain a lot of mobile organic matter and a lesser amount of mineral nitrogen, such as well-rotted cattle and pig manure, sapropel and sapropel composts. Fresh manure and poultry dung that contain a lot of mineral nitrogen are not suitable for use with bacterial preparations; in these cases, manure is applied to the soil, and bacterial preparations are used for seed treatment.

The Institute for Engineering and Environmental Problems in Agricultural Production began research on crop rotations with organic elements in the Leningrad Region 2016, studying the effects of the level of mineral nutrition provided by organic fertilizer and additional biological nitrogen provided by the introduction of the nitrogen-fixing microorganism Flavobacterin™. The soil on site is humose, coarse loamy *Gleyic sod-podzolic* developed on calcareous moraine, with a weakly acidic reaction and medium to high levels of available P and K. Experiments with potatoes were conducted with organic fertilizers prepared industrially from poultry manure. Biological fungicides VitaplanSP, and Kartofen, based on *Bacillus subtilis* (strains VCM-B-2604D and VCM-B-2605D developed by the Russian Research Institute of Plant Protection) were used in the experiment. Potatoes were treated with bio-preparations at the time of planting and by foliar spray during the growing season. A small rotary harrow was used for weeding.

The yield of potatoes depends very much on the weather. In 2017, generally unfavourable for potatoes, a yield of 17.8–18.7 t/ha was achieved with the use of biological preparations and compost. In 2018, the yield of tubers was 17.8 t/ha even on the control variant without compost and biological products; the use of biological preparations produced an additional 35–37% (more than 6 t/ha). In the variant using 80 kgN/ha of compost not supplemented by biological preparations, the same productivity was achieved as in the variants with only biological preparations without compost (24.5 t/ha). The use of compost together with bio-preparations yielded 27.6–29.3 t/ha. In 2019, the control yielded 19.9 t/ha; the use of bio-fungicides increased the yield to 24.1 t/ha. Compost also significantly increased the yield: the variant with compost but without bio-fungicides yielded 25.8 t/ha. Combination of Flavobacterium with compost yielded 41.6 t/ha of marketable tubers; a yield of 40.4 t/ha was obtained by using bio-fungicide Kartofen and compost at a dosage of 160 kgN/ha.

Combination of agro-technical measures made a difference by activating the soil microflora, and this improved the supply of nutrients to the crop; in variants with bio-fungicides, the potato plants themselves were better developed; and the compost provided a prolonged supply of nutrients. As a result, the best variants achieved yields matching those under intensive conventional practice.

Prospects for Organic Agriculture in Russia

The Federal law *On organic products and amendments to certain legislative acts of the Russian Federation* that came into force on 1 January, 2020 (Govt Russian Federation 2018) lays down stringent requirements for the conduct of organic agriculture, most of which comply with those of the EU and the International Federation of Organic Agricultural Movements. Most artificial chemicals are banned, which poses problems for providing crops with nutrients and protecting them from weeds, pests and diseases. Organic farming must realize the full biological potential of crops through choice of appropriate organic fertilizers and permitted agrochemicals, protective and stimulating biological products, as well as best practices of soil treatment and plant care adapted to local conditions (Minin et al. 2018; Popov et al. 2018). The scientific basis is an adaptive, landscape approach aimed at a more complete use of natural processes and cycles, as far as possible closing biogeochemical cycles to cut the cost of non-renewable resources, preserving biodiversity and, at the same time, providing high-quality food (Zhuchenko 2008). Organic farming is well-suited to small-scale producers who will be able to enter the market with attractive, high-quality local products, produced with minimal impact on the environment.

Today, the Russian market for organic products is $160 million but only 10% is met by domestic production. Natural conditions and a lot of idle land offer big opportunities for increasing organic production. The aspirational target is 10–15% of total agricultural production (Mironenko 2018) but in 2016, the total amount of land in Russia certified for organic farming amounted to only 290,000 ha, and most of this was certified for future projects. Reganold and Wachter (2016) noted a steady increase in the number of organic farms, the extent of organically farmed land, the amount of research funding devoted to organic farming and the market for organic foods. Recent international reports recognize organic agriculture as an innovative farming system that balances many sustainability goals and will be increasingly important in global food and ecosystem security. Although organic farming systems produce lower yields than conventional agriculture, they are more profitable, environmentally friendly and supply equally or more nutritious products that contain less pesticide residues than conventionally grown produce.

Organic farming pays special attention to soil fertility. Minimum tillage and the use of compost and legumes contribute to the preservation of soil organic matter (Huhta and Minin 2014), which provides greater stability of crop production (Müller-Lindenlauf 2009). Regeneration of soil fertility is achieved by:

- Use of organic fertilizers and plant residues as well as naturally occurring mineral fertilizers
- Activation of soil microbiological activity and nitrogen fixation by legumes and green manure crops and use of preparations of nitrogen-fixing microorganisms
- Rational tillage
- Agro-technical control (including application of biological preparations) of weeds, pests and diseases (Prizhukov 1989; Holdshtein and Boincean 2000; Gorchakov and Durmanov 2002; Boincean 2016).

The development of an effective system of crop protection is crucial. To this end, multifunctional biological products based on strains of antagonistic microbes are being developed and successfully used. Bio-pesticides not only have a direct target effect on harmful objects but also increase the resilience of protected crops (Novikova 2016; Novikova et al. 2016). Various physical methods of pest control, in particular, on potato crops are also applied (Dvořák 2011).

Scientific Research on Biologisation of Agriculture

Pure and applied research on every stage of the cycle of innovation—from reception of new ideas to commercialization—needs to be interdepartmental, interdisciplinary and international. We need:

- A new generation of agro-technologies built on the principles of conservation of nature and resource-saving use of biological and agrochemical factors.
- Assessment of the impact of agricultural systems of different degrees of intensification (organic, intensive, integrated, etc.) on soil fertility, crop productivity, product quality and the environment in the context of climate change.
- Optimization of the status of carbon and nutrients in the soil.
- Design and implementation of crop rotations with a greater share of soil-improving forage crops, legumes, grasses, and mixed-species crops.
- Innovative methods of converting organic wastes for the benefit of the environment and regeneration of soil fertility.
- Development of genotypes and new varieties of grain and forage crops characterized by high productivity and resilience.
- Development of new kinds of organic and bio-fertilizers and microbiological plant protection products that meet the requirements of organic production.
- Scientific justification of the usefulness of organic products.
- Improved legislative and regulatory framework for production and sale of organic products.

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Chapter 12
Ending the Recurrent Agricultural Crisis: LOME Legumes, Oilseeds, Methanation

Eugeniu Triboi and Anne-Marie Triboi-Blondel

Abstract Agriculture in Western Europe has been characterized by bouts of overproduction and quests for protein-, energy- and nitrogen autonomy, sustainability and better food quality. The recurrent crisis stems from the abandonment of farm self-sufficiency and the adoption of simplified farming systems that depend on fossil fuels and their derivatives. The LOME concept is a proven alternative based on **L**egumes (providing nitrogen and energy), **O**ilseeds (energy) and **Me**thanation of biomass. It can integrate cropping and livestock or operate solely as a combined food-plus-energy system. It exports carbon as cash crops and biogas but recycles the digestate to return all nutrient elements and a goodly portion of carbon to the soil. Compared with conventional intensive agriculture, LOME provides significantly increased crop production, energy and environmental services and is much less reliant on fossil fuels.

Keywords Legumes · Oil seeds · Methanation · Combined food-plus-energy systems

Diagnosis of the Crisis of Agriculture in Europe

At opposite ends of Europe, France, Romania and Moldova have experienced very different histories and find themselves at different stages of development. France, one of the most developed countries, is also an agricultural powerhouse. Productivity grew rapidly in the 1950s and 60s with a five-fold increase in crop yields, but it has hit a ceiling and, in the recurrent agricultural crisis, a farmer commits suicide every other day. In the East, agriculture is still a major economic activity—though far from attaining its potential. An analysis of the agricultural crisis in the West, particularly in France, may help the East avoid an unsustainable trajectory and its consequences.

In France, several events have contributed to this crisis:

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Phase 1: 1959–1973: Replacement of legumes, formerly grown over 3 million ha, with maize silage and grass leys (2.1 million ha). This substituted massive application of synthetic nitrogen fertilizer for symbiotic, biological nitrogen fixation. Moreover, French livestock was now dependent on imported soya, mainly from the USA. Following a drought in 1973, the USA stopped exports, and *protein autonomy* became an objective. Protein and oilseed crops were promoted in a drive for a clean protein-production sector.

Phase 2: The oil shocks of 1973–1979. Oil had been cheap, so synthetic nitrogen was cheap too. Following the oil price shocks, mineral fertilizers and especially nitrogen fertilizer also shot up in price. *Energy and nitrogen autonomy* became a major concern.

Phase 3: Industrial intensification of agriculture has degraded the environment through pollution, loss of biodiversity and global heating. *The environment and the quality of food* have become major concerns.

Phase 4: Overproduction induced by the international situation, increasing productivity and sectoral organization is manifest in continually falling farm gate prices (Allan and Dent 2021). Within the European Union, a surplus of 30 million ha of farmland is foreseen.

For all these reasons, the mission of agriculture needs to evolve by combining agricultural production with its trade and transformation. This is the focus of the new discipline of bio-economics that focuses on the food chain from production to ultimate consumption.

Things were different in the Soviet bloc where ideology decreed the end of the peasant-spirit individualist and creation of big collective and state farms where mechanisation and chemicalisation of agriculture would transform productivity. Environmental impact and the quality of the products were not amongst the evaluation criteria but ideology could not replace biology and technology, and the results were disappointing. Following the collapse of the Soviet Union, agriculture was privatized—creating, on the one hand, smallholdings and, on the other hand, big corporate farms that have adopted industrial technology without worrying too much about its sustainability. Being financed largely by Europe, the environmental and quality criteria imposed by liberalization of the market should be respected—but it would be best to learn how to avoid the recurring agricultural crisis of the West, so as to avoid arriving in the same place.

Leaders of the agricultural and political worlds confront the situation with the considered opinion that ‘the crisis originates from the low prices imposed by agro-industrial sectors, by distribution, by overproduction linked to the international situation, farm structure, EU regulations and standards, epizootics, climate…’ In other words: ‘It is someone else’s fault!’ Sticking plaster has been applied in the shape of minor price adjustments, restructuring debt, reducing charges, deferring some taxes and some social contributions that, in France, will benefit 200,000 farmers and stockbreeders. And to heal the underlying malaise? A billion euros is to be spent on ‘preparing the future’ by promoting breeding channels in national and international markets, creating meat-export platforms, promoting local sourcing, reinforcing and accelerating investment to modernize sectors and primary processing industries, administrative simplification and implementation of environmental obligations … But not a word about the mode of production, nor about the mission and place of agriculture in the future development of the country.

The Mission of Agriculture in Sustainable Development

In Europe, future agriculture will be conditioned by at least three challenges:

1. ***Growth***. Europe is not homogeneous; its member states have followed different trajectories. As Constantinople fell to the Ottoman Turks in 1453, it managed to pass the ball to the West. This was the origin of the Renaissance which, in turn, led to the scientific, agricultural and industrial revolutions of the seventeenth, eighteenth and nineteenth centuries and extraordinary economic evolution. These developments were stifled in the East where there was no Renaissance, no industrial development and agriculture remained the mainstay of the economy. Today, the GDP of countries in Western Europe is €30–40 thousand, of which agriculture contributes about 1% (1.6% in France, 0.7% in Germany). In the East, GDP is around €20 thousand, of which more than 3% comes from agriculture (4.3% in Romania, 10.3% in Moldova). Future growth is likely to depend on digital technologies, robotics and artificial intelligence that need knowledge and investment that agriculture cannot provide.
2. ***The environment***. The industrial revolution brought about a new geological and biological era, the Anthropocene, which *will* condition the future. Arresting and correcting this thrust is a major challenge, recognized by the award of the 2018 Nobel Prize for economic sciences to Paul Romer and William Nordhaus for their work on sustainable development and impact on the environment.
3. ***Energy*** is and will continue to be a key to the future. Europe depends on non-renewable energy sources. In France, 70% of energy consumption is supplied by fossil fuels; imports of fossil fuels induce a trade deficit of about €70 billion, almost 90% of the total trade deficit. Despite its less-developed industrial sector, the East, too, imports energy. This is a key issue for any future development that requires cheap energy.

In this global context, future agriculture has its own three challenges:

a. ***Food security***. Between the eleventh and nineteenth centuries, there were 10–16 famines every century. International trade and agricultural science and technology have gifted unprecedented food security—so much so that, nowadays, more people suffer from obesity than suffer hunger. In our world, food shortages are a matter of inaccessibility caused by poverty, armed conflict, population displacement and poor governance rather than local agricultural potential. But with a global human population of 7.8 billion, projected to increase to 9.8 billion by 2050, countries that have to import cereals, and that is most of them, are always at risk of food insecurity. An alternative argument recommends restricting production to negate the effects of overproduction: low prices, storage costs, environmental impact, etc.

If these alternatives are unacceptable, is there is middle way by which we may benefit from the achievements of research, continue to improve productivity, while respecting the environment? Yes, there is! By photosynthesis, plants use solar energy to produce glucose from atmospheric CO_2. Some is used for immediate growth and respiration; the rest is stored as starch, lipids, cellulose, lignin, etc.—cereal grains contain about 70% of starch. Nitrogen, from the soil or fixed symbiotically from the air, is combined as proteins—the protein content in legumes is 3–4 times higher than in cereals. The greater part of nitrogen in legumes is of symbiotic origin; other species that store lipids and proteins, such as rapeseed and sunflower, draw on nitrogen from mineralisation of soil organic matter—or from synthetic nitrogen fertilizers. Plants store more renewable energy than they consume, thereby creating reserves of carbon (C) and nitrogen (N) as biomass, and we have an interest because biomass has many uses: food, stock feed, energy and green chemistry (it contains all the molecular wealth needed for the industry to develop new intermediates and finished products in addition to or in substitution for those now derived from fossil resources). *Therefore, growing plant biomass is one of the foundations of a low-carbon economy* (https://www.ifpenergiesnouvelles.fr).

b. ***The environment***. Future agriculture should not only do no harm to the environment, it should be responsible for management of the environment. Production while preserving the environment should be the mission for agriculture.

c. ***Energy***, for power (diesel fuel, electricity …) and the manufacture of fertilizers, pesticides, etc., is the major cost for any kind of agriculture (Vert and Portet 2010). Being derived mainly from imported fossil fuels, it is a major factor driving outsourcing of agriculture, its vulnerability, and its future development. Thus, *energy autonomy* is a prime objective—*and it is achievable by using biomass grown on the farm*. Moreover, biomethane can be injected into the gas network or, in the absence of reticulation, eco-generation. An installed capacity of 100 kW produces about 800 MWh of electricity worth €120,000 and an equivalent amount of heat.

The LOME Concept as a Foundation for Future Agriculture

Agricultural research has been dominated by single-factor studies. However, Gardner and Drinkwater (2009) by meta-analysis of 217 field experiments involving nitrogen application showed that the practices that aim to increase N uptake from fertilizers (N rate, application timing, side dressing, banding and so forth) had less effect than multi-process practices like crop rotation or manuring where sources of C and N were re-coupled. In the same vein, Porter et al. (2009) estimate that combined food and energy (CFE) systems generate significantly more organic energy and need less fossil-fuel energy than conventional agriculture. Moreover, they provide non-market environmental services valued much in excess of current levels of EU farm-support payments. The researchers conclude: ‘a socially desirable future goal would be to develop further the concept of energy-neutral farming systems, as represented by the CFE system, to farming systems that are greenhouse-gas neutral in the sense that losses of carbon and non-carbon are balanced by carbon sequestration’.

This is the objective of the LOME concept: Legumes, Oilseeds and Methanation, which matches up to all three challenges. The three levers are interdependent: the Ls produce nitrogen and, also, energy as carbon; the Os produce energy; both constitute a substrate for the production of energy by the ME. C-energy is the main item exported; the other elements (N, P, S, K, Ca, Mg, etc.) are returned to the soil in an easily assimilable form as the by-product of anaerobic digestion.

Legumes: In France since 1959, the area occupied by legumes has decreased by 3 million ha: a loss of at least 600,000 tonne of symbiotic nitrogen that was replaced by synthetic fertilizer nitrogen. The energy used to make this fertilizer is equivalent to 600,000 tonne of crude oil. Excessive application of nitrogen fertilizers (in total 835,000 tN per year) has polluted streams and groundwater, and the loss of home-grown protein has had to be compensated by imports of soybeans (80% of requirements). Since legumes are factories for producing of nitrogen and carbon, can they satisfy the nitrogen needs of high-productivity agriculture instead of fossil fertilizers? Again, the answer is Yes—*provided that we also value carbon in the form of energy to compensate for the loss of a cash crop by using its biomass to generate biogas.*

Oilseeds: By producing oil that may be used almost directly as fuel and, also, proteins, oilseeds contribute to autonomy of both energy and protein. In France, about 2.5% of arable land is used to produce bio-fuel, of which 80% is oilseeds—but these crops are fertilized with synthetic nitrogen that diminishes the energy gain. It remains to design new *energy cropping systems* that use not only the carbon of energy crops, but all of the available biomass (crop residues and intermediate crops) fertilized by nitrogen fixed by legumes and recycle other nutrients. In this case, oilseeds and other energy crops will find their place.

Methanation is a biological process that transforms carbon from organic matter into methane (CH_4) by anaerobic fermentation. The biogas contains 50–70% CH_4 along with CO_2. After separation of the CO_2, the biomethane can be used to produce heat and electricity. The digestate that remains after fermentation is an ideal fertilizer because it contains a portion of unprocessed organic matter and all necessary plant nutrients. In France, the 2011 law of modernization of agriculture recognizes methanation as an agricultural activity that produces renewable energy and additional income but, also, lessens dependence on mineral nitrogen and nitrogen-related pollution; it complements and extends traditional cropping and stockbreeding activities, so its efficiency should be assessed at the farm level and not just at the level of anaerobic digestion.

Future Agriculture in the Future Society

What would agriculture applying the LOME concept be like, and how would it fit into the future society? First, a certainty: the introduction of legumes as a renewable source of carbon and nitrogen ensures autonomy in nitrogen and energy. Biomethane can be injected into the gas network or, in the absence of reticulation, used on-site to generate electricity. LOME is based on experimental results from a long-term experiment (30 years) at INRA Clermont-Ferrand in which we compared a conventional cropping system (without legumes) with a system that included 20% of lucerne:

Crop system	1	2	3	4	5	6
Conventional	Corn	Corn	Wheat	Oilseed	Corn	Sugar beet
LOME	Lucerne	Lucerne	Wheat	Oilseed	Corn	Sugar beet

Over two years, lucerne produced about 1000 kgN/ha, 800 in above-ground biomass and 200 kg in the soil. Using this concept, a 100 ha farm growing 20% lucerne, 30% wheat, 20% maize, 20% oilseed and 10% sugar beet, and using the biomass produced by lucerne, intermediate crops and crop residues (straw, stubble, beet tops) can generate annually about 700 t dry matter for methanation that would produce 200,000 m^3 of methane (2000 m^3/ha) equivalent to 2000 MWh energy (Table 12.1) worth €300,000 in electricity generation.

Suppose now that in an intensive conventional farming system, 20% of the area is used for energy crops for biofuels. These two years of energy crops (rapeseed, corn, beet, etc.) can produce about 6000 m^3 CH_4/ha or 6000 × 20 ha = 120,000 m^3 CH_4 per crop rotation. This is only 58% of energy produced in the LOME system

Table 12.1 Biomethane and N supply by LOME crop system

Crops	Area, ha	Dry matter, tonne/ha	LOME (*20% lucerne*)			
			Total dry matter, t	CH_4, m^3/ha	Total CH_4, m^3	Total kg N
Lucerne1 Wheat straw	10 10	7 5	70 50	335 190	24,000 9500	X 750
Lucerne 2 Oilseed straw	10 10	15 2	150 20	335 150	50,250 3000	10,000 100
Wheat straw Vetch	20 20	5 5	100 100	190 335	19,000 33,500	250 2500
Corn stover	20	7	140	170	23,800	700
Sunflower silage + Lucerne Sugar beet tops	10 10 10	10 1 4	100 x 40	300 320	30,000 12,960	1500 1000
Total	100		670		206,010	17,300
Average/ha ~2000 m^3 CH_4/ha + 170 kg N						

because, in LOME, all crop residues and cover crops are used for methanation. Moreover, in the LOME system, the nutrients N, P, K, Mg, Ca, etc., and a significant amount of carbon-energy are returned to the soil with the methanation digestate. In our example, we recover 17,000 kgN, of which 70% comes from legumes, which ensures total autonomy in nitrogen (170 kgN/ha). Thus, the replacement of synthetic nitrogen fertilizers by the nitrogen produced by the legumes and recovered with the digestate has a double benefit: both saving fossil energy necessary for the production of mineral N and production of renewable energy and symbiotically fixed nitrogen.

Where livestock is the main enterprise, the biomass is intended for stock feed and the manure goes for anaerobic digestion. In these circumstances, the use of biomass is optimized according to profitability. Assuming production of 10 tonne manure per animal, then from a 50 ha farm with 100 cattle, 1000 tonne manure is available containing about 5500 kgN, 3500 kgP_2O_5 and 8000 kgK_2O. In addition, by methanation producing 60 m^3 of biomethane per tonne of manure (200 m^3 per dry tonne), the farm produces 60,000 m^3 biomethane, or about one third of the production of a LOME system on 100 ha without animals. In addition, the digestate recycles all the nutrients. If we extrapolate to 10% of the livestock in France (20 million), Romania (2 million) and Moldova (300 thousand), then we could produce about 12, 1.2 and 0.18 million m^3 of biomethane and 110,000, 11,000 and 1650 t of nitrogen, respectively, for the three countries using 100 kgN/ha can fertilize 1,100,000, 110,000 and 16,500 ha, respectively. So, with methanation of manure and, possibly, some of the plant biomass, total autonomy in nitrogen and possibly other nutrients is assured. And the introduction of methanation makes for greater flexibility in the system.

In France, intensification of agriculture by using mineral nitrogen and maize silage for stock feed was accompanied by the loss of 3 million ha of lucerne. If we reinstate 1 million ha of lucerne, that would produce more than 10 billion m^3 of methane, equivalent to 40 million MWh electricity (worth 6 billion euro at €15/MWh) and an equivalent amount of heat to produce 40 million MWh of electricity which requires a total installed power capacity of 5300 MW or 10,000 installations of 500 kW each; this is nearly the position in Germany where, in 2015, 8726 methanation plants were in place with a total capacity of 3905 MW. But to reach this level, Germany has been installing more than 1000 methane plants per year for several years; whereas in France, we have only 400 installations and a rate of development of 40–50 installations per year.

If our million hectares of lucerne occupies 20% of the land in the rotation, then 5 million ha cultivated according to the LOME concept and producing 170 kgN/ha will fix 850,000 tonne of nitrogen. This is more than 40% of the total amount of nitrogen used in French agriculture on 26 million ha, so the concept is viable even for organic farming where nitrogen is the main limiting factor. Colleagues in the leading countries in this field insist on coupling this role of legumes with anaerobic digestion; for example, Germany, which produces 65.5 million m^3 of digestates, recycles 390,153 tN, 74,075 tP and 331,472 tK, of which 60% is from non-leguminous energy crops and 40% from livestock.

Biofuels present another challenge within the goal of energy self-sufficiency. In France, the 2015 legislation on energy transition set a target of 15% of renewable fuels by 2030. In 2016, the overall rate of incorporation of biofuels was 7.5%, and the area occupied by industrial and energy crops was 504,426 ha: rapeseed (68%), wheat (16%), sugar beet (10%) and sunflower (5%), producing the equivalent of 5000 m^3 of methane per ha. However, these non-leguminous crops are fertilized with 100–200 kgN/ha (in all, 50–100 thousand tonne of synthetic N that requires 0.5–1 million MWh of energy equivalent to 50–100 million m^3 CH_4).

It is in our interest to produce these biofuels in the LOME system—let us call it the *LOME energy system*. Of the 5 million ha, 20% will be under lucerne and 10% under non-leguminous energy crops that will produce 12.4 billion m^3 of methane ($10 + 2.4$). Used as fuel, this energy corresponds to 12,400 kilotonne petrol-equivalent (ktep), which represents more than 20% of consumption by transport in France (Germany currently produces 7000 electrical ktep and France only 500 ktep). Thus, for France, the production of renewable energy *by agriculture* would easily cover its direct and indirect needs (evaluated at 3–4 million ktep); the remaining 30–50 million ktep would satisfy almost all the energy consumption of the transport sector (~50 million ktep) which represents 30% of national energy consumption. *The import of oil and gas represents 88% of the French trade deficit, and, yet, this mission of agriculture is totally ignored.*

Biomethane in the Energy Mix

In 2017, the share of renewables in gross energy consumption in the EU was 17.5% (16.3% for France, 24.5% for Romania); the 2020 targets are 20% (23 and 24%), respectively. A major difference between the two countries is the contribution of nuclear energy: 40% for France, 12% for Romania. Another is the origin of oil and gas, Romania being almost self-sufficient. In France in 2016, the total investment for renewable energy was €6.7 billion, of which 26% was in wind turbines, 11% photovoltaic and less than 3% in biogas. The installed electricity generation capacity in 2018 was 15,000 MW from onshore wind, 10,000 MW solar and 137 MW biogas, and the 2023 projection is 24,000, 19,000 and 270 MW, respectively. In 2017, public utility charges for electricity related to renewable energies were €4.6 billion which corresponds to subsidies allocated to generation from renewable sources: 61% to photovoltaic, 25% to wind and14% to other sources amongst which the injection of biomethane into the gas network was subsidized to the tune of €33 m.

Actually, anaerobic digestion is much more efficient than the wind or sun. For investments 4–9 times lower, it produces energy equal to 20 times photovoltaic and only 3 times lower than wind energy, as well as producing a storable product and producing it night and day, wind or no wind. This anomalous situation arises because anaerobic digestion has been evaluated only on industrial criteria rather than evaluating it as an agricultural activity that has direct marketable and indirect effects on the environment—global heating included.

If the LOME concept, allied to anaerobic digestion, is to become a mainstream agricultural activity, we need to ask ourselves: (1) How do we convince decision makers to take action? (2) Do we have the necessary agronomic and technical knowledge?

There are many big farms (>500 ha) in Romania and Moldova. They will be the easiest to convince because their size brings economies of scale in the cost of the installations and the optimization of related works. In France, with much smaller farms, several farmers would need to cooperate to reach an optimal size if methanation remains an agricultural activity driven by farmers. The situation is different for industrial methane generation where farmers are merely suppliers of biomass. However, *we do have all the necessary knowledge*, if not know-how, because the results of so-called classical agronomic research apply in the LOME concept. Obviously, changing the concept of themes like the nitrogen and carbon cycles in the soil will require specific approaches and field experiments that might be undertaken within new *experimental domains*, preferably in/with the current research institutes.

Conclusions

1. In today's intensive agriculture, the challenges of productivity, energy and the environment are not compatible. Fossil energy is a drag on productivity, and even if agricultural techniques were improved, the environmental challenge will persist. On the other hand, if agriculture is a source of renewable energy, then productivity could continue to grow, and the management of the environment would become an agricultural reality because agriculture will no longer be a source of greenhouse gases or of pollutants like nitrates and pesticides. Instead, it will participate significantly in the establishment of a sustainable, decarbonized economy.
2. We already know enough to end the recurrent crisis in agriculture and to make it, once again, a national priority. If agro-ecology is complemented by the bio-economy, we ensure the maximum use of solar energy through the production of biomass (renewable carbon). At the same time, by optimizing the use of biomass between food and non-food (such as energy and fertilizers), we may conserve the environment.
3. Porter et al. (2009) conclude: 'such novel agro-ecosystems combining food and energy (CFE) that simultaneously produce food, fodder and bio-energy can provide significantly increased net crop, energy and non-marketed ecosystem services (ES) compared with conventional agriculture and require markedly less fossil-based inputs. Extrapolated to the European scale, the value of non-marketed ES from CFE systems exceeds current European farm subsidy payments. Such integrated food and bio-energy systems can thus provide environmental value for money for European Union farming and non-farming communities'.

4. Decision makers would do well to heed Seneca (63-65): '*It's time to act … It is hours that are taken away by force, or filched away, or have merely slipped from your hands. But the most shameful loss is that which comes from neglect; and, if you take heed of it, the largest portion of our life passes while we are doing ill, a goodly portion while we are doing nothing, and the whole while we are doing that which is not the purpose … Hold every hour in your grasp. Lay hold of today's task, and you will not need to depend so much on tomorrow's … Nothing is ours, except time*'.

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Chapter 13
Diversity of Crops in Rotation: A Key Factor in Soil Health and Crop Yields

Boris Boincean, Marin Cebotari, and Lidia Bulat

Abstract Intensification of agriculture during the era of cheap industrial inputs neglected crop rotation; it was supposed that crop rotation could be replaced by fertilizers and pesticides. Now, we know better. Data from the long-term field experiment on crop rotations and fertilizers on the *Typical chernozem* of the Bălți Steppe in Moldova show that the *effect of crop rotation*—the difference between yields of crops in rotation and yields from continuous monocropping—is much greater than the *effect of fertilization*—the difference between yields of crops on fertilized and unfertilized plots. Fertilization diminishes the effect of crop rotation but does not replace it. The effect of fertilization is greater under continuous monocropping because of poor soil health. Improving soil health by a diverse crop rotation that includes perennial legumes and grasses improves all soil functions and reduces dependence on costly synthetic fertilizers, irrigation, and chemical control of weeds, pests and diseases.

Keywords Effect of crop rotation · Effect of fertilization · Soil health · *Chernozem*

Introduction

Agricultural intensification in the second half of the twentieth century depended on industrial inputs: mechanization, power from fossil fuels, synthetic fertilizers and pesticides derived from the same fossil fuels, and irrigation. This is still the dominant model, but it is not sustainable; it burns up more energy than it harvests, soil is being lost much faster than it can be made, water resources are overdrawn in every important agricultural region, and the damage to the environment and public health is only now becoming apparent.

Crop rotation is the centrepiece of a sustainable farming system, and each of its components should be directed towards improving soil fertility and function. A wealth of experimental data demonstrates that there is nothing so cheap and, yet, so effective in improving soil fertility and productivity. Crop rotation does not eliminate

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deficits of water and nutrients or the invasion of weeds, pests and diseases but, by respecting crop rotation, it is possible to rein in the consumption of both mineral fertilizers and pesticides (Boincean and Dent 2019; Gliessman 2000; Kirschenmann 2010; Magdoff and van Es 2018; Snapp and Pound 2008; Soule and Piper 2009).

The Selectia Long-Term Field Experiment

A long-term field experiment on crop rotation was established on the *Typical chernozem* of the Bălți Steppe at the Selectia Research Institute for Field Crops in 1962. Continuous monocropping on fertilized and unfertilized plots was added in 1965. The soil texture is heavy clay; the content of soil organic matter (by Tiurin's method) is 4.8–5.0%, pH_{water} 7.3 and pH_{CaCl2} 6.2, total nitrogen 0.20–0.25%, phosphorus 0.09–0.11% and potassium 1.22–1.28%.

The experiment encompasses eight crop rotations with different proportions of row crops (from 40 to 70%) including 10–30% of sugar beet, 10–20% of sunflower, and 20–40% of maize. Winter wheat occupies 30% in each rotation but is sown after different predecessors: on the first field after early-harvested predecessors, in the second field after maize silage, and in the third field after corn-for-grain. Sugar beet follows winter wheat sown in different links of the rotation: after a mixture of winter vetch-and-winter rye for green mass, maize silage, and corn-for-grain in rotation 4; after winter wheat following lucerne in rotation 5; after black fallow in rotation 2; after maize silage in all crop rotations.

Systems of soil tillage and fertilization are determined by the crop, as reported by Boincean (2015a, b). No fertilizers are applied in crop rotation 7; rotation 3 has the same alternation of crops as rotation 7. There is also fertilized and unfertilized continuous wheat, sugar beet and corn-for-grain. In crop rotations, the plot size is 283 m^2 with three replicates. In continuous cropping, the plot size is 450 m^2 with no replicates. Farm practice is typical for the region and in accordance with the recommendations of the research institutions. The cultivated crop varieties and hybrids are registered in the state register for crops.

Results and Discussion

Crop Productivity

Winter wheat: Table 13.1 presents the average yields of winter wheat for the period 2004–2018 in the same crop rotation but sown after the mixture of spring vetch-and-oats for green mass, after maize silage, after corn-for-grain and also the yields of continuous wheat on fertilized and unfertilized plots.

Table 13.1 Yields of winter wheat (t/ha) after different predecessors in crop rotations and of continuous wheat, 2004–2018, Selectia RIFC

Predecessors	Fertilization		Extra yields from fertilization (%)	Yield decrease relative to the crop following vetch-and-oats	
	Unfertilized	Fertilized		Unfertilized	Fertilized
Vetch-and-oats	4.42	5.14	0.72/16	–	–
Maize silage	2.95	4.70	1.75/59	1.47/33%	0.44/9%
Corn-for-grain	2.51	3.96	1.45/58	1.91/43%	1.18/23%
Continuous wheat	1.99	3.29	1.30/65	2.43/55%	1.85/36%

The best yields, both on unfertilized and fertilized plots, have been achieved by sowing winter wheat after the early-harvested mixture of vetch-and-oats: 4.42 and 5.14 t/ha, respectively. The poorest yields were from continuous wheat: 1.99 and 3.29 t/ha on unfertilized and fertilized plots, respectively. The benefit of mineral fertilizers is less after an early-harvested predecessor (0.72 t/ha or 16%) and greater after late-harvested predecessors (1.45–1.75 t/ha or 58–59%) and under continuous wheat (1.30 t/ha or 65%). However, fertilization cannot compensate for the lack of good predecessors in the rotation; the yield reduction for winter wheat as a result of sowing after late-harvested predecessors was equal to or significantly greater than the extra yields from fertilization.

In 2012, drought cut yields significantly relative to the average for 2004–2018 (Table 13.2). This was the case after all predecessors in crop rotation and, also, with continuous wheat; the benefits of fertilization were less in all cases. Relative to winter wheat sown after the mixture of vetch-and-oats, yield reduction of wheat sown after late-harvested predecessors and from continuous wheat remained much the same as the 2004–2018 average on unfertilized plots, but the reduction was significantly greater on fertilized plots, especially for late-harvested predecessors. So, under drought conditions, respecting good predecessors is more effective than application of mineral fertilizers.

Sowing winter wheat after black fallow forfeits a year's income and has no agronomic advantages relative to other early-harvested predecessors, even in drought years (Table 13.3). Continuous wheat yields poorly, especially in drought conditions.

Table 13.2 Yields of winter wheat (t/ha) after different predecessors in crop rotations and from continuous wheat in drought conditions (2012), Selectia RIFC

Predecessors	Fertilization		Extra yields from fertilization (%)	Yield decrease relative to the crop following vetch-and-oats	
	Unfertilized	Fertilized		Unfertilized	Fertilized
Vetch-and-oats	3.52	4.52	1.0/28	–	–
Maize silage	2.3	2.74	0.61/29	1.39/405%	1.78/39%
Corn-for-grain	1.66	2.23	0.57/34	1.86/53%	2.29/51%
Continuous wheat	1.11	2.58	1.47/132	2.41/69%	1.94/43%

Table 13.3 Yields of winter wheat (t/ha) after different predecessors in crop rotations and in continuous monocropping on fertilized plots, average for 2004–2018 and in the 2012 drought, Selectia RIFC

Predecessors	Share of row crops in the rotation, %	Yields, t/ha	
		2004–2018 average	2012
Lucerne in the third year after first cut	40	5.12	4.54
Black fallow	50	5.49	4.80
Mixture of winter vetch-and-winter rye	60	5.16	4.27
Maize silage	70	4.90	3.29
Continuous winter wheat	0	3.29	2.58

Sugar beet: Sugar beet is more productive in the rotational link where winter wheat is sown after a mixture of vetch-and-oats than in the crop rotation link where winter wheat was sown after maize silage, especially on fertilized plots. Fertilization of sugar beet produced an extra 10.3 t/ha (43%) in the crop rotation link with early-harvested predecessors of winter wheat. Continuous sugar beet is not viable (Table 13.4); the yield reduction of continuous sugar beet is far greater than any extra yields from fertilization, especially in drought conditions (Table 13.5).

Corn-for-grain is an enigma. It responds less to crop rotation and fertilization than either winter wheat or sugar beet (Table 13.6). The extra yields from fertilization in crop rotation links where wheat was sown after vetch-and-oats and after maize silage averaged 0.5 t/ha (10.5%) and 0.69 t/ha (14%), respectively. For continuous corn-for-grain, the extra yield from fertilization was three times higher than for corn in rotation. This is a typical example of how improving the nutrition for a weak root system can increase yields—and it has become the norm under contemporary farming systems that do not respect crop rotation.

In absolute terms, the extra yield from fertilization of continuous corn is about the same as the yield reduction from non-compliance with crop rotation on the unfertilized plot: 1.73 t/ha (51%) and 1.85 t/ha (35%), respectively. The loss of yield

Table 13.4 Yields of sugar beet (t/ha) in different links of crop rotations and of continuous sugar beet, average 2004–2018

Links of crop rotations	Fertilization		Extra yields from fertilization (%)	Yield decrease relative to link following vetch-and-oats	
	Unfertilized	Fertilized		Unfertilized	Fertilized
Vetch-and-oats–winter wheat–sugar beet	23.9	34.2	10.3/43	–	–
Maize silage–winter wheat–sugar beet	27.7	25.5	−2.2/−89	+3.8/+16%	8.7/25%
Continuous sugar beet	4.9	9.8	4.9/100	19.0/388%	24.4/249%

Table 13.5 Yields of sugar beet (t/ha) in different links of crop rotations and of continuous sugar beet in the 2012 drought

Predecessors	Fertilization		Extra yields from fertilization (%)	Yield decrease relative to link following vetch-and-oats	
	Unfertilized	Fertilized		Unfertilized	Fertilized
Vetch-and-oats–winter wheat–sugar beet	6.0	4.3	−1.7/−28	–	–
Maize silage–winter wheat–sugar beet	5.7	8.2	2.5/44	0.3/50%	+3.9/91%
Continuous sugar beet	0.8	1.5	0.7/88	5.2/87%	2.8/65%

Table 13.6 Yields of corn-for-grain (t/ha) in different rotational links and of continuous corn, 2004–2018

Links of crop rotation and continuous corn	Fertilization		Extra yields from fertilization, t/ha (%)	Yield decrease relative to link following vetch-and-oats	
	Unfertilized	Fertilized		Unfertilized	Fertilized
Vetch-and-oats–winter wheat–sugar beet–corn-for-grain	5.25	5.80	0.55/10.5	–	–
Maize silage–winter wheat–sugar beet–corn-for-grain	4.93	5.62	0.69/14	0.32/6%	0.51/9%
Continuous corn	3.40	5.13	1.73/51	1.85/62.5%	0.67/12%

from fertilized continuous corn is less relative to the unfertilized crop rotation link with early harvested predecessors of winter wheat but is still 0.67 t/ha (12%). Under the drought conditions of 2012, yields were significantly depressed but the trends were the same (Table 13.7).

It goes without saying that crop rotation cannot be replaced by fertilizers. *The effect of crop rotation* is the difference between yields of crops in rotation and yields from continuous monocropping on fertilized and unfertilized plots. *The effect of fertilization* is the difference between yields of crops on fertilized and unfertilized plots in crop rotation and in continuous monocropping. Table 13.8 presents the average values for 2004–2018. For all crops, the effect of crop rotation on unfertilized plots is greater than the effect of fertilization. However, in absolute terms, the effect of fertilization is significantly higher in continuous monocropping than in crop rotation, except for sugar beet. The reason for this is poor soil health under a continuous monoculture; the weaker capacity of the root system to absorb nutrients has to be compensated by extra mineral fertilizers. Moreover, infestation by weeds, pests, and diseases is greater than in a diverse crop rotation. By growing crops in rotation, it is

Table 13.7 Yields of corn-for-grain (t/ha) in different rotational links and in continuous corn in the 2012 drought

Links of crop rotation and continuous corn	Fertilization		Extra yields from fertilization, t/ha (%)	Yield decrease relative to link following vetch-and-oats	
	Unfertilized	Fertilized		Unfertilized	Fertilized
Vetch-and-oats–winter wheat–sugar beet–corn-for-grain	3.74	3.04	−0.70/−19	–	–
Maize silage–winter wheat–sugar beet–corn-for-grain	2.81	2.45	−0.36/−13	0.93/25%	0.59/19%
Continuous corn	3.72	4.68	0.96/26	0.02/0.5%	+1.64/+6%

Table 13.8 Effect of crop rotation and fertilization for different crops in the long-term field experiment at Selectia RIFC, t/ha and %, average for 2004–2018

Crops	Effect of crop rotation		Effect of fertilization	
	Unfertilized (%)	Fertilized (%)	Crop rotation (%)	Continuous monocropping (%)
Winter wheat	+2.43/55	+1.85/36	+0.72/16	+1.30/65
Sugar beet	+19.0/38	+2.44/249	+10.3/43	+4.90/100
Corn-for-grain	+1.85/35	+1.00/17	+0.55/10.5	+1.73/51

possible to cut or even eliminate the use of mineral fertilizers, especially nitrogen, and pesticides.

Water-Use Efficiency

Winter wheat abstracts about half of its water from the topmost metre of soil (Table 13.9). Irrespective of the predecessor, its water-use efficiency in crop rotation is significantly greater than continuous wheat: 257.3–407.6 tonne water per tonne grain, compared with 580.9 t/t. The same applies to drought years like 2009 but with greater water consumption per tonne of grain (Table 13.10).

Sugar beet follows winter wheat in the same crop rotation but in different links of the rotation. Stocks of soil water in spring are much the same, whether the wheat was sown after an early-harvested predecessor (a mixture of winter vetch-and-winter rye), maize silage or corn-for-grain, but differences were established by harvest time (Table 13.11). More water was drawn from the topmost metre of soil in the crop rotation link following the early-harvested predecessor and in the rotation with three years of lucerne. In both cases, greater crop yields were achieved: 32.6 and 35.5 t/ha, respectively, with a water-use efficiency of 48.8 and 51.0 tonne roots per tonne of

Table 13.9 Water use by winter wheat after different predecessors in rotation and by continuous wheat, 2004–2018

Predecessors	Soil layers, cm	Soil water stocks, mm		Soil water consumption during growing season, mm	Share of 0–100 cm soil layer in total water consumption, %	Yield, t/ha	Water-use efficiency, t/t
		Spring	After harvest				
Lucerne in third year after first cut	0–100	176.7	65.1	111.6	54	5.12	407.6
	0–200	356.7	148.0	208.7			
Black fallow	0–100	170.5	78.0	92.5	49	5.49	342.3
	0–200	353.5	165.6	187.9			
Vetch-and-oats for green mass	0–100	174.8	73.7	101.1	51	5.16	382.8
	0–200	353.5	156.0	197.5			
Maize silage	0–100	161.9	75.1	86.7	49.5	4.90	357.3
	0–200	341.3	166.2	175.1			
Continuous winter wheat	0–100	166.6	62.6	104.1	54.5	3.29	580.9
	0–200	357.6	166.5	191.1			

Table 13.10 Water use by winter wheat in rotation and by continuous wheat in the 2009 drought

Predecessors	Soil layers, cm	Soil water stocks, mm		Soil water consumption during growing season	Share of 0–100 cm soil layer in total water consumption, %	Yield, t/ha	Water-use efficiency t/t
		Spring	After harvest				
Lucerne in third year after first cut	0–100	187.1	52.1	135.0	61.3	4.35	506.2
	0–200	373.6	153.4	220.2			
Black fallow	0–100	186.3	63.7	133.6	51.6	4.62	514.3
	0–200	377.3	139.7	237.6			
Vetch-and-oats for green mass	0–100	198.3	83.5	114.8	47.3	4.59	529.0
	0–200	399.2	156.4	242.8			
Maize silage	0–100	177.7	71.3	106.4	44.6	4.49	531.2
	0–200	377.6	139.1	238.5			
Continuous winter wheat	0–100	185.6	63.7	121.9	50.3	1.82	1331.9
	0–200	404.0	161.6	242.4			

water consumed, respectively. Continuous sugar beet consumed 119.2 tonne water per tonne of roots.

This pattern was exaggerated under the drought conditions of 2009 (Table 13.12); sugar beet following winter wheat sown after late-harvested predecessors suffered a

Table 13.11 Water use by sugar beet in different crop rotation links and by continuous sugar beet, 2004–2018

Predecessors	Soil layers, cm	Soil water stocks		Soil water consumption in growing season	Share of 0–100 cm soil layer in total water consumption, %	Yield, t/ha	Water-use efficiency t/t
		Spring	After harvest				
Vetch-and ryewinter wheat–sugar beet	0–100	165.3	73.8	91.5	58	32.6	48.8
	0–200	320.7	161.7	159.0			
Maize silage–winter wheat–sugar beet	0–100	161.6	84.4	77.2	50	29.2	53.3
	0–200	320.9	165.3	155.6			
Corn-for-grain–winter wheat–sugar beet	0–100	162.1	83.2	78.9	52	28.2	53.7
	0–200	319.6	168.1	151.5			
Continuous sugar beet	0–100	176.3	107.8	68.5	59	9.8	119.2
	0–200	341.0	224.2	116.8			
Lucerne–winter wheat–sugar beet	0–100	166.3	72.9	93.4	52	35.5	51.0
	0–200	324.4	143.5	180.9			

Table 13.12 Water use by sugar beet in different rotation links and by continuous sugar beet in the 2009 drought

Predecessors	Soil layers, cm	Soil water stocks		Soil water consumption during growing season, mm	Share of 0–100 cm soil layer in total water consumption, %	Yield, t/ha	Water-use efficiency t/t
		Spring	After harvest				
Vetch-and ryewinter wheat–sugar beet	0–100	173.7	31.9	141.8	53	26.4	101.4
	0–200	366.2	98.3	267.9			
Maize silage–winter wheat–sugar beet	0–100	177.2	84.7	92.5	42	24.4	89.8
	0–200	358.4	139.2	219.2			
Corn-for-grain–winter wheat–sugar beet	0–100	211.5	37.1	174.4	55	20.4	155.1
	0–200	432.2	115.8	316.4			
Continuous sugar beet	0–100	191.0	92.0	99.0	44	6.4	353.0
	0–200	380.1	154.2	225.9			
Lucerne–winter wheat–sugar beet	0–100	176.2	35.7	140.5	52	31.5	85.3
	0–200	359.5	90.9	268.6			

severe yield penalty. Unfortunately, this is the usual situation in systems dominated by row crops. The highest yield and water-use efficiency of sugar beet in drought conditions was achieved in the crop rotation link with winter wheat following lucerne: 31.5 t/ha requiring 85.3 t water/t roots. In view of the likelihood of more common, more severe droughts in the future, farmers across the steppes would do well to respect crop rotation that includes perennial legumes and grasses.

Corn-for-grain hardly reacts to different links in the crop, rotation (Table 13.13). The capacity of continuous corn-for-grain to exploit soil water is significantly less: water-use efficiency in rotation is 403–575 tonne water per tonne grain but 1889 t/t for continuous corn-for-grain when soil water exploitation from both the 0–100 cm and 0–200 cm soil layers is much reduced. As with sugar beet, the rotational link with lucerne is advantageous both in terms of the yield of corn and access to soil water reserves, especially from the 0–100 cm soil layer. In drought year 2016, the influence of sugar beet as a predecessor for corn-for-grain on yield of corn was negative, even in the crop rotation link with lucerne (Table 13.14).

Including lucerne in the rotation gives the corn better access to water from deeper soil layers relative to crop rotation links without lucerne; the share of the 0–100 cm soil layer in the total water consumption from 0 to 200 cm was 76.3 and 82.0–91.2%, respectively. And water-use efficiency was higher in crop rotation links than in continuous monocropping (403.4–575.7 tonne water per tonne grain compared with 1726.5 t/t). Clearly, growing corn-for-grain in crop rotation, with or without with lucerne, is a better proposition than continuous corn, more so in drought conditions (Table 13.14).

Table 13.13 Water-use efficiency by corn-for-grain in different crop rotation links and by continuous corn on fertilized plots, 2004–2018

Crop rotation links and continuous corn	Soil layers, cm	Soil water stocks, mm		Soil water consumption in growing season, mm	Share of 0–100 cm soil layer in total water consumption, %	Yield, t/ha	Water-use efficiency t/t
		Spring	At harvest				
Rye-and-vetch–winter wheat–sugar beet–corn-for-grain	0–100	149.6	76.3	73.3	60	5.80	210.7
	0–200	283.9	161.7	122.2			
Maize silage–winter wheat–sugar beet–corn-for-grain	0–100	138. 2	79.4	58.6	51	5.90	194.2
	0–200	290.0	175.2	114.6			
Lucerne–winter wheat–sugar beet–corn-for-grain	0–100	153.1	74.1	79.0	66	6.19	194.0
	0–200	281.3	161.2	120.1			
Continuous corn-for-grain	0–100	147.3	96.1	51.2	53	5.13	1889.0
	0–200	316.0	219.1	96.9			

Table 13.14 Water-use efficiency by corn-for-grain in different crop rotation links and by continuous corn in the 2016 drought

Crop rotation links and continuous corn	Soil layers, cm	Soil water stocks, mm		Soil water consumption in growing season, mm	Share of 0–100 cm soil layer in total water consumption, %	Yield, t/ha	Water-use efficiency t/t
		Spring	At harvest				
Rye-and vetch–winter wheat–sugar beet–corn-for-grain	0–100	162.1	2.1	160.0	82	3.41	575.7
	0–200	241.2	44.9	196.3			
Maize silage–winter wheat–sugar beet–corn-for-grain	0–100	137.5	41.5	96.0	91	2.61	403.4
	0–200	214.0	108.7	105.3			
Lucerne–winter wheat–sugar beet–corn-for-grain	0–100	152.2	3.5	148.7	76	3.81	511.8
	0–200	228.0	33.0	195.0			
Continuous corn-for-grain	0–100	121.0	61.8	59.2	73	4.68	1726.5
	0–200	270.3	189.5	80.8			

Nitrogen-Use Efficiency

Nitrogen from mineral fertilizer is costly; apart from the expense of the fertilizer, there is the energy needed in its manufacture and the low nitrogen-use efficiency (NUE) of nitrate fertilizers, losses coming both from leaching and emissions of oxides of nitrogen to the atmosphere.

Winter wheat: NUE was lowest for winter wheat sown after vetch-and-oats, 26.4%; but higher after late-harvested predecessors and under continuous wheat, 47.7–64.2 % (Table 13.15).

Simultaneously, the share of soil fertility in yield formation is higher for winter wheat sown after an early-harvested predecessor, 86% and lower after late-harvested predecessors and under continuous wheat, 60.5–63.4%. It follows that by respecting a good crop rotation with early-harvested predecessors for winter wheat, the use of fertilizer nitrogen can be cut. The same goes for phosphate fertilizers.

Sugar beet: NUE was 68.7% in the crop rotation link with wheat following an early-harvested predecessor and the share of soil fertility in yield formation was 69.9%. Nitrogen from mineral fertilizers was ineffective in the crop rotation link where winter wheat was sown after maize silage; in other words, the share of soil fertility in yield formation was 100% (Table 13.16). Continuous sugar beet is not viable and application of mineral fertilizers doesn’t help.

Table 13.15 Nitrogen-use efficiency by winter wheat in crop rotation and by continuous wheat, 2004–2018

Predecessors	Yields of winter wheat, t/ha		Extra yield from fertilization, t/ha	N taken up by extra yield, kg/ha	N applied with mineral fertilizers, kg/ha	Share of soil fertility in yield formation, %
	Unfertilized	Fertilized				
Vetch-and-oats	4.42	5.14	0.72	23.8	90	86
Maize silage	2.95	4.70	1.75	57.8	90	63
Corn-for-grain	2.51	3.96	1.45	47.9	90	63
Continuous wheat	1.99	3.29	1.30	42.9	90	60.5

Table 13.16 Nitrogen-use efficiency by sugar beet in crop rotation (sown after winter wheat) and by continuous sugar beet, 2004–2018

Predecessors of winter wheat	Yields of sugar beet, t/ha		Extra yields from fertilization, t/ha	N taken up by extra yield, kg/ha	N applied with mineral fertilizers, kg/ha	N-use efficiency, %	Share of soil fertility in yield formation, %
	Unfertilized	Fertilized					
Vetch-and-oats	23.9	34.2	10.3	41.2	60	68.7	70
Maize silage	27.7	25.5	−2.2	–	60	0	100
Continuous sugar beet	4.9	9.8	+4.9	19.6	60	32.7	50

Corn-for-grain: Mineral fertilizers have not been applied to rotational corn-for-grain because corn makes effective use of nutrients from the soil without supplementary fertilizers. The extra yields in both crop rotation links (Table 13.17) are the residual action of fertilizer applied to previous links of the rotation. The share of soil fertility in yield formation is high, even in the case of continuous corn-for-grain (66.3%).

Conclusions

1. Yields of crops in rotations are higher than from continuous monocropping.
2. The *effect of crop rotation* on unfertilized plots for winter wheat, sugar beet and corn-for-grain was, on average over 2004–2018: 2.43 t/ha (55%), 19.0 t/ha (388%) and 1.85 t/ha (35%), respectively. This is much greater than the *effect of fertilization* in crop rotation for winter wheat, sugar beet and corn-for-grain: 0.72 t/ha (16%), 10.3 t/ha (43%) and 0.55 t/ha (10.5%), respectively.

Table 13.17 Nitrogen-use efficiency by corn-for-grain in rotation and by continuous corn, 2004–2018

Crop rotation links and continuous corn	Yields of corn-for-grain, t/ha		Extra yield from fertilization, t/ha	N taken up by extra yield, kg/ha	N applied with mineral fertilizers, kg/ha	N-use efficiency, %	Share of soil fertility in yield formation, %
	Unfertilized	Fertilized					
Vetch-and-oats–winter wheat–sugar beet–corn-for-grain	5.25	5.80	0.55	12.7	–	–	90
Maize silage–winter wheat–sugar beet–corn-for-grain	4.93	5.62	0.69	15.9	–	–	88
Continuous corn-for-grain	3.40	5.13	1.73	39.8	60	66	66

3. The effect of fertilization is significantly greater in continuous monocropping than in crop rotation for all crops except sugar beet. For winter wheat, sugar beet and corn-for-grain: 1.85 t/ha (36%), 24.4 t/ha (249%) and 1.0 t/ha (17%), respectively.
4. A greater diversity of crops, grown in rotation, increases soil health and function, which cuts or even eliminates the need for synthetic nitrogen fertilizers, pesticides and irrigation.
5. Water-use efficiency is significantly higher in crop rotations than in continuous monocropping and higher still in crop rotations that include perennial legumes, especially in drought conditions.
6. Optimal management of crops and fertilization cuts nitrogen losses. The share of soil fertility in yield formation is very high for crops grown in rotation: for winter wheat, corn-for-grain and sugar beet, on average for 2004–2018: 86, 90 and 70%. Continuous monocropping is less efficient although nitrogen-use efficiency is higher under continuous monocropping than in crop rotation.

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Chapter 14
Performance of Crops in Rotation Under Mineral and Organic Systems of Fertilization

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Abstract Modern agriculture ignores the laws of crop rotation and applies excess mineral fertilizers and pesticides. This has degraded soil health and resilience—although the effects may be masked by high crop yields. Results from the long-term field experiment with different systems of fertilization in crop rotation on *Typical chernozem* at Selectia Research Institute for Field Crops at Bălţi, in Moldova, prove this assertion and offer a better way forward. The widening gap between farm-gate prices for agricultural commodities and the cost of mineral fertilizers means that the extra yields from application of fertilizer do not repay the cost. In crop rotation, the lion's share of yield formation comes from inherent soil fertility, and with the exception of sugar beet, the optimal system of soil fertilization is application of farmyard manure. Nitrogen-use efficiency from mineral fertilizers is low, even when applied together with farmyard manure, with known and unknown consequences for the environment. Improving soil health by better provision of fresh sources of energy for soil biota is the most reliable way to decrease dependency on mineral fertilizers.

Keywords Crop rotation · Mineral fertilizers · Organic fertilizers · Soil fertility · N-use efficiency

Introduction

Building soil fertility is essential for transition from the unsustainable present to a more sustainable future farming system. Based on the experimental evidence, we argue that the problem can be solved by shifting from dependency on industrial inputs to an agro-ecological approach that depends on more-local, renewable resources of energy and closes the cycles of carbon and nutrients on the farm and within the landscape, so that most outputs become inputs.

For more than half a century, the dominant concept of agricultural intensification has been soil fertilization using mineral fertilizers. But the widening gap between

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farm-gate prices for agricultural commodities and increasingly costly industrial inputs has complicated the equation, especially for higher rates of mineral fertilizer—the extra yields obtained cannot repay the expense of the fertilizers. Organic fertilizers are more efficient financially, as well as from an ecological perspective. They deliver good yields and, simultaneously, restore soil fertility and soil health. By helping to cut back on mineral fertilizers, they reduce the risk of nitrate pollution of streams and groundwater, the emission of nitrogen oxides to the atmosphere and the substantial greenhouse gas emissions associated with the manufacture of nitrate fertilizers (Boincean and Dent 2019; Doran 1996; Magdoff and van Es 2018). However, organic manure is in short supply.

The quite different influences of organic and mineral fertilizers on soil fertility and crop productivity are demonstrated by the long-term field experiment with different systems of fertilization on *Typical chernozem* at Selectia Research Institute for Field Crops at Bălţi in the Republic of Moldova. Mineral fertilizers are depleting stocks of soil organic matter to depths of more than one metre. On the other hand, organic and mixed organo-mineral systems of fertilization in crop rotation are building up the stock of soil organic matter (Boincean et al. 2014).

Experimental Site and Methods

The soil of the experimental site is heavy loam *Typical chernozem*. The initial content of soil organic matter ranged from 4.3 to 5.1%, total nitrogen 0.24–0.26%, total phosphate 0.12–0.13% and potassium 1.2–1.4%; pH_{water} was 6.6–7.1. The experiment began in 1973 comparing four systems of fertilization (Table 14.1):

- unfertilized control (I)
- mineral fertilizers (II—NPK_1, III—NPK_2, IV—NPK_3)
- combined manure and mineral fertilizers (V—10 t/ha manure + NPK_1, VI—10 t/ha manure + NPK_2, VII—10 t/ha manure + NPK_3, VIII—15 t/ha manure + NPK_1, IX—15 t/ha manure + NPK_2, X—15 t/ha manure + NPK_3)
- manure (XI—15 t/ha manure, XII—residual action of previous fertilization).

The experiment includes four replicates; in the first replicate, the layout of plots is systematic, and the others are randomized. Each experimental plot is 242 m^2 (5.6 m × 43.2 m).

For sugar beet, maize and sunflower, mineral fertilizers are applied annually before autumn tillage; for winter wheat, half the nitrogen is applied in the autumn and remainder in spring; farmyard manure is ploughed in before sowing sugar beet (60 t/ha) and sunflower (30 t/ha). Spring barley and vetch-and-oats make use of the residual action of manure and fertilizer applied to previous crops.

The following prices ($US/tonne) have been used to calculate the recovery of mineral and organic fertilizers by the extra yields of different crops (Stadnic and Boincean 2018):

Table 14.1 Systems of fertilization for different crops in crop rotation, 2015–2019

Systems of fertilization	Crops					
	Vetch-and-oats	Winter wheat	Sugar beet	Corn-for-grain	Spring barley	Sunflower
Control (no fertilizer)	–	–	–	–	–	–
NPK 75 kg a.i./ha	–	N_{60} P_{30} K_{30}	N_{30} P_{30} K_{30}	N_{60} P_{30} K_{30}	–	N_{60} P_{30} K_{60}
NPK 130 kg a.i./ha	–	N_{90} P_{60} K_{60}	N_{60} P_{60} K_{60}	N_{90} P_{45} K_{45}	–	N_{60} P_{90} K_{60}
NPK 175 kg a.i./ha	–	N_{120} P_{60} K_{60}	N_{90} P_{120} K_{90}	N_{150} P_{60} K_{60}	–	N_{120} P_{60} K_{30}
10 t/ha manure + NPK 75 kg a.i./ha	–	N_{60} P_{30} K_{30}	N_{30} P_{30} K_{30}	N_{60} P_{30} K_{30}	–	N_{60} P_{30} K_{60}
10 t/ha manure + NPK 130 kg a.i./ha	–	N_{90} P_{60} K_{60}	N_{60} P_{60} K_{60}	N_{90} P_{45} K_{45}	–	N_{60} P_{90} K_{60}
10 t/ha manure + NPK 175 kg a.i./ha	–	N_{120} P_{60} K_{60}	N_{90} P_{120} K_{90}	N_{150} P_{60} K_{60}	–	N_{120} P_{60} K_{30}
15 t/ha manure + NPK 75 kg a.i./ha	–	N_{60} P_{30} K_{30}	N_{30} P_{30} K_{30}	N_{60} P_{30} K_{30}	–	N_{60} P_{30} K_{60}
15 t/ha manure + NPK 130 kg a.i./ha	–	N_{90} P_{60} K_{60}	N_{60} P_{60} K_{60}	N_{90} P_{45} K_{45}	–	N_{60} P_{90} K_{60}
15 t/ha manure + NPK 175 kg a.i./ha	–	N_{120} P_{60} K_{60}	N_{90} P_{120} K_{90}	N_{150} P_{60} K_{60}	–	N_{120} P_{60} K_{30}
15 t/ha manure	–	–	60 t/ha	–	–	30 t/ha

- ammonium nitrate (N-34, 5% active ingredient (a.i.)—363.3
- amofos (N-10% and P-50% a.i.)—566.58
- potassium chloride (K-60% a.i.)—484.51
- farmyard manure—5.24
- winter wheat (grain)—133.88
- sugar beet (roots)—32.41
- corn-for-grain—107.69
- sunflower—315.79.

The amount of nitrogen taken up by crops per tonne yield is calculated according to Andries (2012).

Results and Discussion

All systems of fertilization increased yields significantly (Table 14.2).

From an agronomic perspective, the optimal system of fertilization for winter wheat is NPK 130 kg active ingredient/ha plus the residual action of 10 t/ha of farmyard manure, yielding 5.59 t/ha, or 147% of the control. Increasing the application of manure did not significantly increase the grain yield. The same applies to sugar beet: application of 10 t/ha of farmyard manure + NPK 130 kg a.i./ha yielded 33.28 t/ha, or 138% of the control; increasing the rates of both organic and mineral fertilizers did not significantly increase the yield but application of farmyard manure, alone, gave the same yields as application of farmyard manure supplemented by mineral fertilizers.

We observe the same pattern in corn-for-grain. The optimal system of fertilization was NPK 130 kg a.i./ha plus the residual action of 10 t/ha of farmyard manure, yielding 8.78 t/ha or 126% of the control. There was no significant increase in yield from increasing the rate of mineral fertilizer alone, or from applying a higher rate of fertilizer together with a higher rate of farmyard manure (15 t/ha). However, the residual action of farmyard manure alone yielded 8.30 t/ha or 120% of the control.

In the case of sunflower, yields remained much the same regardless of fertilization. For sunflower as well as for corn, the optimal rate of mineral fertilizers is the lowest—NPK 75 kg a.i./kg. Manure is applied before sunflowers to restore soil fertility. Vetch-and-oats for green mass and spring barley make very efficient use of the residual action of previously applied manure and fertilizer, yielding 151 and 226% relative to the control.

To calculate the share of soil fertility in yield formation (Table 14.3), we assume that 100% of the yield in the control arises from inherent soil fertility, i.e. from the mineralization of soil organic matter. For instance, the extra yield of winter wheat from the application of NPK 75 kg a.i./ha is 15%; the difference makes up the share of soil fertility in yield formation $(100 - 15) = 85\%$. In the case of rotational spring barley under most of the systems of fertilization, the yield comes exclusively from soil fertility.

Table 14.2 Yields of crops in rotation with different systems of fertilization, average for 2015–2019

Systems of fertilization	Crops											
	Vetch-and-oats, green		Winter wheat		Sugar beet		Corn-for-grain		Spring barley		Sunflower	
	t/ha	%	t/ha	%	t/ha	%	t/ha	%	t/ha	%	t/ha	%
Control (without fertilization)	14.84	100	3.81	100	24.2	100	6.95	100	1.71	100	1.58	100
NPK 75 kg a.i./ha	17.01	115	4.89	128	31.35	130	8.1	117	2.86	167	2.05	130
NPK 130 kg a.i./ha	18.20	123	5.19	136	32.9	136	8.01	115	3.19	186	1.9	120
NPK 175 kg a.i./ha	19.57	132	5.47	144	33.0	136	7.79	112	3.43	200	2.0	127
10 t/ha manure + NPK 75 kg a.i./ha	19.84	134	5.11	134	32.6	135	8.1	117	3.39	198	1.88	119
10 t/ha manure + NPK 130 kg a.i./ha	20.62	139	5.59	147	33.28	138	8.78	126	3.6	211	1.94	123
10 t/ha manure + NPK 175 kg a.i./ha	20.59	139	5.16	136	31.86	132	8.29	119	3.87	226	1.93	122
15 t/ha manure + NPK 75 kg a.i./ha	21.97	148	5.43	143	32.5	134	8.96	129	3.63	212	2.01	127
15 t/ha manure + NPK 130 kg a.i./ha	22.01	148	5.36	141	32.85	136	8.9	128	3.66	214	1.91	121
15 t/ha manure + NPK 175 kg a.i./ha	22.42	151	5.42	142	33.54	139	8.84	127	3.85	225	2.05	130
15 t/ha manure	18.08	122	4.82	127	32.65	136	8.3	120	3.14	184	1.92	121
Residual action N850 P570 K750 kg a.i./ha	15.0	101	4.21	111	28.46	118	7.98	115	2.12	124	1.81	114
DL_{05}	1.5		0.2		1.5		0.4		0.1		0.2	

Table 14.3 Share of soil fertility in yield formation for different crops under different systems of fertilization (%) 2015–2019

Systems of fertilization	Crops						Average
	Vetch-and-oats, green	Winter wheat	Sugar beet	Corn-for -grain	Spring barley	Sunflower	
Control (without fertilization)	100	100	100	100	100	100	100
NPK 75 kg a.i./ha	85.4	71.8	70.5	83.5	33.0	70.4	69.1
NPK 130 kg a.i./ha	77.4	63.9	64.0	84.7	13.7	79.9	63.9
NPK 175 kg a.i./ha	68.1	56.5	63.6	87.9	100	73.5	58.3
10 t/ha manure + NPK 75 kg a.i./ha	66.3	65.9	65.3	83.5	1.6	80.9	60.6
10 t/ha manure + NPK 130 kg a.i./ha	61.1	53.3	62.5	73.7	100	77.5	54.7
10 t/ha manure + NPK 175 kg a.i./ha	61.3	64.5	68.3	80.7	100	78.1	58.8
15 t/ha manure + NPK 75 kg a.i./ha	52.0	57.4	65.7	71.1	100	72.8	53.2
15 t/ha manure + NPK 130 kg a.i./ha	51.7	59.3	64.3	72.0	100	79.1	54.4
15 t/ha manure + NPK 175 kg a.i./ha	48.9	57.7	61.4	72.9	100	70.0	51.8
15 t/ha manure	78.2	73.5	65.1	80.5	16.3	78.7	65.4
Residual action N850 P570 K750 kg a.i./ha	98.9	89.4	82.4	85.1	76.0	85.6	86.2
Average	70.8	67.8	69.4	81.3	11.7	78.9	–

Under all systems of fertilization, soil fertility supports the biggest share of yield formation. For sunflower and corn, the average share of soil fertility in yield formation was 78.9 and 81.3%, respectively, and even under optimal fertilization, the share was 72.8 and 71.1%, respectively. Winter wheat and sugar beet respond better to fertilization; even so, the average share of soil fertility in yield formation was 67.8 and 69.4%, respectively, and 59.3 and 64.3% under the optimal system of fertilization. That is why, it is essential to restore soil fertility—otherwise farming is not sustainable.

We should also take account of the farmers' commercial situation. The industrial model of agricultural intensification emerged at a time of historically low prices for fuel, fertilizers, pesticides and machinery. In those days, it was profitable. Since then, the widening gap between the cost of industrial inputs and farm-gate prices for agricultural commodities has been putting these inputs out of reach (Allan and Dent 2021). Farmers must cut their production costs to stay in business. In Tables 14.4 and 14.5, we have calculated the cost-recovery of fertilizers by extra crop yields over the last five years. The value of the extra yield was divided by the cost of the fertilizer, e.g. for winter wheat, N_{60} P_{30} K_{30} kg a.i./ha was recovered by $US1.22 per tonne of grain ($144.6: $118.5). These figures include only the cost of fertilizer as purchased, without taking account of its transport and application. Quite clearly, application of mineral fertilizers is not justified for corn-for-grain or sunflower—the returns do not meet their cost. Only the lowest rate of mineral fertilizers is repaid by extra yield of winter wheat. For sugar beet, the two lower rates of mineral fertilizers (N_{30} P_{30} K_{30} and N_{60} P_{60} K_{60}) are repaid by extra yields but further increasing the rates of mineral fertilizers is not justified.

Table 14.4 Recovery of mineral fertilizers by extra yields in crop rotation, average 2015–2019

Crops	Rates of mineral fertilizer, kg a.i./ha	Extra yields, t/ha	Value of extra yield, $/ha	Cost of fertilizer, $/ha	Recovery of fertilizers by extra yield, $/t
Winter wheat	N_{60} P_{30} K_{30}	1.08	144.6	118.5	1.22
	N_{90} P_{60} K_{60}	1.38	184.8	205.4	0.90
	N_{120} P_{60} K_{60}	0.58	77.7	237.0	0.33
Sugar beet	N_{60} P_{30} K_{30}	7.15	231.7	86.9	2.67
	N_{90} P_{60} K_{60}	8.70	282.0	173.9	1.62
	N_{120} P_{60} K_{60}	8.80	285.3	291.8	0.98
Corn-for-grain	N_{60} P_{30} K_{30}	1.15	123.8	118.5	1.04
	N_{90} P_{60} K_{60}	1.06	114.2	177.7	0.64
	N_{120} P_{60} K_{60}	0.84	90.5	268.6	0.34
Sunflower	N_{60} P_{30} K_{30}	0.47	148.4	142.8	1.04
	N_{90} P_{60} K_{60}	0.32	101.1	206.4	0.49
	N_{120} P_{60} K_{60}	0.42	132.6	212.7	0.62

Table 14.5 Recovery of the costs of different systems of fertilization in the crop rotation, 2015–2019

Crops	Systems of fertilization	Extra yield, t/ha	Value of extra yield, $US/ha	Cost of fertilizers, $US/ha	Recovery of mineral fertilizers by extra yield, $US/t
Winter wheat	15 t/ha manure + NPK 75 kg a.i./ha	1.62	216.9	197.1	1.11
	15 t/ha manure + NPK 130 kg a.i./ha	1.55	207.5	284.0	0.73
	15 t/ha manure + NPK 175 kg a.i./ha	1.61	215.5	315.6	0.68
	15 t/ha manure	1.01	135.2	78.6	1.72
Sugar beet	15 t/ha manure + NPK 75 kg a.i./ha	8.3	269.0	165.5	1.63
	15 t/ha manure + NPK 130 kg a.i./ha	8.65	280.3	252.5	1.11
	15 t/ha manure + NPK 175 kg a.i./ha	9.34	302.7	370.4	0.82
	15 t/ha manure	8.45	273.9	78.6	3.48
Corn-for-grain	15 t/ha manure + NPK 75 kg a.i./ha	2.01	216.5	197.1	1.10
	15 t/ha manure + NPK 130 kg a.i./ha	1.95	210.0	256.3	0.82
	15 t/ha manure + NPK 175 kg a.i./ha	1.89	203.5	347.2	0.59
	15 t/ha manure	1.35	145.4	78.6	1.85
Sunflower	15 t/ha manure + NPK 75 kg a.i./ha	0.43	135.8	221.4	0.61
	15 t/ha manure + NPK 130 kg a.i./ha	0.33	104.2	285.0	0.37
	15 t/ha manure + NPK 175 kg a.i./ha	0.47	148.2	291.3	0.51

(continued)

Table 14.5 (continued)

Crops	Systems of fertilization	Extra yield, t/ha	Value of extra yield, $US/ha	Cost of fertilizers, $US/ha	Recovery of mineral fertilizers by extra yield, $US/t
	15 t/ha manure	0.34	107.4	78.6	1.37

Application of 15 t/ha of farmyard manure together with mineral fertilizers maintains the same trend as separate application of mineral fertilizers. Wheat, corn-for-grain and, especially, sunflower do not repay even the lowest rate of supplementary mineral fertilizers. For sugar beet, the optimal system of soil fertilization in crop rotation is 15 t/ha of farmyard manure + N_{30} P_{30} K_{30} kg a.i./ha, but the most cost-effective system of fertilization is farmyard manure alone. Manure also restores inherent soil fertility, which is essential for sustainable agriculture, but the cost of carting manure is driving a search for an alternative. Bringing animals into the fields is one solution; minimum soil disturbance combined with green manure crops and maximum recycling of crop residues is another.

Analysis of nitrogen-use efficiency from mineral fertilizers (Table 14.6) shows the highest efficiency for the lowest rates of mineral fertilizers and the lowest efficiency for the highest rates fertilization. For winter wheat and sugar beet under the mineral system of fertilization (NPK_1, NPK_2 and NPK_3), N-use efficiency was 59.4, 50.6 and 16.0% and 95.3, 58.0 and 39.1%, respectively. Under the same system of fertilization, N-use efficiency was significantly lower for corn-for-grain and sunflower: 44.1, 27.1 and 12.9 and 31.3, 21.3 and 28.0%, respectively. Application of farmyard manure together with mineral fertilizers significantly increased N-use efficiency for winter wheat, sugar beet and corn-for-grain, though not for sunflower. Bearing in mind that two crops in the rotation are not fertilized but benefit from the residual action of previous fertilization in the rotation, N-use efficiency for all crops is higher for the systems of fertilization with 15 t/ha manure + NPK_1, NPK_2 and NPK_3: 100, 80.5 and 61.5%, respectively. Clearly, manure is contributing to increased N-use efficiency of mineral fertilizers, but it would be good to know how much nitrogen is taken from different sources (manure, mineral fertilizers and soil). This needs further research.

Putting aside the N taken up by extra yields from the immediate or residual action of farmyard manure, N-use efficiency from mineral fertilizers is relatively low; for the NPK_1, NPK_2 and NPK_3 rates of application, it is 36.2, 23.6 and 20.8%, respectively. This means big losses of nitrogen through nitrate leaching to groundwater and emissions of nitrogen oxides to the atmosphere. A reliable way to cut the use of synthetic fertilizers and benefit the environment is to improve soil health by providing fresh sources of energy for the soil biota in the shape of green manure crops, crop residues and manure. The efficiency of fertilizers is higher under continuous cereals and short rotations than in a diverse crop rotation but that is another story (Boincean et al. 2020; Boincean and Dent 2019).

Table 14.6 Nitrogen-use efficiency (%) for different crops under different systems of fertilization, 2015–2019

Systems of fertilization	Crops															
	Vetch-and-oats				Winter wheat				Sugar beet				Corn-for-grain			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Control (no fertilizer)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
NPK 75 kg a.i./ha	2.2	13.7	–	–	1.1	35.6	60	59.4	7.3	28.6	30	95.3	1.2	26.5	60	44.1
NPK 130 kg a.i./ha	3.4	21.2	–	–	1.4	45.5	90	50.6	8.7	34.8	60	58.0	1.1	24.4	90	27.1
NPK 175 kg a.i./ha	4.7	29.8	–	–	0.6	19.1	120	1.0	8.8	35.2	90	39.1	0.8	19.2	150	12.9
10 t/ha manure + NPK 75 kg a.i./ha	5.0	31.5	–	–	1.3	42.9	60	71.5	8.4	33.6	30	100	1.2	26.5	60	44.1
10 t/ha manure + NPK 130 kg a.i./ha	5.8	36.4	–	–	1.8	58.7	90	65.3	9.1	36.3	60	60.5	1.8	42.1	90	46.8
10 t/ha manure + NPK 175 kg a.i./ha	5.8	36.2	–	–	1.4	44.6	120	37.1	7.7	30.6	90	34.0	1.3	30.8	150	20.5
15 t/ha manure + NPK 75 kg a.i./ha	7.1	44.9	–	–	1.6	53.5	60	89.1	8.3	33.2	30	100	2.0	46.2	60	77.1
15 t/ha manure + NPK 130 kg a.i./ha	7.2	45.2	–	–	1.6	51.2	90	56.8	8.7	34.6	60	57.7	2.0	44.9	90	49.8

(continued)

Table 14.6 (continued)

Systems of fertilization	Crops															
	Vetch-and-oats				Winter wheat				Sugar beet				Corn-for-grain			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
15 t/ha manure + NPK 17 kg a.i./ha	7.6	47.8	–	–	1.6	53.1	120	44.3	9.3	37.4	90	41.5	1.9	43.5	150	29.0
15 t/ha manure	3.2	20.4	–	–	1.0	33.3	–	–	8.4	33.8	–	–	1.4	31.1	–	–

Systems of fertilization	Crops													
	Spring barley				Sunflower				All crops in the rotation			All crops taking account of N from manure		
	1	2	3	4	1	2	3	4	2	3	4	2	3	4
Control (no fertilizer)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
NPK 75 kg a.i./ha	1.2	31.1	–	–	0.5	18.8	60	31.3	154.2	210	73.4	154.2	210	73.4
NPK 130 kg a.i./ha	1.5	40.0	–	–	0.3	12.8	60	21.3	178.6	300	62.9	178.6	300	62.9
NPK 17 kg a.i./ha	1.7	46.4	–	–	0.4	16.8	60	28.0	166.7	420	39.7	166.7	420	39.7
10 t/ha manure + NPK 75 kg a.i./ha	1.7	45.4	–	–	0.3	12.0	60	20.0	191.8	210	91.3	21.0	210	10.0
10 t/ha manure + NPK 130 kg a.i./ha	1.9	51.0	–	–	0.4	14.4	60	24.0	239.0	300	79.7	68.2	300	22.7

(continued)

Table 14.6 (continued)

Systems of fertilization	Crops													
	Spring barley				Sunflower				All crops in the rotation			All crops taking account of N from manure		
	1	2	3	4	1	2	3	4	2	3	4	2	3	4
10 t/ha manure + NPK 175 kg a.i./ha	2.2	58.3	–	–	0.4	14.0	60	23.3	214.6	420	51.1	43.8	420	10.4
15 t/ha manure + NPK 75 kg a.i./ha	1.9	51.8	–	–	0.4	17.2	60	28.7	246.9	210	100	76.1	210	36.2
15 t/ha manure + NPK 130 kg a.i./ha	2.0	52.6	–	–	0.3	13.2	60	22.0	241.6	300	80.5	70.8	300	23.6
15 t/ha manure + NPK 175 kg a.i./ha	2.1	57.8	–	–	0.5	18.8	60	31.3	258.3	420	61.5	87.5	420	20.8
15 t/ha manure	1.4	38.7	–	–	0.3	13.6	–	–	170.8	0	–	170.8	–	–

Legend 1—Extra yields, t/ha; 2—N taken up by extra yield, kg/ha; 3—N applied with mineral fertilizers, kg/ha; 4—N-use efficiency, %

Conclusions

- From an agronomic perspective, the optimal system of soil fertilization for winter wheat and sugar beet in crop rotation is 15 t/ha manure + NPK 130 kg a.i./ha and for sunflower and corn-for-grain—15 t/ha manure + NPK 75 kg a.i./ha.
- The widening gap between the cost of mineral fertilizers and farm-gate prices for agricultural commodities means that the extra yields from application of fertilizer do not repay the cost. The most cost-effective system of soil fertilization in crop rotation is application of 15 t/ha of farmyard manure.
- In crop rotation, the share of inherent soil fertility in yield formation for winter wheat and sugar beet under optimal soil fertilization is 59.3 and 64.3%, respectively, and 73.5 and 65.1%, respectively, with manure alone. For corn-for-grain and sunflower under optimal fertilization, the share of soil fertility in yield formation is 71.1 and 72.8%, respectively, and 80.6 and 78.7%, respectively, with manure alone.
- N-use efficiency from mineral fertilizers applied together with 15 t/ha farmyard manure in crop rotation is relatively low; for NPK 75, 130 and 175 kg a.i./ha, it is only 36.2, 23.6 and 20.8%, respectively—with known and unknown consequences for the environment.
- Improving soil health by better provision with fresh sources of energy for soil biota is the most reliable way to decrease dependency on mineral fertilizers.

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Chapter 15
Preventative Restoration of *Ordinary Chernozem* Before Implementing Zero Tillage

Valerian Cerbari and Tamara Leah

Abstract Zero tillage is not appropriate for compacted soils that have lost both humus and structure. First, they must be loosened. Research on restoration of the compacted arable layer of *Ordinary chernozem* demonstrated physical, chemical and biological benefits from subsoiling and incorporating successive crops of spring and autumn vetch. The regenerated soil became friable and better able to support fundamental life processes; the content of organic matter, especially fresh organic matter, was increased; and, over the next 4 years under a five-field rotation, the quality and quantity of crops increased substantially.

Keywords Chernozem · Compaction · Soil rehabilitation · Soil fertility · Zero tillage

Introduction

The World Soil Charter (FAO-UNESCO 2015) proclaims the soil's primary role in maintaining life on Earth but soil exploitation has now reached, or maybe exceeded, a critical level. Good soil is hardly renewable. We're not making any more, and regeneration is possible only if the soil isn't worked to exhaustion, and if strict conditions of protection and preservation are respected (Cerbari 2010, 2011; Leah and Leah 2018a). Conservation Agriculture (CA) can be such a system for long-term soil protection and conservation (Reicosky 2021). One of its fundamental tenets is zero tillage, so maintaining a protective mulch of crop residues. However, it is absolutely necessary to recognise that zero tillage is not appropriate for compacted soils. Before adopting zero tillage, compacted soil layers must be broken up to enable roots and rainfall to penetrate (Black 1973; Leah 2018).

Arable soils have been much degraded by intensive farming and, since the 1950s, mouldboard ploughing to a depth of 35 cm has intensified the loss of humus, breakdown of soil structure, and exhaustion of plant nutrients (Berca 2011; Canarache

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1990; Conservation Agriculture 2019; Lal 2011). But adoption of no-till is problematic if the arable layer is compacted to a dry bulk density of as much as 1.5–1.7 g/cm^3. Therefore, we have tested methods of preventive restoration of the arable layer using green manure in tandem with deep soil loosening.

Results and Discussion

Research was carried out over the agricultural years 2014–2018 on the Natcubi Agro LLC in Cahul District, Republic of Moldova. The soil is clayey *Ordinary chernozem* (Table 15.1) developed on the flat high terrace of the Prut River. At the time the experimental plots were established, the field had been under zero tillage for two years (Table 15.2).

No particular preparations had been made for the introduction of no-till so, to assess the impact of two years zero tillage, the no-till soil was compared with conventionally cultivated soil.

Under no-till, the topsoil exhibited three layers:

0–5 cm	Mulch and clods created by the passage of the seed drill
5–10 cm	Massive, somewhat fissured by previous disking when sown to row crops

Table 15.1 Particle-size distribution of *Ordinary chernozem* at Natcubi Agro

Horizon and depth, cm	Fraction size, mm; content % w/w					
	1.0–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	<0.01
Ahp1 0–5	10.6	44.4	9.3	9.4	26.3	45.0
Ahp1 5–10	10.3	45.1	8.6	9.2	26.8	44.6
Ahp1 10–20	12.0	43.3	6.7	10.5	27.5	44.7
Ahp2 20–30	12.0	43.1	6.9	10.1	27.9	44.9
ABh 30–50	10.8	44.0	5.4	11.0	28.8	45.2
Bh1 50–60	9.6	44.2	7.2	10.0	29.0	45.2
Bh2 60–80	9.2	44.4	5.6	12.3	28.5	45.4
BC 80–100	11.2	43.3	6.2	11.0	28.3	45.5

Table 15.2 Scheme of field trials

Variants of field trial		
1. Control field	2. Field sown with vetch for seed	3. Experimental field where 2 harvests of vetch were incorporated into the soil
	Area 1 ha, width 50 m, length 200 m	Area 1 ha, width 50 m, length 200 m

10–30 cm Massive, structureless.

Over years of intensive cultivation, loss of humus and mechanical destruction of soil aggregates, the plough layer had become severely compacted. Beneath the superficial drilled layer, this hard massive layer remained in place.

Successful zero tillage and all the other components of CA absolutely demand preventive soil restoration—which may be achieved only by breaking up the massive layer and adding organic matter from any source (Cerbari 2011; Leah and Leah 2018b). In most cases, the most practicable method is the systematic use of green manure. Autumn- and spring vetch were sown in relay and the green mass turned into the soil; accompanied by subsoiling at a depth of 30–35 cm. The first harvest of autumn vetch was disked into the experimental plot on 12.05.2015. On the same day, spring vetch was sown, to be disked in at the end of September (Fig. 15.1). Data and composition of the autumn and spring vetch harvests are shown in Table 15.3.

Fig. 15.1 Autumn vetch disked into the experimental plot

Table 15.3 Harvest of autumn- and spring vetch

Harvest	Green mass, t/ha	Moisture content, %	Dry mass, t/ha	Ash	N	P_2O_5	K_2O	C
				% dry mass				
May 12, 2015, autumn vetch green mass incorporated into the soil								
Main harvest	26.0	81.6	4.8	10.5	3.9	0.6	4.2	41.6
Roots, total mass in the 0–30 cm layer			1.9	10.2	1.7	0.5	1.6	40.6
Total crop residue incorporated into the soil			6.7	10.4	3.3	0.6	3.5	41.1
September 30, 2015, spring vetch green mass incorporated into the soil								
Main harvest	17.0	67.9	5.5	10.9	3.1	0.7	1.5	41.2
Roots, total mass in the 0–30 cm layer			2.1	10.6	1.6	0.5	1.3	41.6
Total crop residue incorporated into the soil			7.6	10.7	2.7	0.6	1.4	41.4
Total crop residue of two harvests incorporated in the soil			14.3	10.5	3.0	0.6	2.4	41.2

Restoration of the nutrient status of agricultural soils is a strategic imperative; nutrient reserves in the arable layer are critically depleted. Using vetch as green manure solves the nitrogen problem but not the phosphorus problem so 100 kg of ground phosphate was applied at the time of autumn and spring seeding of the back-to-back vetch crops.

As a result of the incorporation of green manure, there was a tangible change in the condition of the 0–20 cm arable layer: lesser bulk density and penetration resistance contributed to ready penetration of the roots of the succeeding crop of winter barley. The structure of the 0–10 cm and 0–20 cm soil layers (measured by dry sieving) and total pore space (measured by bulk density) improved (Fig. 15.2). However, the water stability of the structure didn't improve. The content of organic matter in the soil layer receiving green manure increased by 0.3% but this remains labile organic matter, only slightly mineralised by soil microbiological processes; it is not yet humus (Fig. 15.3).

At the same time as the soil's physical and chemical condition improved, so did its biological condition as demonstrated by the performance of the following barley crop. The average barley yield on the control plot was 4.9 t/ha, on the plot where the green manure was incorporated, the barley yielded 7.1 t/ha (Fig. 15.4 and Table 15.4), an increase of 2.2 t/ha over the control; the value of the extra harvest was: 2.2 t grain × MDL2200 = MDL4840 or $US257. The following harvest of rape seed in the 2017 attained 4.1 t/ha, the harvest increase of 1.0 t/ha worth MDL7100 or $377. The following winter wheat crop, harvested in 2018, yielded 4.6 t/ha, a harvest increase of 0.8 t/ha and its gluten content was 23% compared with the control 25%; its money value 0.8 t grain × MDL3300 = MDL2640 or $140. The money value of the 3-year harvest increase was: 4840 + 7100 + 2640 = MDL14,580 or $775.

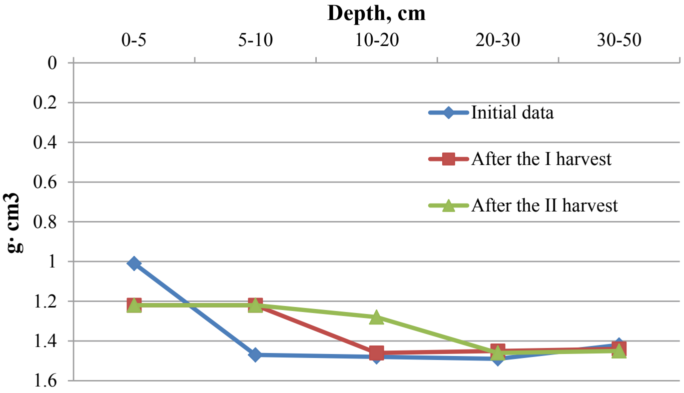

Fig. 15.2 Bulk density of the soil in the experimental variants

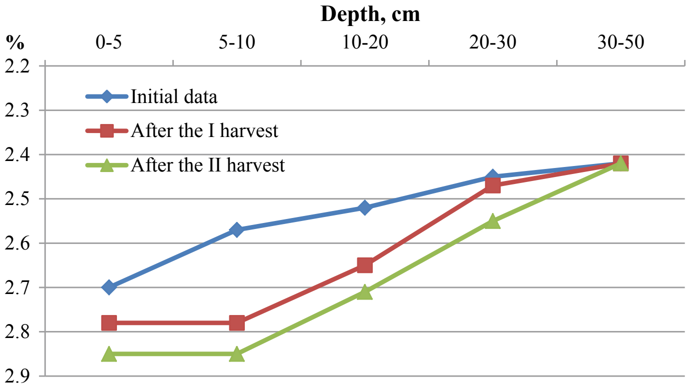

Fig. 15.3 Soil organic matter in the experimental variants

Fig. 15.4 Barley following incorporation of successive harvests of vetch green mass

Conclusions

- No-till CA is inappropriate for compacted soils. First, physical and chemical constraints must be removed. This has been demonstrated by research worldwide.
- On *Ordinary chernozem*, disking into the soil of two successive crops of autumn and spring vetch regenerated the physical, chemical and biological properties of the 0–20 cm arable layer which became visibly friable and full of life. The humus balance was positive. Crop quality and quantity increased substantially.
- Sowing perennial legumes in the crop rotation and cover crops of annual legumes as green manure are fundamental elements of Conservation Agriculture.

Table 15.4 Barley yields (t/ha) on the control and after incorporation of green manure

No of strip	Variant	Barley harvest, t/ha (moisture content 8%)						Harvest yield versus control	
		1	2	3	4	5	Average	t/ha %	Probability of essential difference, %
1	Control	4.5	4.7	5.1	5.2	5.0	4.9	–	–
3	After the incorporation into the soil of two harvests of vetch	7.1	7.2	6.9	7.0	7.3	7.1	2.2 44.9	99.0

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Chapter 16
Step-By-Step Along the Path to Sustainability

Hans Ramseier, Michaela Burkhart-Pastor, Sabrina Lüthi, and Christian Ramseier

Abstract FAO estimates that agricultural production must increase by about 50% by 2050 to meet the needs of the growing human population and our growing demand for meat and dairy products; this against a backdrop of shrinking farmland. If more food is to be produced on less land in the long term, it needs to be done in the most resource-efficient way. Consistent integrated farming systems, organic farming, intercropping, under-sowing and green manures are all potential ways of moving step-by-step towards sustainability. However, consumers must also be prepared to adapt their eating habits and to pay the proper price for food; governments have to create corresponding policy and legal frameworks; and the challenge for agricultural research is to develop more productive, more resource-efficient farming systems suited to diverse regional conditions.

Keywords Sustainable agriculture · Mixed crops · Under-sowing · Green manures

Introduction

Agriculture is at a crossroads. In 2018, 2.65 billion tonne of grain was harvested worldwide, more than ever before, but the harvest is far from equally distributed—more than 800 million people are starving, and at the same time, nearly 2 billion are overweight. Only 40% of the food produced is used directly as food; the rest is processed into stock feed, fuel and industrial raw materials (World Agricultural Report 2019). These are risky trade-offs between food, stock feed, bio-fuel, human well-being and ecological stability.

Agriculture and the food system as a whole face big challenges. The UN estimates that human population will increase to about ten billion by 2050. Nearly, all this growth will take place in what are, at present, low- and middle-income countries where diets are switching towards greater consumption of meat and dairy products so, if this pattern of demand is maintained, agricultural production will have to

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increase by around 50% over 2013 levels (FAO 2017). A further point, especially relevant to the Western world, relates to high-quality requirements and food waste; for example, in Switzerland, one third of all food does not even reach the table (FOEN 2018).

Farmland is shrinking worldwide. The German Environment Agency estimates that ten million hectares of farmland are lost every year; and a quarter of global soils have significantly less humus and nutrients than 25 years ago or can no longer be used for farming at all (UBA 2015). And, yet, food has become cheaper and cheaper so that the average consumer spends less and less of his or her income on food (Allan and Dent 2021); in Switzerland, this figure was just a little over 6% in 2016 (FSO 2019).

All these factors have far-reaching consequences for food and farming. At the same time, there has been a global trend towards specialisation and bigger farms; workforce productivity has greatly increased so that immense amounts of food are produced per worker; farming systems are simplified to the point of monocropping. To maintain systems of this sort requires correspondingly greater inputs of fertiliser, plant protection products and water. This may be profitable in the short term but it is certainly not sustainable in the longer term. So, what is the sustainable alternative? On the one hand, we must bring tried-and-tested traditional knowledge to modern farming systems but, on the other hand, we need innovation. Let us consider some approaches in more detail.

Consistent Integrated Farming

Essentially, integrated farming systems support the agro-ecosystem and the health of crops with as little-as-possible direct interference with natural conditions—by making use of preventive measures such as crop selection (e.g. suitable location), variety selection, crop rotation, attention to the health of the soil and the crops, cultivation technique, plant nutrition and encouragement of beneficial insects (Fig. 16.1).

To this end, valuable assistance can be provided by decision-making tools like early warning systems, prognostic and expert systems, and recognition of pest-control thresholds. Should direct intervention become necessary, then mechanical, biological and bio-technological measures are employed in the first instance. Chemical/synthetic products are a last resort and, if at all possible, selective chemicals should take precedence over broad-spectrum agents. The aim is to achieve optimal effectiveness while minimising unwanted side effects. Compared with conventional farming, rigorously implemented integrated farming can increase productivity through savings on input costs without any loss of yield.

In recent years, we have made several field trials comparing the integrated approach with conventional systems. For example, in trials on 13 farms with an integrated approach employing 0–1 fungicide treatment as opposed to the conventional approach employing 2–3 fungicide treatments, yields of winter wheat under

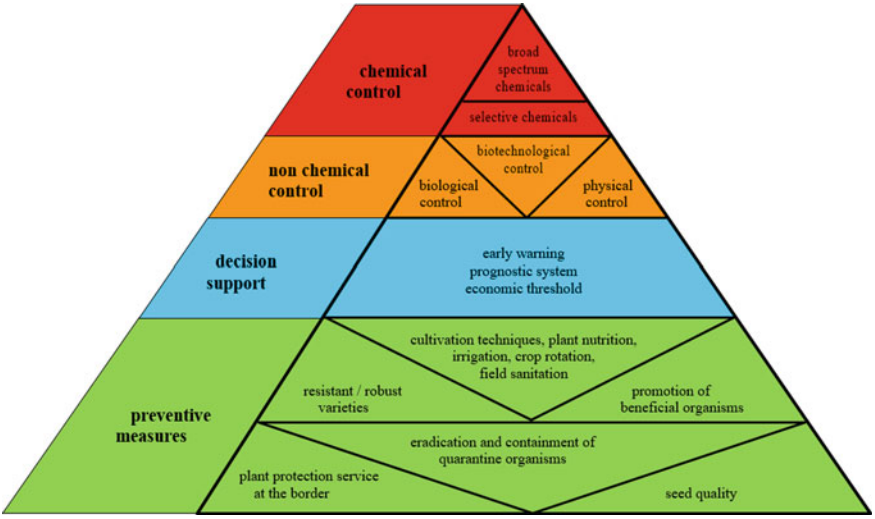

Fig. 16.1 Principle of integrated pest management. The classic IPM pyramid shows the measures that agricultural producers can introduce on their farms. This expanded diagram also includes measures at national level (lower section: preventive measures). *Source* Federal Office for Agriculture, Switzerland

conventional practice averaged 78.6 dt/ha; and under integrated practice 74.8 dt/ha. In block trials with 4 replicates at two locations in 2019, winter barley yielded 96.9 dt/ha under conventional practice and 95.3 dt/ha under integrated practice. Thanks to lower input costs, the financial returns from the integrated system are equal, if not better.

Organic Farming

The objective in organic farming is similar to the rigorous approach taken in integrated farming but with even more weight on integrating the whole farm operation and cycling of materials; absolutely no synthetic chemical plant protection products or freely soluble mineral fertilisers are used. In the lowlands of Switzerland, organic farms used to be traditional, mixed livestock and arable farms, which meant that closed nutrient cycles were achievable, and there were very few available and approved pesticides. Nowadays, with the promotion of organic farming, there are more and more organic farms with few livestock or, even, no animals at all. Moreover, the number of approved organic crop protection products has risen significantly.

Intercropping

Intercropping is one option for using the available natural resources more efficiently. It is traditional in the tropics and, formerly, also in Western Europe; indeed, mixed crops were and are the standard forage crops in Switzerland so adopting intercropping is, actually, ‘back to the future’. There are countless variants: for example, companion crops can be sown within the same row, in separate alternate rows, or mixed sowings over a wide area. One special form of mixed planting is *relay intercropping*, where crops are not only mixed in the field but one is sown later than the other. Relay intercropping was developed in regions where planting two main crops consecutively (double cropping) is not viable because the growing season is too short (Howard 2016).

Martin-Guay et al. (2017) considered the wealth of advantages of intercropping. Their analysis of 939 investigations from 126 studies worldwide shows that, where companion crops were planted, total yields were usually greater than where one crop was grown alone—even under stressful conditions like drought (Himmelstein et al. 2016). Depending on the focus of the investigations, further advantages of intercropping were proven for each location: greater and more reliable yields, greater diversity, better pest and disease control and lower weed pressure (Malézieux et al. 2009; Lithourgidis et al. 2011; Chapagain and Riseman 2014). They conclude that intercropping is a real opportunity for sustainable intensification of agriculture. As usual with researchers, they also conclude that more research is needed if this system is to be implemented successfully!

Intercropping Cereals and Grain Legumes

This cropping system is practised on many farms in Switzerland, especially organic farms. In most cases, winter peas or field beans are combined with cereals for producing stock feed (Clerc et al. 2015). Winter peas with barley and field beans with oats have proved good partners; the cereals act as a support for the legumes which, otherwise, have a tendency to lodge. The recommended quantities of seed are 80% of the normal amount of seed for peas and 40% of the normal amount of barley.

Cereal/Lupin Mixtures

Lupins are undemanding; they thrive even on acid soils. In 2016, in cooperation with the Research Institute of Organic Agriculture, trials were carried out using blue lupin (*Lupinus angustifolius*) with several companion crops. Along with other factors, the land equivalent ratio (LER) was calculated as a yardstick of productivity: this is the ratio of the area under sole cropping to the area under intercropping needed to give equal amount of production at the same management level. It is the sum of the

Table 16.1 Relative yields and land equivalent ratio (LER) of the different mixed crops with blue lupin (variety Boruta), Rümikon, Switzerland 2016

Relative yields and LER					
Crop varieties	Yield (dt/ha)		Relative yield		
	Lupin	Partner	Lupin	Partner	LER
Boruta	18.92		1		1
Boruta/SO 395-12	9.08	26.89	0.48	0.63	1.11
Boruta/SO Buggy	10.00	17.98	0.53	0.45	0.98
Boruta/ST Trado	16.96	5.10	0.90	0.24	1.13
Boruta/WT Arti 8	18.17	6.04	0.96	0.29	1.25
Boruta/red fescue	20.89	0.00	1.10		1.10
Spring oats 395-12		42.86		1	1
Spring oats Buggy		39.84		1	1
Spring triticale Trado		21.53		1	1
Winter triticale Arti 8		21.07		1	1

fractions of the intercropped yields divided by the sole-crop yields (FAO 1985). With one exception, the LER was always greater than 1, so land resources are better used under intercropping than in sole cropping.

It turns out that in these mixtures, the crop variety is crucial: the best results were achieved with a mixture of lupin *Boruta* and the winter triticale variety *Arti 8*, which gave an LER of 1.25 (Table 16.1). Martin-Guay et al. (2017) noted an average LER of 1.3; the poorer average LERs in the Swiss studies might be explained by good crop rotation, organic practice and favourable growing conditions when no major stress situations occurred.

Maize/Beans Mixture

In 2011, the Thünen Institute for Organic Farming, in Germany, carried out initial trials of a maize/bean mixture which commonly yielded greater crude protein contents than maize silage grown alone (Fischer and Böhm 2017). Our own trials under organic conditions in 2014–2015 showed that the technique works well (Fig. 16.2). Maize was sown at a density of 6–7 seeds/m^2 (and in the control, with maize alone, 10–11 seeds/m^2) and beans (*Phaseolus vulgaris*, *P. coccineus*) at a density of 7–8 seeds/m^2. The maize was sown first, hoed when it reached the four-leaf stage, then beans were sown next to maize rows.

Maize alone yielded 200.6 dt/ha dry matter (DM); the maize component in the mixed batch yielded 178 dtDM/ha so the control produced an additional 13% yield of maize but the difference is not statistically significant. The total dry matter yield in the mixture (maize 178 dt/ha plus beans 16.1 dt/ha) produced an average of

Fig. 16.2 Maize with common bean variety Blauhilde (left) and runner bean Scarlet Emperor (right)

194.1 dtDM/ha (3% less than the control but, again, not a statistically significant difference) (Fig. 16.3).

Ultimately, what counts are the calories and protein produced. On average across all bean varieties, there was no difference in the carbohydrate yield per hectare. However, the variations between varieties were considerable: the mixture containing the bean variety *Trebona* produced only 87% of the yield of maize alone, whereas the mixture with variety *Grünes Posthörnli* achieved 108% of maize grown as a sole

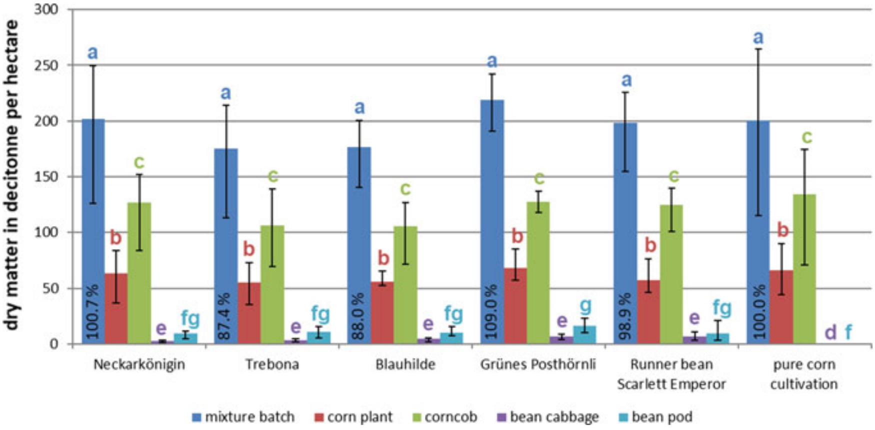

Fig. 16.3 Dry matter yields of the mixture and the individual components in dt/ha, field trial in 2014 in Uettligen, Switzerland. Superscripts mark statistically significant differences ($p < 0.05$)

Table 16.2 Crude protein yield in dt dry matter (DM)/ha of pure corn and the mixture divided into the individual components in dtDM/ha and %. Field trial in Uettligen, Switzerland, 2014

	Crude protein in dtDM/ha Total	Corn plant dtDM/ha (part in %)	Corncob dtDM/ha (part in %)	Bean-herb dtDM/ha (part in %)	Bean-pod dtDM/ha (part in %)
Common bean *Neckarkönigin*	15.7	3.6 (23.0)	10.3 (65.4)	0.3 (2.1)	1.5 (9.5)
Common bean *Trebona*	13.6	3.0 (21.9)	8.6 (63.2)	0.3 (1.9)	1.8 (12.9)
Common bean *Blauhilde*	14.5	3.0 (20.4)	9.4 (64.9)	0.4 (2.7)	1.7 (11.9)
Common bean *Grünes Posthörnli*	18.3	3.7 (20.5)	11.1 (60.7)	0.7 (3.7)	2.7 (15.0)
Runner bean *Scarlet Emperor*	15.0	3.2 (21.3)	9.6 (64.0)	0.8 (5.2)	1.4 (9.5)
Average beans	**15.4**	**3.3 (21.4)**	**9.8 (63.7)**	**0.5 (3.1)**	**1.8 (11.8)**
Pure cultivation maize	**14.8**	**3.9 (26.5)**	**10.9 (73.5)**		

crop. Similarly, there was on average no difference in crude protein yield but there were considerable variations between varieties; the mixture with bean variety *Grünes Posthörnli* produced the highest crude protein yield of 18.3 dtDM/ha—24% more than maize grown alone (Table 16.2).

The trial was repeated in 2015, with similar results. In 2018, a further trial was planted using popcorn, polenta, two varieties of climbing bean and one scarlet runner bean. Unfortunately, the weather was so dry in Switzerland that the beans died from lack of water.

Under-Sowing

The main purpose of under-sowing is to avoid the need for herbicides. It also arrests soil erosion and, if the under-sown crop is a legume, it fixes nitrogen. First and foremost, the successive crop can benefit from the fixed nitrogen bound in soil organic matter but, in the case of oilseed rape, the rape itself can benefit from being under-sown with a crop including frost-sensitive legumes. The presence of autumn-sown, frost-sensitive legumes results in 20–40 kgN/ha higher nitrogen uptake compared with a rape crop without under-sowing (Lorin et al. 2016). Our own trials with four different under-sown mixtures were carried out over four years (Table 16.3).

Table 16.3 Under-sowing trial of oilseed rape, Zollikofen, Switzerland 2015–19

	kg/ha											kg/ha
	Egyptian clover *Trifolium alexandrinum*	Persian clover *Trifolium resupinatum*	Fenugreek *Trigonella foenum-graecum*	Niger seed (ramtil) *Guizotia abyssiniea*	Buckwheat *Fagopyrum esculentum*	Common flax *Linum usitatissimum*	Lentil *Lens culinaris*	Common vetch *Vicia sativa*	Grass pea (chickling pea) *Lathyrus sativus*	Lacy phacelia *Phacelia tanacetifolia*	Subterranean clover *Trifolium subterraneum*	Total
Colza fix	3			2	7		7	5	6			30
S2			6		5	4	12		7			34
Ra1		4	3							3	8	18
Ra2		3	3	3					3		6	18
H	Control 1 (pre-emergence herbicide treatment)											
0	Control 2 (no weed control, no under-sowing)											

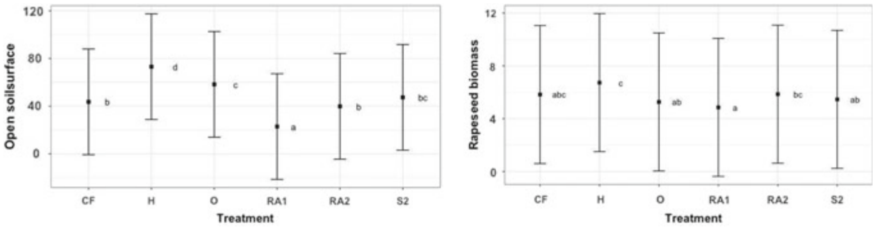

Fig. 16.4 Bare soil surface, %, 30 days after sowing of the oilseed rape (left) and oilseed rape biomass production in the spring (right). Control of herbicide (H) and zero (O) in comparison with several under-sown mixtures. Results from 4 experimental years. Superscripts mark statistically significant differences ($p < 0.05$)

The under-sown crops achieved varied coverage 30 days after sowing the rape (Fig. 16.4, left). In the best cases, weed suppression is almost as good as with herbicide treatment. However, weed suppression alone is not conclusive; the rape must not suffer from direct competition with the under-sown crop. A biomass survey in spring, shortly before flowering, is a good indicator of yield; it shows that the best mixtures (RA2) achieve practically the same biomass as the procedure with herbicide treatment (Fig. 16.4, right). Therefore, in the case of oilseed rape, we may assume that under-sowing can replace herbicide treatment without loss—but it only works if there are no problem weeds, such as thistles, and if the field is cleaned, e.g. by shallow stubble cultivation after harvesting the preceding crop.

Under-sowing has other benefits:

- It prevents soil erosion at the rape's seedling stage
- The above-ground biomass of the under-sown plants contains 4-54 kgN/ha, depending on the mixture and year
- The under-crop deters cabbage stem flea beetle (*Psylliodes chrysocephala*). Significantly fewer flea beetle larvae were counted in spring in the fields with undercrops (Fig. 16.5).

Green Manures

In arable farming, green manures play a key role in conserving and converting nutrients. A fast-growing cover crop following the harvest protects the soil from erosion and leaching of nutrients and improves soil structure and water infiltration. Legumes offer additional potential as green manures because their symbiosis with rhizobia adds nitrogen. Our own study evaluated 19 legume species grown as cover crops in Switzerland. Field experiments in 2010 and 2011 were set up to monitor the biomass production and nitrogen content of 19 legumes and two non-legumes. The proportion of nitrogen derived from atmospheric N_2 (%Ndfa) was assessed using the ^{15}N natural abundance method. In parallel, a pot experiment was set up to determine the species-specific *B* values necessary to apply this method.

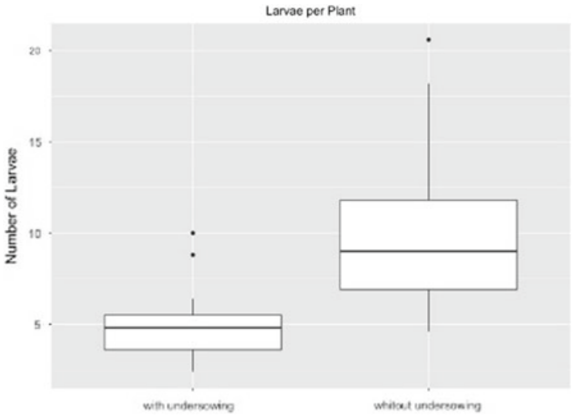

Fig. 16.5 Number of cabbage stem flea beetle larvae per rape plant in spring 2019 in the procedures with and without under-sowing. With under-sowing, lower numbers of larvae are statistically significant (*p* 0.0003865)

Some species produced a goodly amount of biomass in three months, up to 6.86 tDM/ha for *Vicia faba*. Five species, *Lathyrus sativus*, *Pisum sativum*, *Vicia sativa*, *V. villosa* and *V. faba*, acquired more than 100 kgN/ha through biological fixation; substantial amounts of nitrogen were also assimilated from the soil. Values of %Ndfa were very variable between and within species, ranging from zero to almost 100%. Some legumes accumulated substantial amounts of N, even in a short growing period, and could play a valuable role in fixing renewable nitrogen in crop rotations (Büchi et al. 2015); that is why our current trials are focussing on green manure mixtures with a high proportion of legumes. Green manure mixtures offer several advantages over sole crops: by reliable emergence, they optimise the use of root space, nutrients, water and light; winter-grown frost-sensitive green manures provide successful live mulching of spring crops; and the mulched soil stays workable in spring and warms up quickly if the frozen green manure has a light colour, such as peas.

Contract Farming—Solidarity Agriculture

Consumers have become distanced from the production of their food. They no longer understand what is needed to produce enough healthy food in an environmentally friendly way; so, this year, we launched a small project called *My Vegetables*, in which the farmer provides land, equipment, tillage, sowing and planting fruit and vegetables and know-how for maintenance work and harvest (WhatsApp, field surveys). The crops were sown/planted in a few rows but over a length of 200 m for efficiency (Fig. 16.6). The consumer (or the consumer family) rents 5 or 10 m of the whole width of the strip (so has different vegetables and fruits throughout the season) and is responsible for maintenance (e.g. weeding) and harvest.

We have found that the consumer learns what it takes to produce food, learns to appreciate it again, re-thinks its quality standards and is willing to pay a fair price.

Fig. 16.6 Contract-solidarity agriculture to bring the consumer back closer to food production. *My Vegetables* project at Münsingen, Switzerland 2019

Conclusion

Agriculture and the food industry face severe challenges. As things stand, global agriculture is making perilous trade-offs between production of food, stock feed and fuel on one hand and, on the other hand, ecosystem services, ecological stability and our own well-being. Adoption of ecological elements like integrated production and intercropping within mainstream farming systems could be one response; and another could be up-scaling ecological farming systems such as strict organic farming and permaculture/agroforestry.

Governments must play their part in promoting such approaches. We, the consumers, must also be prepared to contribute by moderate consumption with a higher proportion of plant-based foods, and by avoiding food waste (e.g. a return to the concept of nose-to-tail eating), quality requirements should also be reconsidered. Not least, we must be prepared to pay a fair price for our food (Allan and Dent 2021). All might be achieved if the consumer is brought back closer to farming, so as to foster understanding of food production. Models such as contract farming and solidarity agriculture can help this to happen.

The challenge for agricultural research is to develop more productive, more resource-efficient farming systems suited to local and regional circumstances.

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Chapter 17
Standards for Heavy-Metal Contamination of Irrigated Land in Ukraine

Sviatoslav Baliuk, Maryna Zakharova, and Ludmila Vorotyntseva

Abstract Technogenic loading of heavy metals in soils and irrigation water boosts the capacity of these metals to migrate and accumulate in crops. Regulatory limits and quality standards for irrigation water have been elaborated from review of international standards and long-term observations of the composition of irrigation waters, the trajectory of soil processes, and crop quality. Norms have been set following ecological criteria, taking account of the levels of contamination of irrigation water, soils and crops by heavy metals. Methods for improving the quality of contaminated soils include the application of ameliorants and adsorbents, flushing with substances that increase the solubility of heavy metals, phytomelioration, selection of resistant crops, and bio-remediation using microorganisms.

Keywords Heavy metals · Irrigation water · Standards · Crops · Soil amelioration

Introduction

Worldwide, governments are awakening to the need for action to arrest pollution, degradation and destruction of soils (FAO 2015; Baliuk et al. 2015; Tóth et al. 2016; Wuana and Okieimen 2011; Darwish 2018; Evdokimova et al. 2011). Soil plays a pivotal role in food safety; it determines the composition of food and feed at the beginning of the food chain—and irrigation changes every component of the natural environment so particular attention should be paid to monitoring soil and water (Alloway 2013; Bambara et al. 2015; Dragovic et al. 2008; Malakar et al. 2019; Lu et al. 2016). Increasing awareness of the importance of fruit and vegetables in our diet, and identification of food as the main source of many contaminants, underscore the need to monitor heavy metals in soil, water and crops.

Contamination of the water-soil-crops system by heavy metals poses significant risks to agro-ecosystems and public health. Heavy metals are essential components of the water-soil-crop system but they become hazardous contaminants when their

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content exceeds allowable levels. The Codex Alimentarius developed by The World Health Organization and FAO (1995) identifies safe limits for contaminants in fruit, vegetables, fish and fish products, and animal feed (Rodriguez-Eugenio et al. 2018). Our research focuses on assessment of heavy-metal contamination in the water-soil-crops system of technogenically contaminated, irrigated farmland and development of case-specific measures for detoxification.

Materials and Methods

Research has been conducted in the Forest-steppe and Steppe zones of Ukraine which encompass 98% of irrigated land in the country. The subjects are:

- *Irrigation water*: river water from the Dnieper and Dniester rivers and Dnieper water storage
- *Irrigated soils*. The total area of irrigated lands in Ukraine is 2.1 million ha but nowadays only 0.5–0.7 million ha is irrigated annually. The soils are principally *Typical, Ordinary* and *Southern chernozem*, *Meadow-chernozemic* and *Dark-chestnut solonetz*
- *Irrigated crops:* grains, vegetables, fodder and industrial crops.

Field investigations, modelling, laboratory and statistical studies have been undertaken. Some 650 soil samples were selected on an irregular grid with GPS referencing, taking account of soil and lithological heterogeneity. More than 100 samples were taken from test crops immediately prior to harvest. Irrigation water samples were tested several times during the growing season; in total some 280 samples from irrigation sources were analysed. Mobile heavy metals in soils were determined by extraction with ammonium acetate solution at pH 4.8 for one hour using a soil: extractant ratio of 1:5. The heavy-metal content of crops was determined by ashing at 550 °C for 5 h and dissolving the ash in 10% HCl. Irrigation water samples were analysed after drying and dissolving the precipitate in M HCl. In all cases, metals were determined by atomic absorption spectroscopy. Statistics were performed using Statistica 10 and MapInfo 11.0.

Results

The quality of irrigation water influences the direction of soil processes. It may lead to salinity, sodicity and contamination. To evaluate water quality, we employed an experimental-expert assessment approach to the water-soil-crop system. We reviewed extensive material on quality indices of irrigation water according to characteristics of the water and content of materials harmful to the state and function of agro-ecosystems and the environment. Simultaneously, we studied the stability of soil systems and crop quality. From complex analysis of the data, we proceeded to standards for irrigation water quality based on ecological criteria, so as to predict any likely threats to the environment and public health.

Atmospheric deposition of heavy metals is increasing continuously. Irrigation intensifies the hazard of contamination of soils and crops, so standards are needed for the heavy-metal content of irrigation water, soils and crops. Review of international standards and regulations shows much variability. Ukraine has adopted a State Standard *Quality of natural water for irrigation* that determines environmental criteria and indicators for assessing the quality of natural waters that are used for irrigation. Criteria are established on the basis of water quality for irrigation but the requirements of public health and environmental protection should also be taken into account. Table 17.1 presents a basis for limiting anthropogenic loads under irrigation.

The concentration of heavy metals in irrigation water increases from Forest-steppe to Steppe under a drying climate and with mineralization of natural waters (Table 17.2). Such increase is common for ponds, lakes and water storages but is

Table 17.1 Water quality for irrigation by content of heavy metals and microelements, mg/dm^3

Element	Assessment of water quality		
	Class 1—Suitable	Class 2—Limited suitability	Class 3—Unsuitable
Aluminium	<2.0	2.0–5.0	>5.0
Lithium	<1.0	1.0–2.5	>2.5
Iron	<2.0	2.0–5.0	>5.0
Zinc	<0.5	0.5–1.0	>1.0
Manganese	<0.5	0.5–1.0	>1.0
Chromium	<0.2	0.2–0.5	>0.5
Molybdenum	<0.005	0.005–0.01	>0.01
Vanadium	<0.05	0.5–0.1	>0.01
Tungsten	<0.03	0.03–0.05	>0.05
Bismuth	<0.05	0.05–0.1	>0.1
Fluorine	<0.8	0.8–1.5	>1.5
Boron	<0.2	0.2–0.5	>0.5
Selenium	<0.01	0.01–0.02	>0.02
Nickel	<0.08	0.08–0.2.	>0.2
Copper	<0.08	0.08–0.2	>0.2
Cobalt	<0.02	0.02–0.05	>0.05
Lead	<0.02	0.02–0.05	>0.05
Cadmium	<0.005	0.005–0.01	>0.01
Beryllium	<0.05	0.05–0.10	>0.10
Arsenic	<0.02	0.02–0.05	>0.05

Table 17.2 Content of heavy metals in irrigation water of the Forest-steppe and Steppe (mg/dm^3)

Region	Zn	Cd	Ni	Co	Fe	Mn	Pb	Cu	Cr
Forest-steppe (average)	0.016	0.002	0.014	0.010	0.072	0.017	0.024	0.013	0.002
Forest-steppe (local/regional pollution)	0.013	0.002	0.031	0.028	0.150	0.037	0.045	0.010	0.001
Steppe (average)	0.013	0.005	0.023	0.023	0.065	0.022	0.032	0.008	0.009
Steppe (local/regional pollution)	0.015	0.009	0.048	0.060	0.105	0.033	0.077	0.023	0.013

untypical for small and middling rivers and not noted in large rivers like the Dnieper and Danube.

The content of heavy metals in irrigated soils varies by geochemical zones and is higher in the southern Steppe compared with the northern Steppe and Forest-steppe (Table 17.3). However, concentrations are much higher in industrial zones like the Donbas with a high geochemical background and big atmospheric emissions. The priority pollutants are lead, cadmium, nickel and chromium. Irrigation intensifies the migration of heavy metals in soils and promotes leaching from the upper to lower layers. Similar results were obtained by Cui et al. (2004) and Maleki et al. (2014). Table 17.4 illustrates the dependency of the heavy-metal content of crops on the level of contamination and composition of group of metal pollutants in the water-soil-crop system.

Building on international standards and long-term study of heavy metals in the water-soil-crop and water-soil-groundwater systems, we have elaborated principles for setting standards and indices describing the state of natural waters, soils and irrigated produce as affected by technogenic contamination. We have proposed a system of criteria and parameters for assessing the nature and degree of the degradation of irrigated lands (Baliuk et al. 2017) which is the foundation of the Departmental

Table 17.3 Content of heavy metals in the 0–30 cm layer of irrigated soils of Ukraine (mg/kg)

Irrigated soil	Zn	Cd	Ni	Co	Fe	Mn	Pb	Cu	Cr
Without local/regional pollution									
Typical chernozem (average)	1.0	0.1	0.7	0.4	1.9	12.4	1.0	0.2	0.3
Ordinary chernozem (average)	0.4	0.1	0.9	0.5	1.2	10.0	1.0	0.3	0.8
Southern chernozem (average)	0.6	0.1	0.7	0.4	1.6	9.9	1.1	0.4	0.3
Dark chestnut (average)	0.6	0.1	0.7	0.2	2.4	22.9	1.1	0.7	0.2
With local/regional pollution									
Typical chernozem (average)	11.4	0.8	2.0	0.3	2.6	6.2	1.9	2.0	0.2
Ordinary chernozem (average)	0.7	0.7	1.4	1.7	6.4	9.3	5.4	1.0	0.8
Dark chestnut (average)	0.7	0.4	3.1	1.3	4.0	51.2	3.9	0.7	3.2
Background	1.0	0.1	1.0	0.5	2.0	43.0	0.5	0.5	0.1
Maximum allowable concentrations	23	–	4.0	5.0	–	500	6.0	3.0	6.0

Table 17.4 Average content of heavy metals in crops without local/regional pollution (mg/kg)

Crop	Zn	Cd	Ni	Co	Fe	Mn	Pb	Cu
Tomato	1.75	0.01	0.06	0.11	2.30	0.19	0.27	0.14
Cabbage	1.75	0.01	0.11	0.16	1.70	0.54	0.27	0.25
Red beet	3.53	0.02	0.22	0.20	13.40	4.84	0.48	0.68
Carrot	1.84	0.03	0.21	0.14	3.20	0.44	0.44	0.46
Barley (grain)	20.7	0.02	0.4	0.5	31.7	2.1	0.2	2.3
Winter wheat (grain)	27.0	0.02	0.4	0.8	10.3	3.1	0.2	3.4
Corn (grain)	16.7	0.09	0.7	0.5	8	1.6	0.6	1.9
Green peas	8.4	0.01	0.6	0.1	4	0.7	0.1	1.5
Lucerne	4.4	0.06	0.7	0.6	33	10.8	1.3	1.7
Sainfoin	3.1	0.02	0.4	0.5	26	11.4	1.1	0.8
Maize, green mass	5.6	0.2	0.1	0.3	29	9.9	1.1	0.8
MAC[a] in vegetables	10.0	0.03	0.5	1.0	50.0	20.0	0.5	5.0
MAC in grain	50.0	0.03	0.5	1.0	50.0	44.0	0.3	10.0
MAC in rough and succulent feeds	50.0	0.3	3.0	1.0	100.0	–	5.0	30.0

[a] Maximum allowable concentration

Normative Document 33-5.5-06-99 *Water, soil and vegetative resources conservation from heavy metals contamination under irrigation.*

By degradation of soils, we mean processes that lead to loss of soil functions, stability and fertility. Soil degradation is assessed by comparison with soil parameters that are fixed at the outset of observations, or standard soils with the same parameters after the corresponding periods of soil use. Degrees of degradation are determined according to the degree of deviation from the optimum of parameters that define soil fertility:

- *Soils not degraded*: properties and regimes unaffected, fulfilling inherent functions; productivity corresponds with natural fertility (up to 5% deviation from the optimum)
- *Slight degradation*: deterioration of properties and regimes; loss of functions and loss of productivity do not exceed 20%
- *Moderately degraded*: loss of functions and productivity in the range 20–50%
- *Strongly degraded*: loss of functions and productivity more than 50%.

Effective monitoring of soil degradation includes: (1) systematic observation of soil condition, properties and regimes; (2) analysis of soil stability or resilience to degradation; (3) impact analysis of various economic activities, their positive and negative influence on the soil cover; (4) creation of maps and databases; (5) forecast and prevention of degradation processes. On the basis of these observations, levels of ecological hazard and unprofitability are determined, and preventive and soil-regenerating practices are proposed. Building on further work, we have elaborated the National Standard of Ukraine: *Quality of Natural Water for Irrigation. Ecological*

Criteria DSTU 7286:2012. This lays down standards for heavy-metal content in irrigation water. It distinguishes three classes of irrigation water: Class 1—Suitable, which may be applied without limits; Class 2—Limited suitability, which may be used with the proviso that soil and water quality is monitored and ameliorative actions commenced if any deterioration is detected; and Class 3—Unsuitable, because agro-ameliorative actions are not justified economically and ecologically.

Depending on the ecological and agro-amelioration status of irrigated land, areas of further agricultural use are determined and measures are developed to detoxify the soil-crop system. If the level of environmental degradation reaches a high level, agricultural use of such land is inappropriate. Agricultural use of technogenically polluted land that is environmentally hazardous, economically ineffective and does not allow production of pure and safe products is prohibited by Articles 170, 172 of the Land Code of Ukraine *Land Conservation Procedure,* approved by the State Committee of Ukraine for Land Resources (No. 175 dated 17.10.2002) and the Ministry of Agrarian Policy of Ukraine (No. 283 dated 26.4.2013). So methods and techniques for soil cleaning and improving water quality are needed (Sas-Nowosielska 2011)—in particular, ways to improve the quality of irrigation waters, actions to intercept transfer of heavy metals to crops, and selecting appropriate crops and cultivars.

On the basis of analysis and generalization of the results of long-term studies, Baliuk et al. (2014) recommended physical, chemical, biological measures for reducing the toxic effect of the heavy metals in the soil-crop system. These include the introduction of ameliorants and adsorbents into the soil; soil flushing using special substances that increase solubility of compounds of heavy metals; phytomelioration; selection of resistant crops; and bioremediation using microorganisms. A common chemical method is the use of adsorbents*, e.g.* iron-calcium and calcium ameliorants that form complex compounds with heavy metals and, also, fortify the soil adsorption complex with calcium that improves the soil's physical and chemical properties (Table 17.5). At a small scale, detoxification of contaminated Chernozem with iron-calcium sludge from steel-wire production fixed the available forms of pollutants in the soil, reducing their translocation in crops and increasing crop yields by 10–59%.

Table 17.5 Influence of iron-calcium sludge on the content of mobile heavy metals in irrigated *Ordinary chernozem* as determined in ammonium acetate solution at pH 4.8

Depth (cm)	Metal content (mg/kg)								
	Zn	Mn	Fe	Cu	Ni	Co	Pb	Cd	Cr
Control—irrigated soil									
0–25	0.90	10	7.0	0.52	1.55	1.7	14.0	0.47	0.25
25–50	1.05	19	5.0	0.32	0.77	1.0	8.5	1.02	0.25
Soil treated with iron-calcium sludge									
0–25	1.00	15	9.2	0.37	0.95	0.4	5.25	0.40	0.25
25–50	0.85	10	5.0	0.45	1.50	1.0	9.00	0.47	0.30

For soils with a low degree of contamination, ecologically safe methods of detoxification may be applied, making use of the metabolic potential of crops and microorganisms (Oves et al. 2016). Phyto-meliorative measures include growing crops and natural vegetation that can accumulate a large amount of toxic substances within their biomass, weakening their toxic effects while retaining the ability to grow and reproduce. The advantages of this method are safety of use, minimal impact on soil properties, and low cost—but it takes several or, even, many years.

Conclusions

Indices of irrigation water quality, and criteria for heavy-metal contamination of irrigation water, soils and crops have been developed following review of international standards and regulations, and generalization of long-term observations on characteristics and composition of irrigation waters, the trajectory of soil processes, and quality of agricultural produce.

This lays a foundation for development of ways to improve the composition of irrigation water, soils and crops; for instance, by calcium amelioration by application of iron-calcium sludge to the soil, and phyto-meliorant crops. These treatments reduce the content of mobile heavy metals in soil and arrest their uptake.

The design criteria and standards provide a normative basis for ecologically safe agricultural production in Ukraine.

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Chapter 18
Giving Credit Where Credit's Due. A Standard for Soil Health

David Dent

Abstract To qualify for payments from the public purse, farmers must not only grow food but demonstrate good stewardship by delivering public goods: arresting soil erosion, abating floods, recharging groundwater, mitigating global heating… Moreover, discerning consumers seek guarantees that their food is grown sustainably which are not provided by prices and labelling. The proposed Standard for Soil Health meets these needs by matching the condition of the soil with its capacity to grow crops and deliver environmental services. The criteria are ground cover, biological status represented by soil organic matter, and physical status represented by bulk density. These yardsticks also reveal trends, so credit may be given for good management as well as for inherent soil quality.

Keywords Soil health · Public goods · Ground cover · Soil carbon · Bulk density

Context

Soil is the stuff in which plants grow; home to myriad micro-organisms that break-down wastes and toxins and make nutrients available to crops, and to armies of earthworms and smaller creatures that create the pores that regulate the passage of rainfall to streams and groundwater. And it holds more carbon than the atmosphere and all standing vegetation put together—soil is the biggest brake on global heating. Its potential capacity to fulfil these roles—let us call it *soil quality*—depends on climate, topography, and soil type. These are hard to change. But its condition compared with its potential—let us call this *soil health*—is in the hands of the farmer. If farmers are to be paid to deliver environmental services, their performance needs to be measured against a standard. And if they meet this standard, consumers can be confident that their crops are grown sustainably. The proposed Standard of Soil Health specifies three criteria: *living ground cover, biological status* represented by the amount of organic matter, and *physical status* represented by bulk density (Dent

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2019). Others might be considered but the more factors we consider, the more we describe and the less we define.

Attributes of Healthy Soil

1. ***Living ground cover*** protects the soil against the elements. For instance, by absorbing rain splash it arrests soil erosion and maintains the soil's capacity to accept rainfall. Live ground cover may be measured by the *normalised difference vegetation index* (NDVI), a ratio of reflected red and near infra-red light that serves as proxy for the proportion of the land surface covered by green leaves, or *leaf area index* (Yengoh et al. 2015). Twenty years of daily global NDVI data from earth-orbiting satellites are available at 250 m × 250 m resolution (Didan 2015); farmers using drones can measure it for themselves at any desired resolution. *We may set the standard for soil health at a minimum of 70% ground cover, which is enough to stop soil erosion* (Renard et al. 1991).
2. ***Biological status***. The content of organic matter is an integral index of soil fertility. Organic matter fuels the world of the soil, it is the main source of plant nutrients, and it stabilises soil structure—more is better. Arable farming burns off soil organic matter, thereby emitting greenhouse gases equivalent to those of manufacturing industry. On the other hand, an increase of 1% soil organic carbon (SOC) in the top 30 cm, which can be achieved by good husbandry, captures about 40tonne of carbon per hectare. In setting a standard, it is important to know that there is a direct relationship between SOC and the soil's clay content: Fig. 18.1 shows the scatter of SOC values against clay content for topsoils (0–15 cm) in England and Wales.

   Figure 18.2 plots the range of SOC in topsoils under arable and ley grass sampled countrywide on a 5 km grid (2448 samples). The *standard envelope,* constructed by robust statistics in gradations of clay content (0–10, 10–20, 20–30, 30–40 and 40–50%), encompasses 80% of the measured sites. Outliers with higher values are fewer than in Fig. 18.1 which includes soils under permanent grass that maintain greater contents of organic matter. The range of SOC under permanent grass and, also, in arable soils with a high water table or liable to flooding is shown in Fig. 18.3. In both cases, SOC values are significantly greater than in dryland arable.

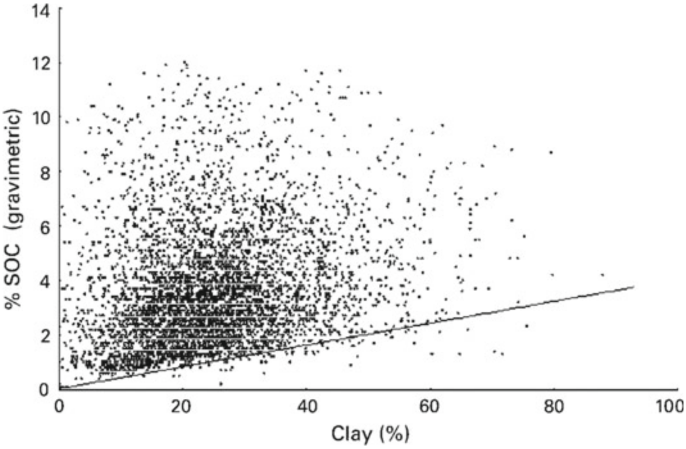

Fig. 18.1 Relationship between SOC and clay content in topsoils in England and Wales (Webb et al. 2003). The greater the soil's clay content, the more organic matter it will hold. The diagonal line from the origin marks a clear lower limit of SOC but the upper boundary depends on soil use and management

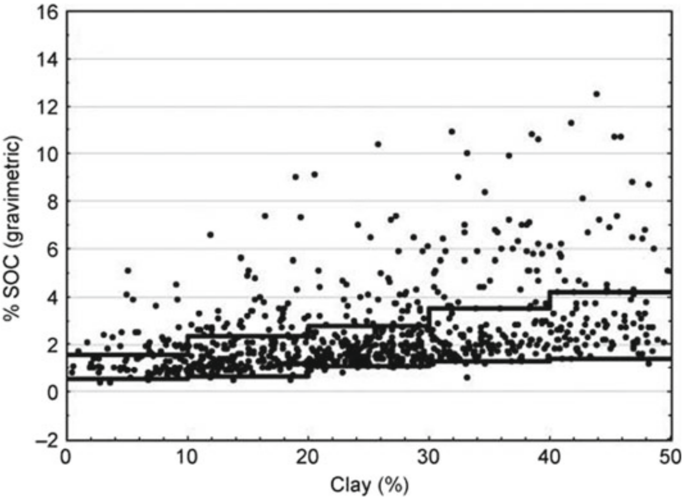

Fig. 18.2 Standard envelope of soil organic carbon values under arable and ley grass

Good soil health is indicated by SOC in the upper part of the standard range for the land use and soil texture in question, or an increasing equivalent soil mass of organic carbon.

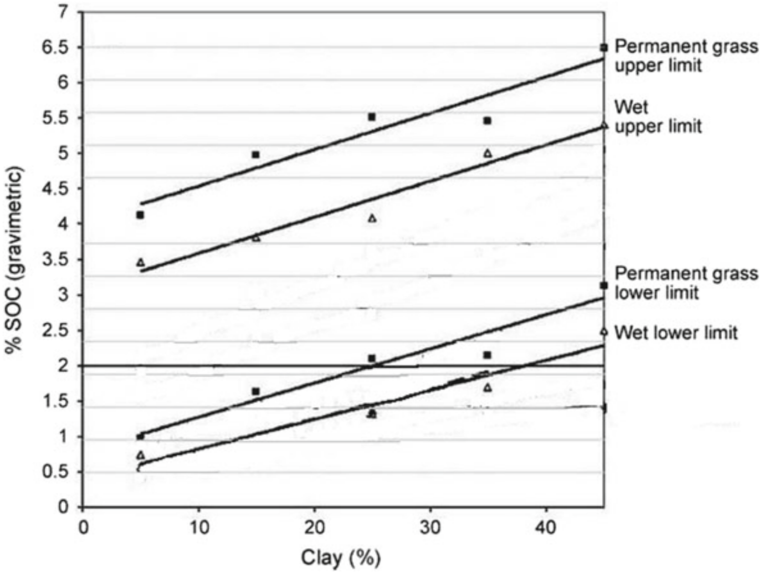

Fig. 18.3 Range of SOC in grassland and in wet soils. Both grassland and wet soils hold much more organic matter than dryland arable (after Verheijen et al. 2005)

3. ***Physical status***. Infiltration of rainfall, water storage and recharge of groundwater depend on the architecture of the pore space; nearly every other soil activity depends on the inhabitants of that pore space. Characterisation of its architecture, let alone its inhabitants, is a challenge but total pore space may be calculated from *bulk density*, the dry mass per unit volume:

$$\text{Total pore space, \%} = 1 - (\text{bulk density}/\text{particle density}) \times 100$$

   The less the bulk density, the greater the pore space, the better the access of roots to water and nutrients, and the greater the soil's capacity to receive rain and transmit drainage to springs and groundwater. Flooding is usually blamed on heavy rain but it's actually caused by runoff from farmers' fields. Poached soil generates runoff, and a heavy soil with a *plough pan* has no capacity to absorb rain if it is already at *field capacity* (the water content of a saturated soil allowed to drain for a couple of days). Even when dry, it can only absorb 60 mm of rain. In contrast, a well-structured soil can absorb 60 mm at field capacity and more than 150 mm when dry—i.e. all but the heaviest rains; so we should consider the condition of both topsoil and the subsoil.

   Farmers and assessors need a ready reckoner that shows the physical condition of the soil and its response to management, and on which field measurements can be plotted. This is Fig. 18.4, which depicts general relationships between

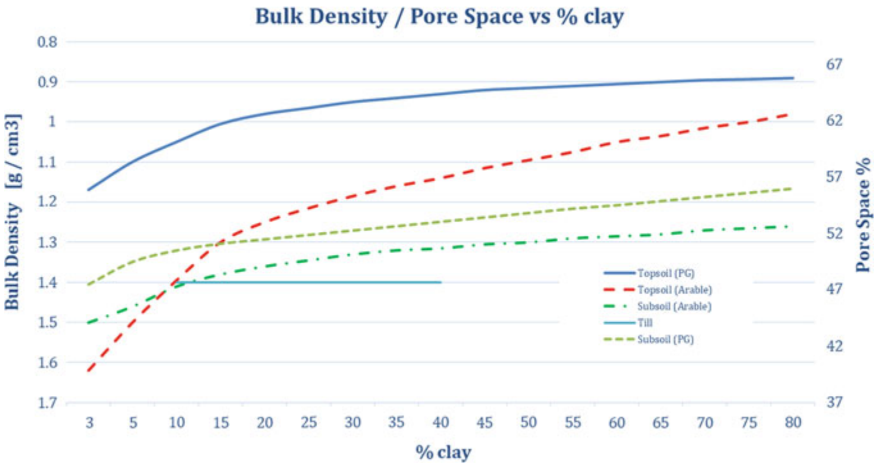

Fig. 18.4 Best-fit curves depicting the relationships between bulk density/pore space and clay content under permanent grass and arable. Sandy soils (<15% clay) to the left, fine loamy and clay soils (>20% clay) to the right. The greater the clay content, the less the bulk density and the greater the pore space. Bulk density is significantly lower and pore space higher under grassland compared with arable; topsoils under permanent grass have 10–15% more pore space than arable; the difference for subsoils is about 5%

> soil texture and the bulk density of the topsoil (0–20/30 cm) and the subsoil immediately below the plough layer or turf (20/30–40/60 cm).
>
> The best-fitting curves for topsoil and subsoil under arable and permanent grass are plotted through some 6500 measured points. Samples were collected from the mid-point of each soil layer so they don't reflect any compaction at the plough sole. This means that they are a fair basis for defining soil health and may be taken as target values to be attained or improved upon.
>
> *Good soil health is indicated by topsoil and subsoil bulk density less than the average for the texture and land use in question, or by measured improvement over a few years.*

However, soils of different texture and composition behave differently in many ways:

Sandy soils are dominated by relatively coarse grains (greater than 0.06 mm diameter) that pack tightly so compaction under cultivation makes the topsoil more compact than the subsoil. Roots don't penetrate when bulk density exceeds 1.4–1.6 g/cm^3 so there are hardly any roots in the subsoil. Coarse grains result in coarse pores so sandy soils exhibit greater than 20–25% air-filled pore space at field capacity. This allows free drainage but, for the same reason, sandy soils are droughty; their available water capacity is only about 14% by volume. There is little the farmer can do to overcome these restrictions, save by adding copious organic matter.

Clay and fine-loamy soils are dominated by platy particles finer than 0.002 mm that tend to pack end-to-face, giving a big total pore space although most of the pores are very small. Two particular kinds of clay and fine loamy soils are differentiated by their origins, namely whether they have been derived from *alluvium*, or *glacial till*. Alluvium is deposited in water, commonly with a pore space of more than 80% (therefore a very low bulk density < 0.3 g/cm^3). Under marsh vegetation, it consolidates to a bulk density of about 0.9 g/cm^3; artificial drainage accelerates the process but these soils remain in the lower range of bulk density. In contrast, glacial till is over-consolidated during its deposition by traction under the weight of the ice. Soils developed in glacial till remain compact; their bulk density immediately below the turf or plough layer is hardly less than 1.4 g/cm^3, irrespective of clay content, and commonly as much as 1.8 g/cm^3 at greater depth.

Peat is partly decomposed organic matter accumulated under water. It follows rules of its own and is not included in Fig. 18.4.

The Devil Is in the Detail

So far, so good. We can scale soil health according to just three tangible attributes. Here, these standards are calibrated using data for England and Wales; the principles are universal but other countries must calibrate their own standards according to the range of values for their own soils. And the greater the certainty required, the greater the cost. Judgement of how best to measure each attribute is a trade-off between precision and accuracy on the one hand, and cost and convenience on the other. For assessing the condition of the soil, many approximate values are better than a few of great precision.

To begin with, there may be several soil types within a single field. A soil survey is needed to delineate these different soils and, in particular, soil texture which is defined according to the proportions of sand (particles between 2 mm and 63 μm), silt (62–2 μm) and clay (finer than 2 μm). For intensively farmed areas, sampling should be undertaken within these mapping units at an intensity of one per 5 ha, according to a rectilinear grid but avoiding headlands. Samples should be measured separately, not mixed together.

For the national database, clay content was measured by the hydrometer method and SOC by wet oxidation (Avery and Bascombe 1974), procedures that demand skill and care, but there are simpler and less costly methods:

- An experienced soil surveyor can assess clay content to better than 10% by the feel of the moist soil.
- Carbon may be determined on an oven-dried, finely ground sample by loss of weight on ignition (LOI) using a conversion factor of 0.58 to arrive at SOC. This needs a drying oven maintaining 105 ± 5 °C, a muffle furnace that can maintain temperatures up to 550 ± 10 °C, flat-bottomed fused silica basins to contain 20 g samples, a desiccator, and a balance weighing to 0.001 g. Most organic matter is burnt off at about 325 °C but soils containing appreciable amounts of clay lose structural water at temperatures between 105 and 500 °C. Ignition at 325 °C for

17 h (Ball 1964) keeps the loss of structural water to a minimum. Alternatively, a temperature of 550 °C for three hours may be used and allowance made for loss of water by clay by introducing an intercept: −1.0 for 10% clay, −2.0 for 20% clay and −3.0 for 30% clay, or applying the formula −0.1046clay + 0.5936LOI (De Vos et al. 2005).

- Measuring bulk density poses no such dilemma. Samples may be collected in cylinders of known volume, ideally about 450 cm^3 to allow for stones and fissures; then dried at 105 °C until there is no further loss of weight, allowed to cool in a desiccator, and weighed to 1.0 g. A standard value of 2.65 g/cm^3 may be assumed for particle density.

Using the Standard in the Field

Conventional arable farming burns off more energy than it captures and harvested crops are carried away from the field, so soil organic matter is depleted unless the losses are made good, for example by application of farmyard manure. Cultivation accelerates the decomposition of soil organic matter. This brings the short-term benefit of releasing plant nutrients but, at the same time, burns off the soil's energy supply and emits carbon dioxide to the atmosphere. Cultivation loosens the plough layer but incrementally compacts the soil at the plough sole, creating a *plough pan*, commonly expressed by a subsoil density of 1.55–1.88 g/cm^3 (42–29% pore space). Pans impede rooting—the rule of thumb is that rooting is restricted by bulk density greater than 1.3 g/cm^3 (Veihmeyer and Hendricksen 1933); pans also impede drainage after rain and the upward flux of water during dry spells. In short, a plough pan restricts the effective soil depth to 25–30 cm.

For instance, we may measure the bulk density of the topsoil and the plough sole in an arable field on the Boulderclay Plateau in East Anglia. Say the measured values are: 1.46 g/cm^3 (45% pore space) in the sandy clay loam topsoil (20–25% clay), and 1.70 g/cm^3 (36% pore space) at the plough sole. These values are within the usual range for these soils but if we compare them with the mean values for arable soils of this texture (topsoil in the range 1.2–1.3 g/cm^3 and subsoil about 1.35 g/cm^3, Fig. 18.4), we see the room for improvement. Bulk densities of the same kind of soil under permanent grass are in the range 0.97–1.0 g/cm^3 for topsoil and 1.3–1.32 g/cm^3 in the subsoil. These represent much higher levels of rainfall acceptance and transmissivity but they cannot be maintained under the plough. However, no-till Conservation Agriculture that maintains > 70% live ground cover and further protects the soil surface with a mulch of crop residues gets at least half way.

Figures 18.5a and b plot the improvement of soil health under no-till over 15 years at Thurlby, Lincolnshire (Reynolds 2019). Figure 18.5a, plots the change of SOC on the relevant part of Fig. 18.2 (the standard envelope of soil organic carbon values under arable and ley grass): the increase from a near-average value of 2.1% in 2003 to 6.25% in 2013 represents an increase of carbon stock of more than 80 tonne/ha in the upper 15 cm. The good tilth is immediately apparent in the field.

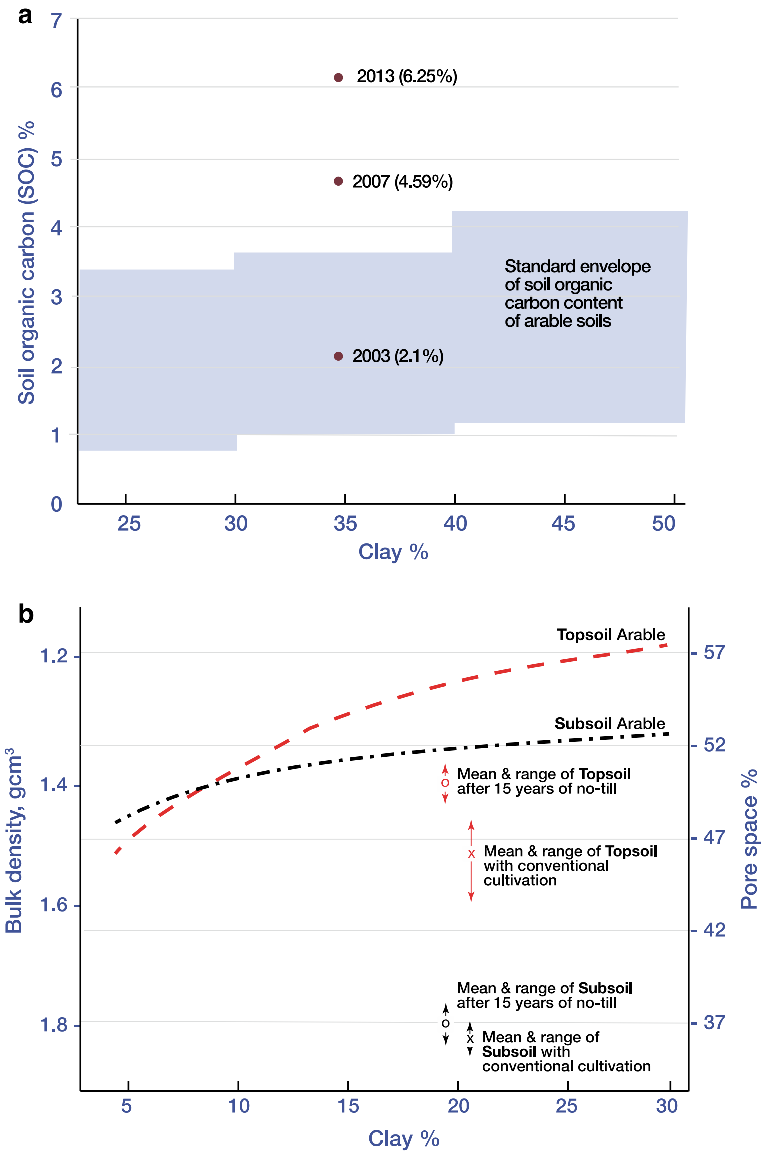

Fig. 18.5 **a** Increase in SOC in the 0–15 cm layer of a clay soil (35% clay) under no-till. At the outset, in 2003, SOC was in the middle of the standard envelope for arable soils but it has much-improved thanks to good management. **b** Bulk density/pore space of a sandy clay loam (20% clay) after 15 years of no-till (left-hand side) and the same soil in adjacent fields under the plough (right-hand side). Under no-till, the physical state of the topsoil is much improved: the mean bulk density is 1.4 g/cm^3 as opposed to 1.5 g/cm^3 under conventional tillage. But there has been no significant rupture of the underlying plough pan that exhibits a bulk density of about 1.8 g/cm^3 and impedes both rooting and drainage

Figure 18.5b plots the contrast in bulk density between no-till and conventional tillage on the relevant part of Fig. 18.4 (the best- fit curves of bulk density for arable soils). While the bulk density/total pore space of the topsoil in question has much improved (from a mean value of 1.55 g/cm^3 or 42% pore space to 1.4 g/cm^3 or 47% pore space), the underlying plough pan is still intact (mean bulk density under both conventional cultivation and after fifteen years no-till remains about 1.8 g/cm^3, equivalent to only 32% pore space). This is unsurprising because the first rule of no-till—*correct any physical or chemical impediment and thereafter inflict no further disturbance*—is almost invariably ignored. But it means that the effective soil depth remains at 30–35 cm and rainfall acceptance and drainage are impaired in spite of the improved condition of the topsoil.

Acknowledgements This chapter is an expanded version of a paper published in the International Journal of Environmental Studies (Dent 2019). The national soil database is maintained by Cranfield University. Further material has been provided by Professor Tony Allan, Mr. Greg Wood, Mr. Tony Reynolds and Mr. John Cherry.

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Part IV
What Else Do We Need to Know?

Why does the same old story have to be repeated?
Why not start a new one?

Mahatma Gandhi

Chapter 19

Pesticides, Insects and Birds on Conventional and Organic Cattle Farms in the Netherlands: Implications for Regulation of Organic Production

Jelmer Buijs and Margriet Mantingh

Abstract The populations of meadow birds in pastoral landscapes have declined seriously since 1970. Apart from changes in land management, this decline could also be related to pesticides in the environment and, consequently, fewer insects. On 15 conventional stock farms and 9 organic stock farms in Gelderland in The Netherlands, samples of concentrated feed, manure and soil were found to contain ecologically significant concentrations of 134 different fungicides, herbicides, insecticides and biocides. No sample was free of pesticides. On average, pesticide residues in concentrated feed were 3.7 times lower in organic concentrated feed than in conventionally produced concentrates but there was not so much difference between conventional and organic farms in levels of pesticide residues in the soil and manure. The observed facts have many implications for the sustainability of organic production. In order to reduce this contamination, practices and regulations of organic production should be revised.

Keywords Organic farms · Pesticides · Contaminated feed · Soil · Manure · Dung beetles · Birdlife

Description of the Research and the Outcomes

In an examination of possible relationships between the decline of meadow birds and the presence of pesticides on stock farms in Gelderland, The Netherlands (Buijs and Mantigne 2019). On average, pesticide residues in organic concentrated feed were 3.7 times lower than in conventionally produced concentrates: 237 and 937 μg/kg, respectively, but we should mention that the average content of pesticides in organic concentrated feed was biased by one sample of organic concentrated feed, probably fake. There was much less difference between conventional and organic farms in levels of pesticide residues in the soil and in the manure.

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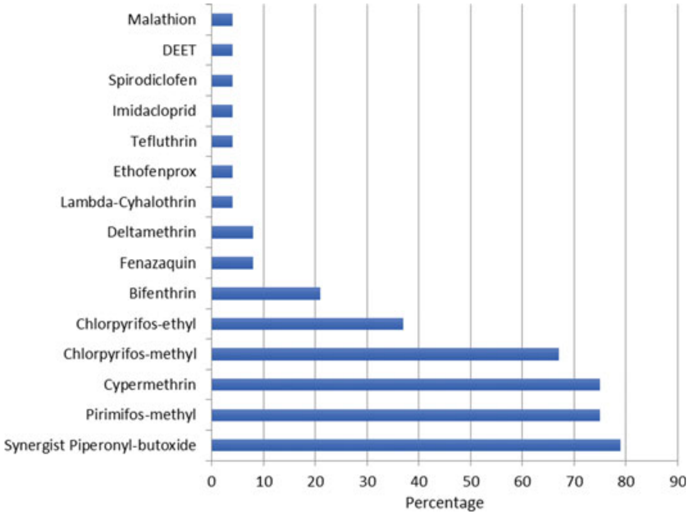

Fig. 19.1 Percentage of samples of concentrated feed in which different insecticides were detected. The 24 samples (organic and conventional) originated from 12 different producers

On 20 of the 24 farms, no anti-parasitic medicines were found above the detection limit in the manure. However, anti-parasitic medicines were found at three conventional farms and, at one organic farm, AMPA, the metabolite of glyphosate, was found in all soils, from both conventional and organic farms, in concentrations ranging from 2 to 249 μg/kg (air dry) soil. The most frequently found insecticides in concentrates (conventional and organic) were pirimiphos-methyl, cypermethrin and piperonyl-butoxide; they were present in 60–70% of the feed samples (Fig. 19.1).

We also studied the population trends of meadow birds using data from the National Flora and Fauna Database (www.ndff.nl) on the number of species and number of individual breeding birds observed on the farms during 20 years from 1998 to 2018. Nearly every species has declined and, at most farms, meadow birds have become very scarce. The skylark has completely disappeared; lapwing and black-tailed godwit have declined on most farms, with the exception of one organic farm on the Randmeer (a coastal area on the south-east coast of the IJsselmeer). More than half of the breeding pairs of all farms surveyed were found on just two organic farms, and anecdotal evidence from the bird protection society indicates that, even at those two farms, too few chicks are reared to sustain the present population.

In order to assess the possible effects on the ecosystem of the substances found, the measured levels of pesticides were linked to the existing ecotoxicological data—although these are often incomplete and contradictory. On the basis of VR (Negligible Risk) and LR50 (Lethal Rate for 50% of test organisms), many of the individual pesticides found are likely to have substantial effects on the ecosystems of both the organically farmed and conventionally managed pastures. This is the more troubling because the combined effects of all these substances taken together, their synergistic

Fig. 19.2 Healthy cowpat with many dung beetles, ants and other arthropods, Switzerland 2019

Fig. 19.3 Cowpat by the River Rhine without any arthropods, 2019

interactions, and their cumulative effects on the ecosystem are unknown. Furthermore, the dose-time-dependent effects of the action of most pesticides are unknown (Tennekes 2010); and the majority of the pesticide metabolites are unknown—and could not be measured. Every pesticide has several or even several dozen metabolites. Only a few metabolites out of thousands could be included in our research programme.

Considering the collected information, we cannot but conclude that the ecosystem of livestock farms is seriously threatened by a plethora of pesticides. This conclusion is supported by the fact that, on most farms, no dung beetles, or hardly any, were found in fresh cowpats—particularly on farms that used concentrates and hay with relatively high concentrations of insecticides (Figs. 19.2 and 19.3).

Implications for Regulation

On the basis of our information, it is likely that the ecosystem of pastoral farms cannot function properly unless the existing Maximum Residue Limits (MRLs) for individual insecticides in feed components are reduced by a factor of 1000. In addition, an MRL for the total amount of pesticides in different kinds of concentrated feed and fodder should be introduced and enforced. At present, MRLs apply only to products for human consumption except when agricultural products (like cereals) are also used for production of concentrated feed, when the MRLs also apply to animal feed. European legislation imposes no MRLs for residues in straw, hay and other roughage consumed as stock feed or used as bedding. They should be established. Moreover, stock farms use veterinary medicines that contain strong insecticides like deltamethrin and permethrin that end up in the manure and on the pastures. It would be better if farms switched to non-chemical control of parasitic insects.

Knowing all this, it is futile to seek protection for meadow birds on land that is exposed to such a load of pesticides, including highly toxic insecticides. At only one conventional farm did the concentrated feed contain less than 1 Âμg of insecticides/kg. On only two organic farms were no insecticides found in concentrates (in a sample of barley and in dried lucerne granules). In all other samples of concentrated feed, whether conventional or organic, we measured from 1 to 720 μg of insecticides per kg. On one conventional farm and on one organic farm, no insecticide residues were detected in manure. However, herbicides and fungicides were found in every sample and, even in those samples in which we did not find insecticides, we cannot exclude the possibility that there were other widely used insecticides that we did not measure (such as phosphine or methyl bromide). These substances are not allowed in organic farming but the organic regulations do not apply to railway wagons, ships and other means of transport that are used to transport organic feed. In the EU, methyl bromide is not allowed even in conventional agriculture, but it is used for protection of agricultural commodities in ships.

Pesticides enter farms mainly through concentrated feed, straw from conventional farms that is used as bedding, and in hay and silage. Veterinary medicines and substances used to control pests in stables and byres may contain very strong insecticides. All contaminants in the manure are spread over the land. And there are other sources of contamination: atmospheric deposition, contaminated surface water, sludge from contaminated ditches and persistent pesticides that have accumulated on farms in the past 70 years.

Implications for Organic Production

The level of soil contamination on organic farms is somewhat less than on conventional farms but organic concentrated feed and manure still contain too many pesticides to protect the ecosystem in the long run. As already mentioned, pesticides in concentrates may originate from the way they are produced, from storage facilities, and from modes of transport. The measures needed to protect the pasture ecosystem against an overdose of pesticides are fairly simple:

1. For livestock farms, the level of pesticide residues in concentrated feed must be made clear by the suppliers so that farmers can make an informed choice.

2. The origin of contaminants in organic feed should be determined and measures taken to eliminate them (this applies also to storage and transport).
3. Organic farms, in particular, should not bring in conventionally grown straw as litter.
4. Maximum Residue Limits (MRLs) for ingredients of animal concentrated feed must be revised on the basis of ecological research.
5. MRLs should be introduced for bedding materials and fodder, taking into account secondary ecological effects on insect populations in manure.
6. Farmers need better information about the ecological consequences of the pesticides they use against parasites in livestock and in byres and stables; likewise for possible alternatives.
7. Methods of analyses with a Limit of Quantification of 1 μg per kg must become available to give certainty, within a few days, about pesticide contamination of feed, fodder, litter etc.

This study suggests that colonization of cowpats by dung beetles is inhibited by pesticide contamination. The exact causal relationship can be determined in the laboratory but that was not in our remit. The average concentration of the insecticide pirimiphos-methyl that we found in positively tested concentrated feed was 61 μg per kg. The recommended dose for the storage of cereals, in absence of other pesticides, is 3 mg active ingredient per tonne (https://www.syngenta.nl/product/crop-protection/actellic-50-w9), i.e. 3 μg per kg. Because of the simultaneous presence of other insecticides and synergists in our samples, it is likely that the concentrations found have a significant impact on insect populations.

We did not investigate the causal relationship between the presence of beetles and bird feeding but it is likely that birds depend on such food sources. Moreover, nutrient cycling from manure is likely to be diminished by pesticides in the manure; many farmers have observed that manure that contains less and fewer pesticides disappears much faster. This also means that parasites in the manure are neutralized faster under healthy conditions. Although the focus of this study was on beetles and birds, the whole organic production system depends on good functioning of biological processes in the soil, manure, and in plants. Neglecting the threat of pesticides can only bring about a collapse of the ecological services that organic farms depend on. This threat has also been recognized by Humann-Guilleminot et al. (2018) in their research of neonicotinoids at 62 conventional, integrated and organic farms in Switzerland.

Consequences for Regulation of Organic Production

Our evidence suggests that the present regulations for organic production do not take account of all potential sources of contamination with pesticides. The fact that organic farms do not themselves spray pesticides is evidently not enough to keep organic farms free from pesticide residues. The first reaction to detecting residues might be to blame the neighbours; but organic farms must first reduce the contamination caused by their own management decisions. For instance, the cereal straw grown on conventional farms that is so popular among organic dairy farms usually contains about a milligram pesticides per kg (Mol et al. 2014). If the pesticides are insecticides like pirimiphos-methyl, cypermethrin, permethrin, imidacloprid and the like, then 1 mg per kg is enough to cause severe ecological damage. So what can we expect from the resulting *organic* manure? It is true that we cannot see, smell or touch those residues but everybody knows that cereal crops on conventional farms are regularly treated with potent chemicals. They are here—there—and everywhere.

Surface water is widely used as stock water and for irrigating vegetables and arable crops but there is almost no surface water in the Netherlands or in Germany that complies with the quality requirements of the EU Water Framework Directive. If organic crops are irrigated with this water, we can expect to find almost every pesticide that is in general use in that organic produce. Again, veterinary medicines often contain strong insecticides like deltamethrin and permethrin. As a rule, the manure of treated animals is mixed with the other manure. So what can we expect about the quality of the manure?

Though the organic concentrated feed contains 3.7 times less pesticides, this does not make a lot of difference to the ecology. According to toxicology, dose-effect relations are usually logarithmic so we might expect that the toxic effect of pesticides found in organic and conventional concentrated feed are not very different. Similarly, it can be expected that toxic effects in soil and manure of organic farms are not much different from those on conventional livestock farms.

It is clear that revision of regulations on organic production should be based on field measurements and observations rather than on ideological, practical or commercial considerations. The present degree of pesticide contamination of organic farms is somewhat less dramatic than on conventional farms—but it is dramatic nevertheless. While the need for revision of regulations is evident, the solution to the problems lies not only in (more and better) regulations but in agricultural education, and in awareness of the issue among farmers and farmers' associations. Action is required. Since 2019 the authors of this article have been actively involved with all groups of stakeholders: by giving lectures and interviews, writing articles and contributing to radio and TV broadcasts on these issues.

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Chapter 20
Fluxes of Reactive Nitrogen and Greenhouse Gases from Arable Land in South-Western Ukraine

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Abstract Conventional wisdom has it that farmland emits lots of reactive nitrogen and greenhouse gases, especially farmland getting big inputs of nitrogen fertilizer. But realistic reduction strategies cannot be developed without measurements spanning at least a whole year to determine region-specific, soil-specific, crop-specific annual fluxes. For the first time, *in situ* measurements of soil-atmosphere fluxes of N_r and GHGs from Southern Black Soils in Ukraine prove them to be no more than a modest source of N_2O; the fertilizer-induced emission factor ($EF_{N2O,}$ estimating the percentage of fertilizer N that is lost as gaseous emissions) is far below the levels suggested by IPCC. Moreover, under winter crops with low N-fertilizer application, they are a sink for CH_4 and NH_3. Measurements also reveal the influence of the weather and soil management practice: for instance, fertigation of vegetable crops and dry–wet cycles triggered pulses of NO and EF_{NO}.

Keywords GHG emissions · Nitrous oxide · NO_x · Ammonia · Southern black soils

Introduction

Terrestrial ecosystems can be both a source and a sink for reactive nitrogen (N_r) and greenhouse gases (GHGs). Indeed, generation and consumption commonly occur simultaneously (Fowler et al. 2013). Recent increases in atmospheric N_r and GHGs are associated with, *inter alia*, manufacture and application of N-fertilizer (Reis et al. 2016; Shang et al. 2019; Sutton et al. 2011). Farmland is also responsible for 46% of anthropogenic methane (CH_4), mainly from paddy rice and livestock, and 54% of nitrous oxide (N_2O), presumably from intensive cropping (Sutton et al. 2011). Both gases have impacts on atmospheric ozone: CH_4 is a precursor of tropospheric ozone, considered to be a photochemical pollutant; while N_2O depletes stratospheric ozone, considered to be the Earth's main shield against UV radiation (Smith et al.

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2007). Global agricultural emissions of these gases are predicted to increase by ~36% by 2030 under business-as-usual (Smith et al. 2014). The consequences could be dramatic because, compared with an equivalent mass of CO_2, the global heating effects of CH_4 and N_2O are 34 and 298 times greater.

Moreover, soils are a significant source of nitric oxide (NO), contributing 18–22% of global NO_x (Bouwman et al. 2002; IPCC 2007) of which 40% of NO is attributed to farmland (Aneja and Robarge 1996). NO affects air quality, public health and ecosystem function as a precursor of ground-level ozone (Wittig et al. 2009; Medinets et al. 2015) and by enhancing the oxidizing capacity of the troposphere (Steinkamp et al. 2009). Exposure to ambient ozone concentration reduces plants' nitrogen-use efficiency, leading to loss of agricultural production and, also, pollution of the environment through leaching of nitrates to streams and groundwater and emission of nitrogen oxides to the atmosphere; for instance, it was estimated that vegetation damage by phytotoxic ozone cost the EU about €7 billion annually (Holland et al. 2006).

Within the EU, agriculture is deemed responsible for 93% of emissions of ammonia (NH_3) that plays a critical role in forming hazardous particulate matter (EMEP 2009). The main NH_3 sources are livestock and the application of high rates of synthetic nitrogen fertilizer. Particulate matter is associated with premature death—it is estimated to reduce life expectancy by over 6 months even in relatively *clean* central Europe; and atmospheric deposition of both NO_2 and NH_3/NH_4^+ as a result of NO and NH_3 emission, respectively, is responsible for loss of biodiversity in natural ecosystems located near or downwind of N sources (Sutton et al. 2011, 2015).

In these various ways, considering just the nitrogen cycle, agricultural soils are a cause of concern—directly affecting the air we breathe, the water we drink, the food we eat, UV radiation that we are exposed to, biodiversity, and environment all around us (Reis et al. 2016). Several contributors to this symposium have emphasized that:

- There is no cheap food without environmental impacts
- Investment in sustainable agriculture is likely to be more effective and cost less than cleaning up pollution and dealing with public health problems and global heating afterward,
- Paying the real cost of sustainably produced food is an investment in clean air, water and soil,
- Personal choice matters. Over-consumption produces pollution. Research and development offer a more sustainable future but willing and working for that future remains a personal choice.

We are always going to need agriculture so, to minimize its environmental impacts, we need comprehensive studies on N_r and GHGs to help develop management strategies that close nutrient loops by increasing N-use efficiency and avoid merely pollution swapping. Thanks to multi-year funding through EU FP6 NitroEurope (2005–2011) and FP7 ECLAIRE (2011–2015), we have, for the first time, directly measured soil-atmosphere N_2O and CH_4 fluxes and N_r exchange in arable land in the south-western Ukraine. These measurements put reactive nitrogen budgets in this part of the world on a realistic basis.

Materials and Methods

Studies were conducted at the Petrodolinskoye Atmospheric Research Monitoring Station and adjacent arable land in Odesa region, south-western Ukraine (Medinets et al. 2016b). The flat study site is 8 km from the River Dniester; the soil *Calcic chernozem* (IUSS 2015); the climate temperate continental, with a mean annual temperature of 10.5 °C (2000–2014) and mean annual precipitation of 432 mm; total annual atmospheric N deposition is about 11kgN/ha, two-thirds of which is organic, associated with marine aerosol formation (Medinets 2014). The crop rotation was: winter wheat (2006)—onions (2007)—tomatoes (2008)—spring barley (2009)—winter wheat (2009/2010)—onions (2010/2011)—carrots (2011)—tomatoes (2012)—beetroot (2013)—onions (2014)—winter wheat; the cereals were rainfed; the vegetables grown with drip irrigation that also supplied NPK fertilizers.

Soil-atmosphere fluxes of N_2O and CH_4 were monitored between September 2009 and December 2010 using static SIGMA (System for Inert Gas Monitoring by Accumulation) auto-chambers ($0.3 \times 1.5 m^2$). Measurements were made before and during the winter wheat crop; three chambers were located ~70 m equidistant in the middle of the field between rows. Gas samples were collected 3 times per day (6:00, 14:00 and 20:00) in FlexFoil bags (www.SKC.com) 2, 35 and 75 min after chamber closure. Samples accumulated in these three bags over one month. Each collected sample was sub-sampled in triplicate into 20 ml vials and analyzed at the Centre for Ecology and Hydrology in Edinburgh by gas chromatography using an ECD-detector for N_2O and an FID-detector for CH_4.

Measurements of soil-atmosphere NO and NO_2 fluxes were undertaken between September 2012 and March 2014 using a dynamic auto-chamber system connected to a CLD88 chemi-luminescence analyser with a photolytic NO_2 converter (Eco Physics AG, Switzerland); details can be found in Medinets et al. (2016a, b). Fluxes of NH_3 were measured in 2009–2010 by the Conditional Time Averaged Gradient system combining a dry-denuder system and sonic anemometer; gas was sampled in triplicate at two heights under neutral, stable and unstable micrometeorological conditions according to the K-theory of Monin-Obukhov (Famulari et al. 2010). Denuder samples were processed according to Sutton et al. (2011) then analyzed by ion chromatography. Statistical analyses employed STATISTICA 7.0 and SPSS Statistics 20.0 (IBM StatSoft).

Results and Discussion

N_2O and CH_4 Fluxes

Under winter wheat and the following onion crop, monthly mean N_2O fluxes ranged between12.8 ± 8.0 and 103.8 ± 36.0 gN/ha (Fig. 20.1b). A slight increase was recorded after tillage in October 2009 and 2010. Significant increases ($p < 0.01$) were observed from April to June 2010, peaking in May (104 ± 36 gN/ha/month), triggered by a combination of management and the weather: fertilization at the end of March and the middle of April; tillage in March and April, rainfall (134 mm); and a rapid rise in temperature during April–June, whereby N-N_2O loss was 187 ± 36 gN/ha (Fig. 20.1a, b).

N_2O emissions correlate with rainfall ($r = 0.51$, $p < 0.05$), which agrees with previous studies identifying rainfall as controlling factor in denitrification (Rees et al. 2013; Skiba and Smith 2000). The fertilization of winter onions in November 2010 hardly affected N_2O emissions, presumably because of the cold and slight rainfall (Butterbach-Bahl et al. 2013; Flechard et al. 2007; Rees et al. 2013). The monthly mean N_2O flux, derived from 9 months of measurements, was 17.9 ± 10.3 gN/ha which corresponds with other studies under cereals with little or no N input (Reeves and Wang 2015; Tellez-Rio et al. 2015). The annual N_2O budget for 2010 was estimated to be 215 ± 123 gN/ha. For the first time, we can calculate the fertilizer-induced N_2O emission factor (EF_{N2O}) for Southern Black Soils based on *in situ* measurements under winter wheat followed by winter onions. It is 0.27%—much below the 1% default value suggested by IPCC (2006).

Monthly CH_4 fluxes ranged between −57.3 ± 88.6 and 20.3 ± 26.1gC/ha (Fig. 20.1c); big changes were not observed but fluctuations in the standard deviation of mean magnitudes indicate a lot of spatial variability, in line with previous findings (Dale et al. 2006). Production and consumption of CH_4 are governed by two unrelated processes that can occur simultaneously: methanogenic archaeobacteria generate CH_4, while methanotrophs (methane-assimilating bacteria and ammonium-oxidizing bacteria) oxidize CH_4. Modest CH_4 emissions registered in autumn, when the soil was moist and enriched in crop residues, might be a result of competitive inhibition of methanotrophs by ammonium-oxidisers (Veldkamp et al. 2001).

On the other hand, strong oxidation of atmospheric CH_4 during May–June 2010 (an uptake of -98.7gC/ha) corresponds with application of fertilizers containing phosphorus and potassium that may inhibit methanogens and stimulate methanotrophs (Babu et al. 2006; Bodelier et al. 2000). Methane production may also be inhibited by nitrates applied or generated in the soil that serves as a substrate for denitrification, which may explain the inverse relationship between CH_4 and N_2O fluxes ($r = -0.61$, $p < 0.05$). Based on the 2010 monthly mean CH_4 flux of −17.3 ± 42.6 gC/ha, we estimate an annual CH_4 budget of −208 ± 511 gC/ha, i.e., the overall tendency was uptake of CH_4, as observed for other arable soils (e.g., Dalal et al. 2008; Hütsch 2001).

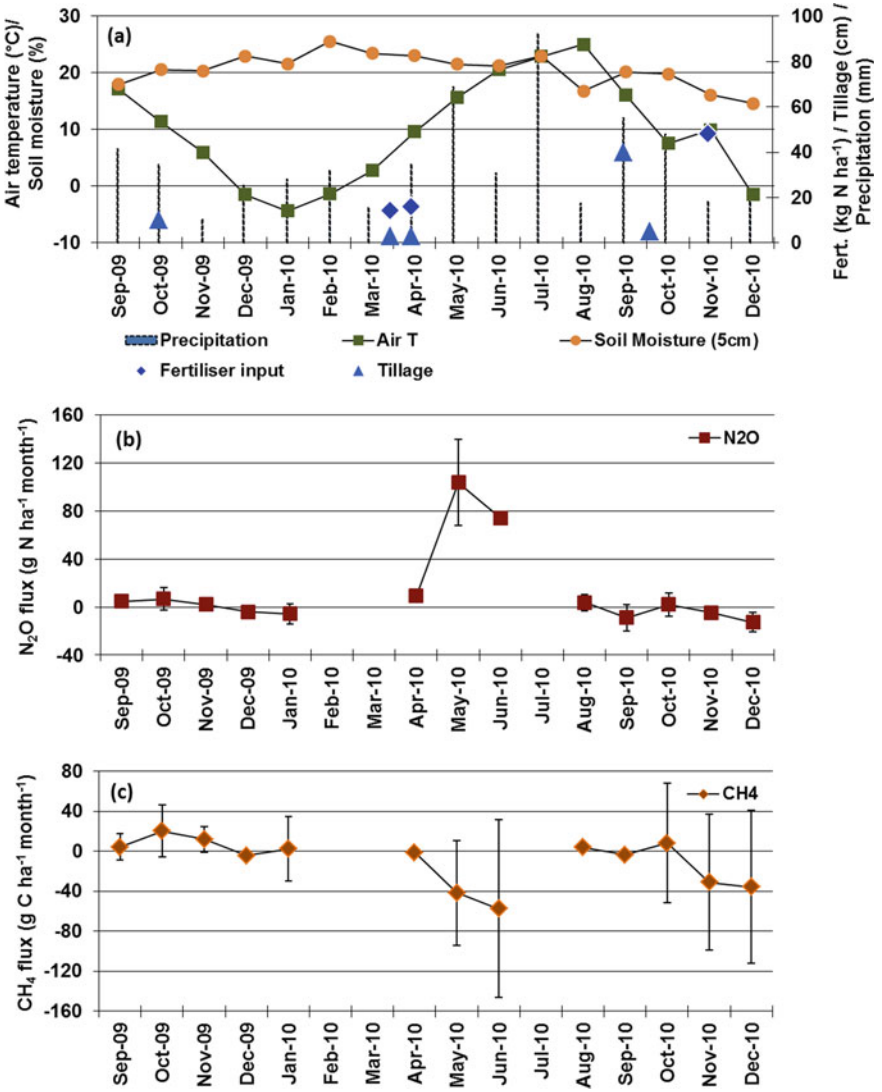

Fig. 20.1 Impacts of field management, *N*-fertilizer application and temporal variability of temperature, rainfall and soil water status on soil (**a**), N_2O (**b**), and CH_4 fluxes (**c**)

N_r Fluxes

Studies of NO and NO_2 fluxes under drip-irrigated (fertigated) beetroot in the 2013 growing season by Medinets et al. (2016b) (Fig. 20.2) revealed an annual NO emission of 0.44 ± 0.78 kgNO-N/ha. This is relatively small compared with published data for other arable crops (Laville et al. 2009, 2011; Cui et al. 2012). However, the

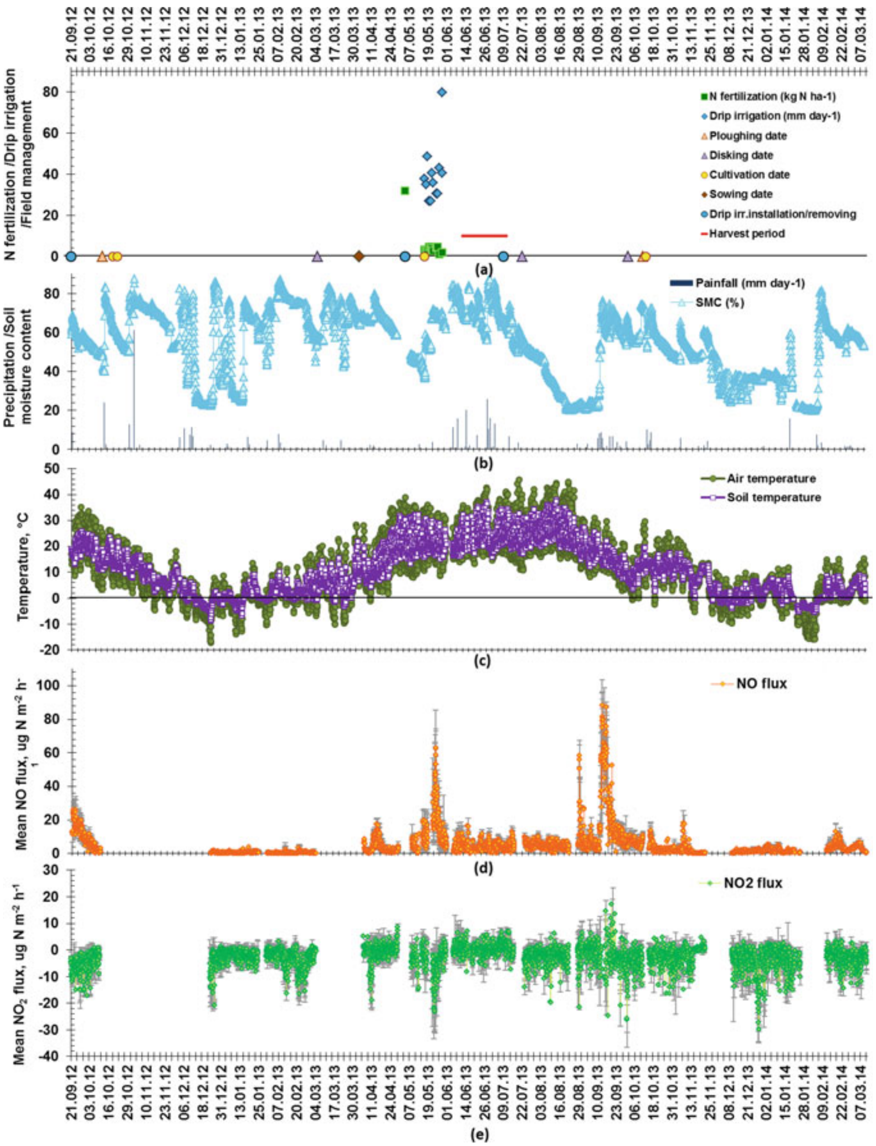

Fig. 20.2 Impact of field management and fertigation events (**a**), temporal variability of soil moisture (SMC) and rainfall (**b**), soil (5 cm depth) and air temperature (**c**) on: soil NO (**d**) and NO_2 fluxes (**e**). Medinets et al. (2016b)

level of NO-N emissions induced by N-fertilizer (69.4 kgN/ha), estimated at 0.63%, was in a good agreement with emission factors reported in the literature: e.g., of 0.50% for barley (Laville et al. 2011) and cotton (Cruvinel et al. 2011), and the global estimates of 0.70% proposed by Bouwman et al. (2002) and IPCC (2007).

The diurnal NO flux depended on temperature (Butterbach-Bahl et al. 2004): maximum NO emission was observed at a soil temperature of 10–20 °C and soil dissolved inorganic N concentrations between 15 and 18 mgN/kg soil dry matter and a soil moisture range of 25–80%. So both aerobic and anaerobic soil conditions contribute to the release of NO (Medinets et al. 2015).

During fertigation, greater NO emissions were measured from the in-row positions compared to between the rows—where emissions responded more to rainfall that, typically, wetted the soil surface and soon decreased as the soil dried (Laville et al. 2009, 2011; Medinets et al. 2019).

Finally, post-harvest pulses of NO corresponding with re-wetting of dry soils carrying crop residues make a big contribution to the annual budget. The annual NO_2 flux was estimated as −0.20 kgNO_2-N/ha; the distinct periods of net NO_2 emissions observed might be associated with significant soil HONO emissions (for details see Medinets et al. 2016b).

Ammonia Dynamics

Between July 2009 and December 2010, net NH_3 fluxes were monitored using the experimental micrometeorological gradient (COTAG) system: monthly mean magnitudes varied from −209 ± 33 to 283 ± 53 gN/ha (Fig. 20.3). Operations during March–May 2010 were hindered by power cuts so we missed any emissions stimulated by spring fertilization; the peak NH_3 volatilization was registered in October 2010 at winter onion sowing. During July–December 2009, a net NH_3 flux of −13.3

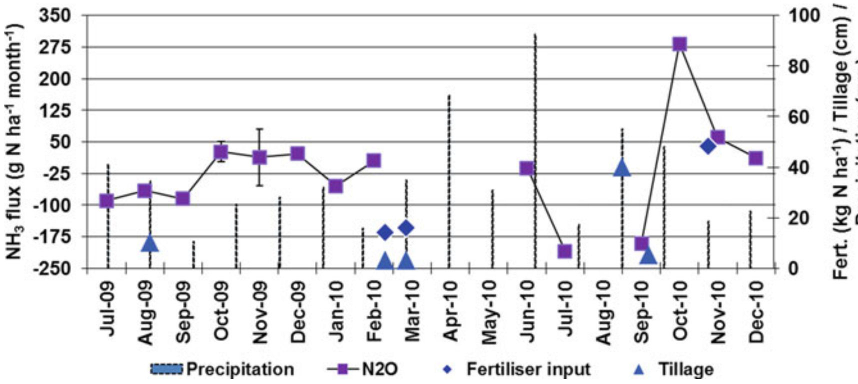

Fig. 20.3 Net monthly mean NH_3 fluxes, rainfall, tillage and N fertilization events

± 26.8 gN/ha indicated that NH_3 emission and deposition were roughly in balance. The higher estimated net uptake of NH_3 for 2010 (-160 ± 322 gN/ha) corresponds with previous studies showing low emissions from cereal cropping with a low N input that might serve as sink for NH_3 emitted from nearby intensively fertilized fields or poultry/livestock enterprises (Meade et al. 2011; Turner et al. 2012).

Conclusions

- Thanks to multi-year funding through EU projects, in situ measurements of soil-atmosphere fluxes of N_r (NO_x and NH_3) and GHGs (N_2O and CH_4) have been carried out on arable Southern Black Soils. The studied agro-ecosystems are a modest source of N_2O: the fertilizer-induced EF_{N2O} (%N from fertilizer emitted as the gas on an annual basis) was shown to be only one quarter of that proposed by IPCC. At the same time, under winter crops with a low N input, they are a sink for CH_4 and NH_3. In situ measurements also reveal that gas fluxes depend on the weather and soil management.
- Under fertigation, Southern Black Soils are a modest source of NO; distinct pulses of NO were observed during fertigation events and, after harvest, during cycles of wetting and drying. The fertilizer-induced EF_{NO} was 0.63%, thereby within the range of published values.
- Long-term measurements, covering at least a whole observational year, are essential to arrive at reliable region-specific, soil-specific, crop-specific annual budgets of soil N_r and GHG fluxes and their seasonal dynamics. This information is needed for inventory and to develop strategies to increase crop productivity by increasing N-use efficiency of crops, and to minimize the environmental impact of harmful emissions.
- If we give them the chance, cropland soils have a great capacity to buffer the global system. Giving them the chance means changing the production paradigm, making use of fundamental and applied research, and innovative technologies.

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Chapter 21
Long-Term Effects of Crop Rotation and Fertilization on Weed Infestation in Winter Wheat

Gheorghe Sin and Elena Partal

Abstract Weed infestation in winter wheat under different cropping sequences and different systems of fertilization, and in continuous wheat, has been estimated within the framework of a long-term field experiment initiated in 1967. Data recorded in 1975 and during 2016–2018 reveal the greatest infestation in continuous wheat and the least in a diverse crop rotation. Weeds decrease in step with the increase in the number of different crops in the rotation. In the course of time, weed density increased and the number of weed species decreased; the dominant species were wild buckwheat (*Polygonum convolvulus*), ivy-leaved speedwell (*Veronica hederifolia*), and yellow foxtail (*Setaria glauca*). Alternation of different crops—each with its own practices of tillage, fertilization, weed and pest control, time of sowing, and harvesting—disturbs the life cycle and proliferation of weeds. Crop rotation has proved to be an effective measure to control weeds. This should be seriously considered in view of the need to cut the costs of production and the use of chemical herbicides and pesticides.

Keywords Weed infestation · Crop rotation · Continuous monocropping · Fertilization

Introduction

What about weeds? The escalating cost of herbicides and pesticides in intensive crop production, quite apart from environmental concerns, has re-ignited interest in other ways to control weeds, pests, and diseases (Weiner et al. 2001). The beneficial effects of crop rotation and fertilization are well known and well researched—in many cases within the framework of long-term field experiments. Research data demonstrate a 10–50% increase in crop yields with crop rotation compared with

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continuous monocropping (Boincean et al. 2021; Wozniak 2019); and greater weed infestation in continuous monocropping is a contributory factor (Karlen et al. 1994; Stevenson et al. 1998; Stojanovič and Cvetkovič 1989).

Rotation of different crop species—each with different methods of soil tillage, fertilization, times of sowing and harvest, and measures for weed control—obviously disrupts the life cycles of weeds, pests, and diseases (Karlen et al. 1994; Liebman et al. 1996; Sin 1988; Wozniak 2019; Young et al. 1994). On the other hand, continuous monocropping encourages invaders and creates demand for more and more pesticides and, thus, incurs substantial costs (Mal et al. 2015; Wozniak and Soroka 2018) including known and unknown implications for the environment (Buijs and Mantigh 2021). Crop rotation suppresses weeds more effectively than continuous monocropping (Dolijianovič et al. 2014; Lapins et al. 2004; Stojanovič and Cretkovič 1989). However, the diversity in weed species is greater under crop rotation than under monocropping (Covarelli and Tei 1988) and weed occurrence is greater in dry years than wet ones, especially in the case of perennial weeds (Montorova and Zaikova 2013). Application of fertilizer influences not only crop growth but, also, weed infestation (Carlson and Hill 1985; Légère et al. 1994; Stevenson et al. 1998; Torlina 2016; Tyr et al. 2001).

The objective of this long-term study, begun more than 50 years ago, is to determine the effect of crop rotation and fertilization on weed infestation under rainfed conditions. For brevity, we present only benchmark data from 1975 and data for the last three years (2016–2018) on the magnitude and floristic composition of weed infestation, and its trends in relation to crop rotation and fertilization.

Materials and Methods

The experiment was initiated in the fall of 1967 on *Leached chernozem* at the National Agricultural Research Institute, Fundulea. It is a part of a long-term experiment involving five cropping systems: continuous winter wheat and continuous maize, a two-crop rotation of wheat and maize, a three-crop rotation (wheat–maize–peas) and four-crop rotation (wheat–sugar beet–maize–sunflower). Five different fertilization treatments are applied to sub-plots of each crop, of which N_0P_0 and $N_{90}P_{60}$ are presented here. The experiment has three replicates in a system of randomized blocks; the main plots are 30 m × 8 m and sub-plots 6 m × 8 m.

Farm practice is conventional except that no herbicides are applied and fertilizer applications follow the experimental design. The winter wheat was drilled at 12.5 cm spacing during 1–10 October, and harvest began in July. Weed infestation was determined at the beginning of April and, again, before harvest in July, by collecting all weeds from a frame area of 25 × 25 cm in 3 replicates for each sub-plot. The floristic composition, number of weeds per species, and fresh and dry biomass were determined in the field and laboratory. The data were subjected to analysis of variance and the effects of experimental factors were considered statistically significant if $P \leq 0.05$.

Results and Discussion

We might expect some relationship between climatic factors and weed emergence, as well as crop performance. The weather differed from year to year (Table 21.1). 2017 and 1975 were the wettest years, 2018 the driest, but there was little difference in temperature although all the years in question were warmer than the mean.

Tables 21.1, 21.2, 21.3, 21.4, 21.5, 21.6, 21.7, 21.8, 21.9, 21.10 and 21.11 present data on weed infestation according to floristic composition, weed density, and dry weed biomass, depending on crop rotation and fertilization. The data from April 1975 (Table 21.2) indicate the highest weed infestation in continuous monocrops and lesser infestation of rotational crops, depending on the diversity of crops in rotation. Alternation of crops also means annual alternation of different farm practices that affect the proliferation of weeds, so that the number and biomass of weeds in unfertilized wheat were diminished by 25–80% and 65–85%, respectively. The dominant species are wild buckwheat *Polygonum convolvulus L.* and ivy-leaved speedwell *Veronica hederifolia* L. The trend of weed infestation is the same in fertilized wheat: 516 weeds/m^2 in continuous wheat and 81 weeds/m^2 in the 4-crop rotation; the dominant species are *Polygonum convolvulus* and flixweed *Sisymbrium sophia* L.

Immediately before harvest (Table 21.3), weed infestation is lower than in spring and rotation-dependent differences among weed densities are less, but more evident in the case of weed biomass. The number of species is greater than in spring; and the dominant species are *P. convolvulus* and yellow foxtail *Setaria glauca (L.) Beauv.* Infestation is less in fertilized wheat because of stronger competition from the crop. We also observe a gradual decrease of weed biomass from monocropping through 2-field, 3-field, and 4-field rotations.

Table 21.1 Meteorological data

Precipitation (mm)						
Year/month	March	April	May	June	July	Total
1975	28	69	64	88	77	326
2016	55	74	81	44	31	285
2017	48	74	66	96	114	398
2018	14	2	34	121	85	256
55-year mean	36	44	60	73	73	286
Temperature (°C)						
Year/month	March	April	May	June	July	Mean
1975	7.1	12.0	17.6	21.2	22.2	16.0
2016	7.3	13.9	15.9	22.9	24.1	16.8
2017	8.6	10.6	16.8	22.2	23.3	16.3
2018	3.4	15.8	19.3	22.6	22.8	16.8
55-year mean	4.7	11.1	16.9	20.7	22.7	15.2

Table 21.2 Weed infestation of winter wheat (%) depending on crop rotation and fertilization, 7 April 1975

Weed species	N_o P_o				N_{90} P_{60}			
	Monocrop	2-field rotation	3-field rotation	4-field rotation	Monocrop	2-field rotation	3-field rotation	4-field rotation
Polygonum convolvulus	40	71	78	42	33	51	70	29
Veronica hederifolia	30	19	3	33	17	2	0	3
Sisymbrium Sophia	12	3	8	0	27	18	21	49
Anthemis arvensis	0	0	0	0	0	0	0	0
Papaver rhoeas	5	1	7	6	6	3	0	2
Cardaria draba	2	1	0	0	1	6	0	0
Sinapis arvensis	5	1	0	5	11	1	6	6
Centaurea cyanus	2	2	2	11	1	16	1	10
Gallium aparine	1	1	1	0	1	1	1	0
Vicia villosa	2	0	0	0	2	0	0	0
Weeds/m^2	461	348	237	94	516	264	259	90
Weed dry weight (kg/ha)	139	49	24	20	237	63	33	13

Weed density: LSD 5%: Cropping system (CS)—6.8; Fertilization (F)—6.2; CSxF—5.0

Tables 21.4, 21.5 and 21.6 present weed infestation in wheat in spring 2016, 2017, and 2018. The differences among the cropping systems are marked: compared with continuous wheat, alternation of more crops creates a more favourable environment for winter wheat and a less favourable environment for weeds. On unfertilized plots, weed density decreases from 161–373 weeds/m^2 in continuous wheat to 42–186 weeds/m^2 in 2-field, 3-field, and 4-field crop rotations, with the lowest weed density recorded in the 4-field rotation. The oddity between 2-field and 3-field rotations may be explained by the presence of a hoed row crop (maize) making up half of the 2-field rotation and one-third of the 3-field rotation.

In respect of the composition of the weed flora, *P.convolvulus* and *V. hederifolia* were dominant but the speedwell is ephemeral and a weak competitor for wheat; scentless mayweed *Matricaria inodora* and poppy *Papaver rhoeas* are also prominent in the fertilized 3-field rotation (Table 21.6). Weed infestation in 2017 and 2018 was

Table 21.3 Weed infestation of winter wheat (%) depending on crop rotation and fertilization, 5 July 1975

Weed species	N_0 P_0				N_{90} P_{60}			
	Monocrop	2-field rotation	3-field rotation	4-field rotation	Monocrop	2-field rotation	3-field rotation	4-field rotation
P. convolvulus	44	41	38	46	62	84	59	36
Setaria glauca	15	26	37	35	13	3	29	26
Anthemis arvensis	7	0	10	1	0	3	0	4
Centaurea cyanus	0	3	6	0	0	3	0	0
Sisymbrium sophia	0	2	0	1	6	0	0	4
Papaver rhoeas	5	7	0	0	0	0	4	2
Gallium aparine	0	5	0	0	13	0	0	0
Sinapis arvensis	6	6	0	0	0	3	4	4
Lathyrus tuberosus	7	7	9	0	0	0	0	0
Thlaspi arvense	0	0	0	1	3	1	0	0
Rubus caesius	0	3	0	0	3	3	4	4
Convolvulus arvensis	0	0	0	6	0	0	0	20
Gallium aparine	16	0	0	0	0	0	0	0
Weeds/m^2	45	64	43	53	31	31	24	30
Weed dry weight (kg/ha)	295	119	74	69	204	88	39	34

Weed density: LSD 5%: Cropping system (CS)—5.0; Fertilization (F)—4.0; CSxF—3.6

higher compared with 2016 as a result of the weather, and fertilization favoured an increase of weed density.

A comparison between weed infestation in 1975 and in 2016–2018 (Table 21.7) shows a decrease of weed density as a result of developments of technology and the effect of crop rotation. Even in continuous wheat, weed infestation was reduced from 516 weeds/m^2 to 293 weeds/m^2 and in rotational wheat from 90–264 weeds/m^2 to 81–214 weeds/m^2. The dominant species remain the same, but *Sisymbrium* disappeared

Table 21.4 Weed infestation of winter wheat (%) depending on crop rotation and fertilization, 4 April 2016

Weed species	N_0 P_0				N_{90} P_{60}			
	Monocrop	2-field rotation	3-field rotation	4-field rotation	Monocrop	2-field rotation	3-field rotation	4-field rotation
P. convolvulus	28	28	53	26	38	43	62	37
Veronica hederifolia	5	62	35	72	26	50	21	62
Centaurea cyanus	6	1	1	0	25	0	0	1
Matricaria inodora	5	2	5	1	6	2	7	0
Ranunculus acer	6	3	2	0	1	0	0	0
Papaver rhoeas	0	3	2	0	3	4	10	0
Gallium aparine	0	1	1	0	1	0	0	0
Vicia villosa	0	0	1	1	0	1	0	0
Weeds/m^2	161	60	112	82	138	106	114	54
Weed dry weight (kg/ha)	140	65	170	121	415	280	110	95

Table 21.5 Weed infestation of winter wheat (%) depending on crop rotation and fertilization, 10 April 2017

Weed species	N_0 P_0				N_{90} P_{60}			
	Monocrop	2-field rotation	3-field rotation	4-field rotation	Monocrop	2-field rotation	3-field rotation	4-field rotation
P. convolvulus	30	14	22	31	33	11	17	23
Veronica hederifolia	48	63	26	69	33	77	8	61
Centaurea cyanus	0	3	5	0	10	0	2	0
Matricaria inodora	5	3	34	0	12		35	3
Papaver rhoeas	0	10	10	0	2	9	3	0

(continued)

Table 21.5 (continued)

Weed species	N_0 P_0				N_{90} P_{60}			
	Monocrop	2-field rotation	3-field rotation	4-field rotation	Monocrop	2-field rotation	3-field rotation	4-field rotation
Gallium aparine	2	3	3	0	4	0	25	0
Vicia villosa	5	2	0	0	2	0	10	12
Ranunculus acer	10	2	0	0	4	3	0	1
Weeds/m^2	241	140	156	119	356	94	118	108
Weed dry weight (kg/ha)	170	120	110	99	270	90	140	130

Table 21.6 Weed infestation of winter wheat (%) depending on crop rotation and fertilization, 13 April 2018

Weed species	N_0 P_0				N_{90} P_{60}			
	Monocrop	2-field rotation	3-field rotation	4-field rotation	Monocrop	2-field rotation	3-field rotation	4-field rotation
P. convolvulus	27	11	11	39	29	13	15	29
Veronica hederifolia	45	70	41	36	36	54	31	45
Centaurea cyanus	4	5	2	3	4	3	6	3
Matricaria inodora	5	3	30	5	13	7	15	7
Ranunculus acer	9	0	2	5	3	2	2	2
Papaver rhoeas	3	6	6	5	9	15	18	10
Gallium aparine	2	2	6	2	5	2	11	2
Vicia villosa	5	3	2	5	1	4	2	2
Weeds/m^2	373	178	186	97	379	228	265	86
Weed dry weight (kg/ha)	270	130	160	100	450	320	165	140

Table 21.7 Weed infestation of winter wheat (%) depending on crop rotation and fertilization, April 2016–18

Weed species	N_0 P_0				N_{90} P_{60}			
	Monocrop	2-field rotation	3-field rotation	4-field rotation	Monocrop	2-field rotation	3-field rotation	4-field rotation
Veronica hederifolia	50	66	34	58	34	60	20	56
P. convolvulus	29	17	29	33	33	22	31	30
Matricaria inodora	5	3	23	2	11	1	17	4
Papaver rhoeas	1	4	6	2	5	3	10	3
Gallium aparine	1	1	3	1	3	4	12	1
Centaurea cyanus	3	2	3	1	11	6	3	1
Ranunculus acer	8	6	1	2	2	1	3	0
Vicia villosa	3	1	1	1	1	3	4	5
Weeds/m^2	258	126	151	86	293	143	214	81
Weed dry weight (kg/ha)	193	105	146	106	398	230	138	122

Weed density: LSD 5%: Cropping system (CS) 5.4; Fertilization (F) 5.0; CSxF 4.6

Table 21.8 Weed infestation of winter wheat (%) depending on crop rotation and fertilization, 1 July 2016

Weed species	N_0 P_0				N_{90} P_{60}			
	Monocrop	2-field rotation	3-field rotation	4-field rotation	Monocrop	2-field rotation	3-field rotation	4-field rotation
Setaria glauca	86	85	64	77	0	96	53	91
Centaurea cyanus	2	2	3	0	11	0	0	3
Sorghum halepense	3	1	0	4	0	3	9	2
P. convolvulus	8	12	30	0	71	0	33	0
Matricaria inodora	0	0	0	0	0	0	5	2

(continued)

Table 21.8 (continued)

Weed species	N_0 P_0				N_{90} P_{60}			
	Monocrop	2-field rotation	3-field rotation	4-field rotation	Monocrop	2-field rotation	3-field rotation	4-field rotation
Papaver rhoeas	1	0	0	0	4	0	0	0
Convolvulus arvensis	0	0	3	19	4	1	0	2
Weeds/m^2	258	258	214	94	190	152	120	86
Weed dry weight (kg/ha)	1220	790	800	720	910	400	420	310

Table 21.9 Weed infestation of winter wheat (%) depending on crop rotation and fertilization, 10 July 2017

Weed species	N_0 P_0				N_{90} P_{60}			
	Monocrop	2-field rotation	3-field rotation	4-field rotation	Monocrop	2-field rotation	3-field rotation	4-field rotation
Setaria glauca	88	90	83	90	33	58	98	77
Centaurea cyanus	1	0	0	0	9	3	2	0
Sorghum halepense	0	0	0	0	0	0	0	0
P. convolvulus	10	10	17	10	58	36	0	23
Matricaria inodora	0	0	0	0	0	0	0	0
Papaver rhoeas	1	0	0	0	0	3	0	0
Convolvulus arvensis	0	0	0	0	0	0	0	0
Vicia villosa	0	0	0	0	0	0	0	0
Xanthium spinosum	0	0	0	0	0	0	0	0
Weeds/m^2	458	216	206	202	311	152	84	90
Weed dry weight (kg/ha)	4320	2310	1780	1480	4180	2260	1380	580

Table 21.10 Weed infestation of winter wheat (%) depending on crop rotation and fertilization, 12 July 2018

Weed species	N_0 P_0				N_{90} P_{60}			
	Monocrop	2-field rotation	3-field rotation	4-field rotation	Monocrop	2-field rotation	3-field rotation	4-field rotation
Setaria glauca	73	22	44	96	27	56	17	60
Centaurea cyanus	0	14	8	0	33	0	20	0
Sorghum halepense	7	43	32	4	13	6	13	0
P. convolvulus	17	21	0	0	27	28	50	40
Matricaria inodora	3	0	0	0	0	0	0	0
Papaver rhoeas	0	0	0	0	0	0	0	0
Convolvulus arvensis	0	0	0	0	0	0	0	0
Vicia villosa	0	0	0	0	0	10	0	0
Xanthium spinosum	0	0	16	0	0	0	0	0
Weeds/m^2	120	96	100	112	62	72	60	71
Weed dry weight (kg/ha)	1190	1150	610	540	4440	2230	2550	1740

and *Matricaria* appeared. Weed biomass varied according to treatments, likewise weed density, without any clear correlation between these indices.

As a result of competition from the crop, weed infestation at harvest in July was less than at the beginning of April. Fewer species were recorded and the dominant species are *Setaria glauca* and *Polygonum convolvulus,* followed by *Centauria cyanus* (Tables 21.8, 21.9 and 21.10). In 2017, only 2 species were found in unfertilized wheat, 3 species in fertilized plots (Table 21.9), while 8 species were registered in spring (Table 21.5). The differentiation among cropping systems is clear: on average over 2016–2018, the weed density decreases by 51–56% from continuous wheat to the 4-field rotation; and dry weed biomass decreases by 45–72% (Table 21.11).

Comparing weed infestation in 1975 with 2016–18, we observe an increase of weed density from 24–64 in 1975 to 77–279, an increase of dry biomass from 34–295 kg/ha to 877–3177 kg/ha, and a decrease in the number of species from 13 to 9. The dominant species are the same: *Setaria glauca* and *Polygonum convolvulus.*

Table 21.11 Weed infestation of winter wheat (%) depending on crop rotation and fertilization, July 2016–18

Weed species	N_0 P_0				N_{90} P_{60}			
	Monocrop	2-field rotation	3-field rotation	4-field rotation	Monocrop	2-field rotation	3-field rotation	4-field rotation
Setaria glauca	82	65	64	86	23	70	56	76
Centaurea cyanus	1	5	4	0	19	2	7	1
Sorghum halepense	3	15	10	4	4	2	8	1
P. convolvulus	12	14	16	3	52	22	37	21
Matricaria inodora	1	0	0	0	0	0	2	1
Papaver rhoeas	1	0	0	0	1	1	0	0
Convolvulus arvensis	0	1	1	7	1	0	0	0
Vicia villosa	0	0	0	0	0	3	0	0
Xanthium spinosum	0	0	5	0	0	0	0	0
Weeds/m^2	279	190	173	136	188	125	77	82
Weed dry weight (kg/ha)	2243	1416	1503	1246	3177	1630	1450	877

Weed density: LSD 5%: Cropping system (CS) 6.0; Fertilization (F) 5.4; CSxF 5.0

Conclusions

- Cropping system and fertilization had obvious effects on weed infestation, whether measured by weed density and biomass or floristic composition and dominance. In a long-term field experiment involving continuous wheat and crop rotations of varying diversity, the greatest weed infestation occurred in the continuous wheat and decreased significantly in step with the increasing diversity of crops in the rotation.
- Fertilization generally favoured weed infestation, but this depended on the crop and the weather.
- Over the years, in this case 33 years, weed density increased and the number of species decreased.
- The dominant arable weeds are wild buckwheat *Polygonum convolvulus,* ivy-leaved speedwell *Veronica hederifolia,* and yellow foxtail *Setaria glauca.*

- It is imperative to cut pesticide usage and production costs. The experimental evidence demonstrates that both aims can be achieved by eschewing continuous monocropping and, instead, adopting diverse crop rotations.

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Chapter 22

Phenotyping of Wheat in Heat- and Drought-Stressed Environments Using UAVs

Karolin Kunz, Yuncai Hu, Boris Boincean, Alexei Postalatii, and Urs Schmidhalter

Abstract To assess the effects of climate change on cereal production and identify wheat varieties that can withstand heat and drought, a field trial was performed during the growing seasons 2016/2017 and 2017/2018 at Bălţi in Moldova, where summers are hot and, very often, dry. Finding varieties suitable for breeding for future climatic scenarios requires detailed information about physiological responses to abiotic stress. The field trial tested 40 wheat varieties from Germany and Eastern Europe. Thermal and multispectral measurements were made using hand-held and aerial instruments and corroborated by destructive plant sampling. Unmanned aerial vehicles (UAVs) can gather a lot of information about the performance of the crop in a short time and without the need for laborious analyses; information that can help to improve farming decisions. Preliminary results show significant differences between German and Eastern European varieties; unsurprisingly, the Eastern European varieties are better adapted to the prevailing conditions and, therefore, less stressed by heat and drought. Vegetation indices, temperature data, and yield parameters can help to identify varieties with advantageous genetic constitution.

Keywords Wheat · Abiotic stress · Phenotyping · Drought tolerance · Climate change

Introduction

Wheat is one of the most important cereal crops, grown on more than 220 million ha every year (Shiferaw et al. 2013). However, wheat production will face severe challenges in the near future from increasing world demand (FAO 2017), a diminishing arable area from erosion and sealing, and global heating that will bring more frequent

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and more severe droughts in its main areas of production (IPCC 2007, Walter et al. 2011 in Aroca 2012).

Farmers need wheat varieties that yield reliably under unfavourable conditions. The optimum growth temperature for wheat is between 20–25 °C (Austin 1990 in FAO 2002). At higher temperatures, in combination with little rainfall, the plants suffer drought stress that reduces dry matter accumulation, cell division, and stem elongation (Asrar and Elhindi 2011; Li et al. 2009; Farooq et al. 2009 in Aroca 2012). Drought during flowering can cause up to 66% loss of yield (Majid et al. 2007 in Aroca 2012). The stomata close to cut transpiration which, in turn, leads to a decrease in photosynthesis (Pask et al. 2012); not only is the number of grains reduced by premature ripening but, also, their size and weight (Saini and Westgate 2000; Dolferus et al. 2011).

A field trial was conducted to test wheat varieties originating from Eastern Europe and Germany for any differences in their tolerance of drought. It is difficult to simulate heat and drought over a large area so a field trial was performed in Moldova where such conditions are usual during the summer months. The varieties from Eastern Europe served as a standard, showing what performance can be achieved under stress by cultivars that have been selected over many generations for continental conditions. Adapted varieties are characterized by faster development, so that they avoid the fierce heat of high summer, in contrast to wheat from more temperate conditions, adapted to a longer growing season. We might speculate that East-European cultivars will do better under hot, droughty conditions than cultivars from temperate regions. Possible differences in drought and heat tolerance of wheat cultivars in Germany have hardly been assessed, so this study will help to identify these differences. The short-term goal is to identify cultivars that are better adapted to rising temperatures and more frequent drought events in Germany. The long-term goal will be to tap into the gene pool of cultivars that have already been selected for these adaptations.

Field Trial

The two-year field trial took place at Bălţi, in Moldova, in the growing seasons 2016/2017 and 2017/2018. Forty wheat varieties (*Triticum aestivum* L.) were grown, 20 from Eastern Europe (Romania, Ukraine, Bulgaria, Moldova), 20 from Germany which included 16 lines and 4 hybrids. The plots were 5m^2 in size and all cultivars were grown in three replicates. No supplementary irrigation was applied. The climate of Bălţi is characterized by hot, dry summers (Table 22.1). Figure 22.1 shows daily meteorological data from October 2016 to July 2017 (A), and from October 2017 to July 2018 (B), respectively. Gold lines mark the day of harvest in both seasons.

Table 22.1 Comparison of site conditions in Bălţi (Moldova) at the site of the field trial, and representative conditions of a field site in Freising, location of the Technical University of Munich

	Bălţi	Freising
Latitude	47.46	48.24
Longitude	27.56	11.44
Soil texture	Clay loam	Silt loam
Mean annual precipitation	530 mm	800 mm
Mean annual temperature	14.1 °C	7.5 °C
Mean summer precipitation	200 mm	350 mm
Mean summer air temperature	18.5–21 °C	13.5 °C

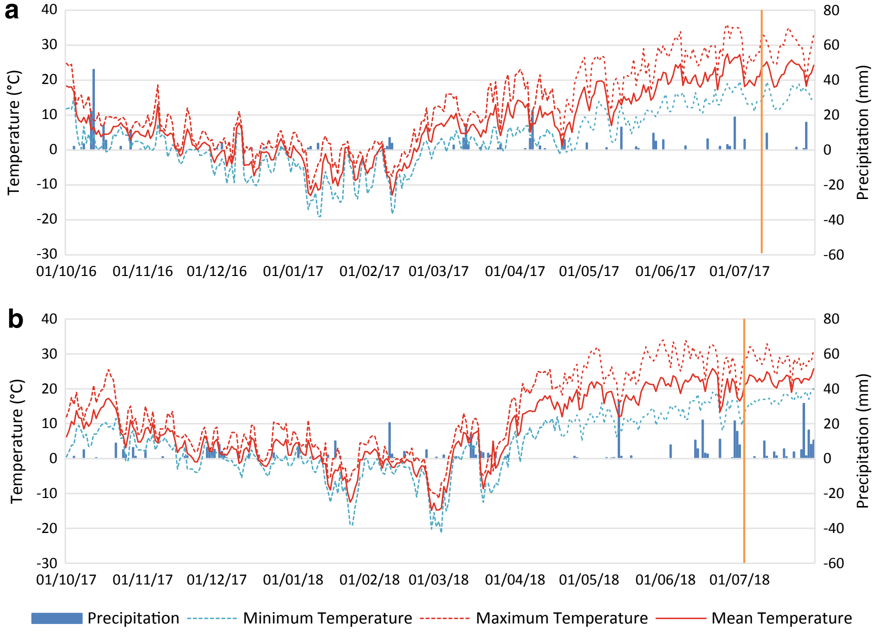

Fig. 22.1 Temperature and precipitation at Bălţi during growing seasons 2016–2017 (**a**) and 2017–2018 (**b**)

Measurements of Spectral Reflectance and Plant Temperature

From anthesis until harvest, reflectance was measured with a HandySpec Field (tec5 AG, Oberursel, Germany) that records spectral reflectance between 302-1148 nm. This broad spectrum allows us to calculate vegetation indices that measure physiological status, nutrient and water content. We calculated the Normalized Difference Vegetation Index (NDVI, $(R_{780} - R_{670})/(R_{780} + R_{670})$, Rouse et al. 1974) and the Water Index (WI, R_{900}/R_{970}, Peñuelas et al. 1997). NDVI indicates the chlorophyll content and vitality of the vegetation, WI its water content. The spectrometer was held

120 cm above ground and 8–10 measurements were taken per plot; means for each wavelength were calculated per plot. As reference for reflectance, solar radiation was recorded at the same time as the reflectance measurements, so measurements were independent of cloud cover. Plant surface temperature was recorded with a Fluke Ti400 thermal camera (Fluke Deutschland GmbH) which has a resolution of 320 × 240 pixels. Pictures were taken from 120 cm above ground on days without cloud cover. Using LabView Fluke software (National Instruments v.12.0f3) soil and plant pixels were separated and only the temperature of the plants was used for further analysis.

In 2018, in addition to using hand-held devices, spectral reflectance and temperature were recorded using an eBee Classic drone (senseFly, Lausanne) equipped with the Sequoia sensor (Parrot Drones SAS, Paris) to measure reflectance of near-infrared, red-edge, red, and green bands, and a thermoMAP thermal camera (senseFly) with a resolution of 640 × 512 pixel (equal to 14 cm/pixel); both sensors took pictures with 80% longitudinal and lateral overlap. For UAV sensing, the same weather conditions were chosen as for the hand-held devices.

Results and Discussion

The NDVI time line (Fig. 22.2) shows the time shift in ripening between the three groups of varieties—German lines, German hybrids, and Eastern European lines. In both years, the varieties from Eastern Europe senesced earlier, thereby escaping the heat of July. German lines began senescence later but the decrease of the NDVI occurred faster, which suggests that the German lines suffered from the drought in late June and early July, ripened prematurely and did not have enough time to fill the grains (Saini and Westgate 2000). The grains hardened before reaching the final size, which led to small, light grains. In 2017, this was again the case for the German lines but the effect was not so pronounced in the German hybrids, which suggests that the hybrids may be better able to cope with drought stress, although they are not actually bred for such conditions. In 2018, a dry spell in April and May shifted all varieties towards earlier senescence—and the ranking of varieties was different from 2017. The Eastern European lines still senesced first (corresponding to lower NDVI values) but the German lines were now second and the hybrids last. However, in 2018 the hybrid seeds represented the F2 generation from the previous harvest rendering the comparison more difficult as the F2 generation show a genetic breakdown. The NDVI values corresponded with the growth stage, which was recorded weekly during the field trial (data not shown). In both years, the Eastern European varieties ripened first, followed by the German varieties. The difference between the growth stages was about two weeks in mid-May; but due to premature ripening, the plants were ripe at the same time.

The Water Index paints a similar picture (Fig. 22.3). In 2017, due to drought and advancing senescence, WI decreased from 236 days after sowing (DAS) until harvest at 271 DAS. The varieties from Eastern Europe showed the lowest values at given

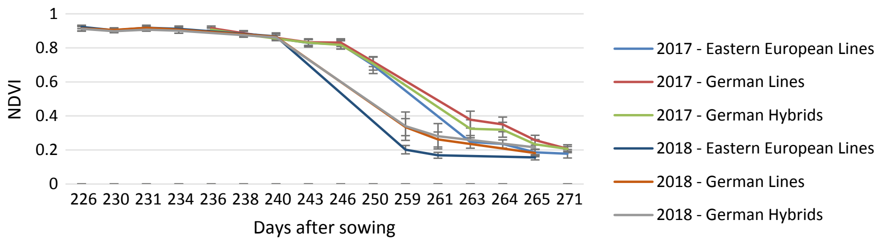

Fig. 23.2 NDVI for 2017 and 2018. Higher NDVI-values indicate higher chlorophyll content. Lower NDVI-values indicate progressing senescence

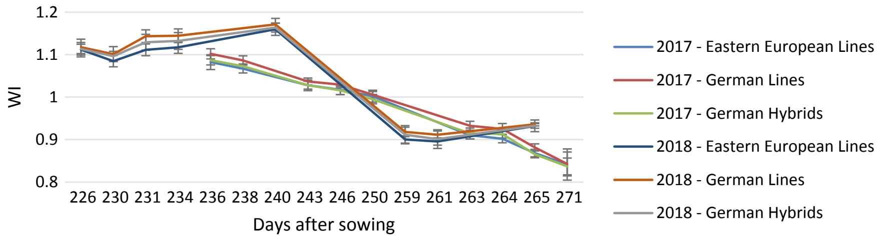

Fig. 22.3 Water Index values in 2017 and 2018

days, hybrids were intermediate, and German lines showed the highest WI-values, indicating increased plant water contents. However, for WI the difference between the varieties was not as distinct as for NDVI. In 2018 WI increased until 240 DAS (May 31, 2018) and decreased rapidly in the following period, reaching a minimum at 261 DAS (June 21, 2018). As shown in Fig. 23.2, NDVI was at a very low level at that time when the plants became senescent. Comparing the increasing WI values after 261 DAS (Fig. 22.3) this signal comes probably comes from weeds which developed thereafter, benefitting from rain in late June.

Figure 22.4a–d illustrates results of the harvest parameters. The most important is the grain yield. Considering that German varieties can achieve up to 8-10t/ha under favourable conditions, a strong reduction can be seen in 2017. Whereas varieties from Eastern Europe reach their average yield level, the yields of German lines and hybrids were impaired. As already seen in the NDVI relationships with grain yield, the hybrids seem to cope better with stress than the German lines, but the difference was not significant. This effect is also visible in the yield data for 2018, though the plants took advantage of additional rainfall and yields were better than in the first year. Very similar results were obtained for the thousand-grain weight (TGW) (Fig. 22.4b). The German varieties, both hybrids, and lines, had significantly lower TGW than the Eastern European lines which, again, suggests premature ripening and failure to store enough starch in the grains. The effect of small, light grains was less marked in 2018 due to rainfall during grain filling when the German varieties were

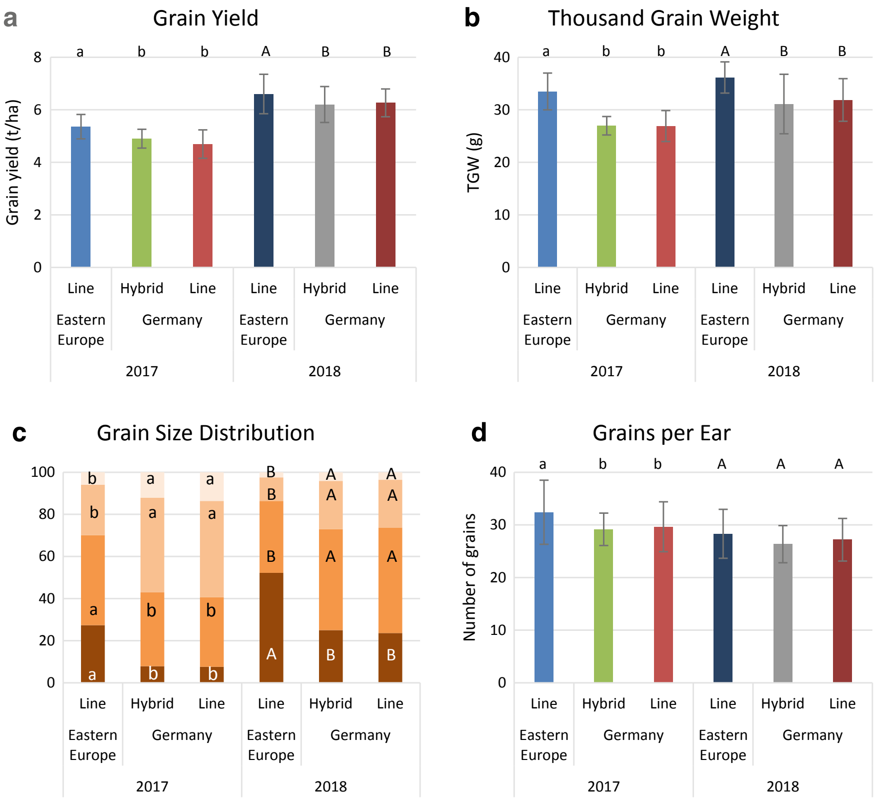

Fig. 22.4 Harvest parameters of the field trials in 2017 and 2018: **a** grain yield (t/ha), **b** thousand grain weight (g), **c** grain size distribution, sizing (shades of gold): >2.8 mm, 2.8–2.5 mm, 2.5–2.2 mm, <2.2 mm, **d** number of grains per ear. Significances were tested within a year and (4c) within one grain size

still green. The Eastern European varieties were already senescing so could hardly benefit from the additional rainfall.

As the number of grains per ear (Fig. 22.4d) showed an opposite effect—less grains per ear in 2018 than in 2017—it can be assumed that larger grains rather than more grains per ear accounted for the extra yield in 2018. Dolferus et al. (2011) found that the grain number is determined before anthesis. In 2018 there was little precipitation until mid-June which may have resulted in a low number of grains, especially for the German varieties. Following, at anthesis and during grain filling, there was more rain resulting in heavier grains than in 2017. This is confirmed by the grain size distribution (Fig. 22.4c): 52% of the grains from Eastern European varieties in 2018 were bigger than 2.8 mm, noticeably more than in 2017 (27%) but, also, significantly higher than the proportions for German hybrids (25%) and German lines (24%) in 2018. For the smaller grain sizes, the effect is opposite. In both years, the proportions of grains, e.g. 2.5–2.2 mm, was smaller for Eastern European varieties (2017, 24%;

2018, 11%) than for German hybrids (2017, 45%; 2018, 23%) and lines (2017, 46%; 2018, 23%). Overall, the difference between Eastern European and German cultivars was significant, however not between German lines and hybrids.

Table 22.2 shows correlations between grain yield and non-destructive measurements of vegetation indices and temperature. In 2017 there was significant correlation between the NDVI and grain yield during grain filling until harvest (250 DAS–271 DAS).

Towards the end of the growing season, the correlation became closer. Plants that were still green (higher value of NDVI) were yielding less at harvest. This was the case for the German varieties and is in line with the above-mentioned results of the NDVI and the harvest parameters. In 2018, the correlation between grain yield and NDVI was not as strong shortly before harvest, and no longer significant at 265 DAS. This supports our findings that the German varieties were able to take advantage of late rains, leading to higher yields than in the previous season. Correlation at anthesis and shortly thereafter in 2018 (230 and 234 DAS) were significant and positive, which

Table 22.2 Correlation (Pearson's *r*) of grain yield with vegetation indices (NDVI, WI) and grain yield with plant canopy temperature (Fluke), respectively

2017	BBCH					
German lines	57	63	72	75	81	90
German hybrids	60	66	74	76	81	91
Eastern European lines	65	66	74	78	86	92
Date	1.6	7.6	14.6	21.6	28.6	5.7
Days after sowing	236	243	250	261	264	271
NDVI	0.10	0.08	**−0.19***		**−0.68***	**−0.53***
WI	−0.18	−0.08	0.01		**−0.47***	−0.16
Fluke		−0.16	0.04	−0.11		0.06
2018	BBCH					
German lines	65	68	71	76	81	88
German hybrids	66	69	72	77	82	88
Eastern European lines	70	72	74	79	86	89
Date	21.5	25.5	31.5	14.6	19.6	25.6
Days after sowing	230	234	240	254	259	265
NDVI	**0.25***	**0.28***	0.17		**−0.38***	−0.05
WI	0.10	0.03	**0.23***		**−0.34***	−0.26
Fluke	−0.09	−0.12	0.05	0.10	0.02	
NDVI eBee			**0.32***	**−0.30***		
Temperature eBee			−0.05	−0.05		

Correlations were calculated for all varieties, BBCH growth stages (Meier 2018) and are presented for the origin groups separately. In 2018, the NDVI and temperature was additionally measured twice with the drone (NDVI eBee, Temperature eBee). Bold numbers and *mark significant correlations was not the case in 2017. WI was significantly correlated with grain yield only at 264 DAS (2017), and 240 DAS and 259 DAS (2018). For 2017, the strong negative correlation is in line with the negative correlation with the NDVI—plants that are green also show higher WI values. In 2017, this resulted in premature ripening causing substantial decreases in yield. Higher WI values at the beginning of grain filling seem to be positively correlated with grain yield, however, this relation was only observed at one single day and needs to be verified in future trials. At 259 DAS 2018, there was a significant negative correlation for the same reason as in 2017 but, as for the NDVI, this correlation was weaker than in 2017 due to the late rains and consequent recovery in grain yield. Temperature data from the hand-held Fluke camera were not significantly correlated and showed much the same low values as the thermal measurements with the drone. NDVI values measured with the drone showed correlations at two days (240 and 254 DAS, 2018) but did not correspond with the values obtained with the HandySpec at 240 DAS. We have only a few days' measurements to compare drone data with those of the hand-held sensors, so we need more to arrive at reliable results.

However, the drone offers an important advantage: carrying the thermal camera across the field trial (120 plots in total) took about 45 min; the drone has a flight time of 5–10 min covering the same area, depending on wind speed and picture overlap. The time difference can cause a bias in the collected temperature data, which can be avoided using the drone. This is not so crucial for NDVI measurements because NDVI does not change so much throughout the day. Disadvantages of the drone are the dependence on wind conditions, laborious data processing afterwards, and the lack of capacity to separate plant pixels from soil pixels at this resolution and flying height. Nevertheless, they can certainly support phenotyping and breeder's decisions.

Conclusions

The results demonstrate that the wheat varieties from Eastern Europe have advantages over German lines and hybrids under hot and droughty conditions. Hybrids show somewhat better performance than German lines but, still, suffer a severe yield reduction compared with the same hybrids grown under a temperate climate. Rainfall during anthesis can help the German varieties to reduce the losses, which indicates that the plants suffer more from drought than from heat, and can withstand heat better with enough water availability. Phenotyping wheat in an environment with abiotic stress helps to identify Eastern European varieties that may be used to improve wheat breeding for future climatic conditions.

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Chapter 23
New Safflower Oil Crops in Russia: Agronomy and Adaptability

Sulukhan Temirbekova, Yulina Afanasyeva, Galina Metlina, Sergey Vasilchenko, and Elena Kalashnikova

Abstract Long-term studies of the biology, morphology, and phenology of safflower cultures introduced to the Central, Volga, and North Caucasus regions have proven the new varieties *Krasa Stupinskaya* and *Pamyati Kapitona Novozhilova* as cover crops for fodder, oilseed and green manure. They do well on sod-podzolic soils. An adaptable technology has been developed for growing the new cultures and, for the first time, relationships are established between temperature and water availability during the growing season, yield of edible oil and its fatty-acid composition—characterized by a high content of oleic and linoleic acids. These varieties are recommended for further breeding programs to improve productivity and oil yield.

Keywords Safflower · Oilseeds · Agronomic characteristics · Adaptability · Disease

Introduction

Vavilov (1967) attached special importance to bringing new species into cultivation to make fuller use of the world´s wild flora. Following his lead, progress has been made in economically viable cultivation of new crops in the more northern areas of Russia (Zhuchenko 2009–11). One of these crops is safflower (*Carthamus tinctorious* L.),

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native to Egypt and India. This is advantageous because edible oils and biologically active substances are mostly imported and crops like safflower promise greater self-sufficiency. Plant breeding aims to increase harvest size and quality by better adapting the culture to the environment, including resistance to diseases and abiotic stress.

Our aim was to introduce safflower in the Central region of Russia, study its characteristics, create varieties adapted for agricultural production and food processing, and develop the technology for its cultivation. Many years of work at the All-Russia Selection-Technological Institute of Horticulture and Nursery and the All-Russia Research Institute of Phytopathology has bred two new safflower cultivars: *Krasa Stupinskaya* and *Pamyati Kapitona Novozhilova.* The former was included in the State Register of Selection Achievements in 2013 (patent № 6930), the latter in 2019 (patent №10,155). These cultivars are recommended for all regions of the Russian Federation as cover crops for fodder, green manure, promising oilseed cultures, and ornamental plants. Best of all, they do well on sod-podzolic soils.

Materials and Methods of Research

The work has been carried out in the Centre of Plant Gene Pool and Bio-resources, All-Russian Selection-Technological Institute of Horticulture and Nursery at Mikhnevo in the Moscow region in 2005–2015, and from 2012–2015 at the All-Russian Research Institute of Grain Crops at Zernograd in Rostov Region and at the Mummovskoe farm of the Russian State Agricultural University—Moscow Timiryazev Agricultural Academy in Saratov region. A comparative study was made of the performance of the cultivar *Krasa Stupinskaya* and its economically valuable features in four regions: Central Federal District (Mikhnevo, Moscow Region), Volga Federal District (Saratov Region), Southern Federal District (Rostov Region) and Central Tajikistan. Phenological observations and biometric assessment were conducted using the Methodology of State Testing of Agricultural Cultures (1983). Harvest definition was carried out on triplicate sample plots, each 10 m^2. The oil content of the seed was determined according to GOST10857 *Oilseeds*, and the fatty acid composition of the oil by GOST30623-98 *Vegetable oils and margarine. Detection method of falsification.*

Agronomic Characteristics of *var. Krasa Stupinskaya*

Krasa Stupinskaya is an annual herb with a tap root that penetrates to 10–20 cm in the northern regions but to 1.5–2 m in the southern regions and Central Tajikistan. The stem is glabrous, erect, branching, and up to 90 cm tall. Leaves are sessile, oval or elliptical lanceolate and fringed with small teeth that end with spines. The dense flower heads (capitula) are 1.5–3.5 cm in diameter, from 5–7 to 20–50 per plant; the flowers are tubular, yellow, or orange in color. The seeds (achenes) are shiny, akin to sunflower, their hard shell makes up 40–50% of the seed weight; they germinate at a soil temperature of 1–2 °C but do better when the soil warms up to 5–6 °C.

Seed was sown at Mikhnevo between 7 and 11 May, in Saratov region on 7 May, in Rostov region on 26 April, in Central Tajikistan on 20–25 December and, also, a spring sowing between 10 and 15 April. Germination was good and seedlings appeared in 3–8 days. The period from budding until flowering was 18–23 days; flowering lasted 29–35 days. Harvesting took place at Mikhnevo on 23 August, in Rostov on 12 August, in Saratov on 16 August, and in Central Tajikistan on 7–10 April and 28 June - 2 July. The growing season from germination to maturation was 96–115 days in Moscow region, 93–95 days in Rostov, 89–103 days in Saratov, and 110 days in Central Tajikistan.

Calculation of harvest indicators gave the following results:

Number of plants per 1 m^2: 26 in Mikhnevo, 30 in the Rostov region (planted for seed), 62 in the Saratov region (planted for forage)

Plant height: 63–80 cm in all regions

Thousand seed weight: Mikhnevo in 2010—50.0 g, in 2011—51.1 g, 2012—48.0 g, 2013 – 30.3 g, 2014—45.2 g, 2015—44.7 g; in Saratov in 2013—30.9 g, 2014—48.1 g, 2015—43.8 g; in Rostov in 2012—42.3 g, 2013—53.4 g, 2014—42.6 g, 2015—46.1 g; and an average of 34.3 g in Central Tajikistan

Seed yield: Moscow region in 2013—0.4 t/ha, 2010–2012—0.8 t/ha, 2014–2015—0.8 t/ha; in Saratov in 2013—0.9 t/ha, 2014—2.0 t/ha, in 2015—0.9 t/ha; in Rostov—1.25 t/ha in 2012, 0.6 t/ha in 2013, 2014—1.1 t/ha, 2015—0.9 t/ha. The average yields in 2010–2015 were 0.7 t/ha in the Moscow region, 0.9 t/ha in Rostov, 1.2 t/ha in Saratov and 1.7 t/ha in Central Tajikistan.

Green manure crops are important for replenishing soil organic matter so expanding the range of green manure crops helps sustainability (Kurilo et al. 2010) and using green manure ensures that the produce is not contaminated by chemicals. A crop of white mustard can provide 90 kg N/ha, which is the same as 20 tonne of manure; lupins can fix and store up to 160 kg N/ha, which is equivalent to 30-35tonne manure. The dry matter yields of the above-ground safflower ranged between 9.1 and 10.0 t/ha, and the below-ground parts from 1.3 to 1.6t/ha. Ploughing in the post-harvest root residues returns 8.5 kg N/ha; ploughing in the whole green mass returns 120kgN/ha, comparable to the average for blue lupin (140 kg/ha). In terms of P_2O_5, safflower green mass corresponds to as much as 40 kg/ha; and ploughing in safflower at the flowering stage increases exchangeable potassium.

Safflower as a Break Crop

A break of safflower controls weeds for the following cereals: in the case of spring barley by up to 24 pieces of viable and germinating seeds (pcs)/m^2 or 62% (2008–2009); and for spelt by 11 pcs/m^2 or 89% (2013–2014) after two years of safflower

Fig. 23.1 Safflower crop 2013 (left) and its effects on the following spelt crop in 2014 (right)

Fig. 23.2 *Krasa Stupinskaya* in bud

(Fig. 23.1). Reduction of infestation in barley and spelt crops after mustard, white and blue lupin averaged was 17–20 pcs/m^{2} or 20% (Fig. 23.2).

Safflower as a Fodder Crop

We found that 100 kg safflower green mass was 76% moisture and contained 22.75 feed units of digestible protein; 100 kg silage was 83% moisture with 15 feed units (1.3 kg of digestible protein); 100 kg of safflower oil cake contained 75.5 feed units.

Fig. 23.3 Safflower flowers and honey

Decorative and Honey Culture

Safflower is an attractive plant with yellow, orange, and red flowers that can beautify the garden as well as the landscape. Long-flowering, bright colours, and fragrance please the senses. Safflower honey has a golden-orange colour (Fig. 23.3).

Safflower Oil Content and Composition

Increasing the oil content of the seed is now a priority. Vavilov attached great importance to studies of variation within the species for chemical signs of quality grades. He repeatedly emphasized the need to identify genetic differences that can be found in different locations. Qualitative differences are determined by genetic characteristics and selection for the quality of oil, as well for technical and nutritional use, require knowledge of genotypic variability of the fatty-acid composition across the range of cultivated species and wild relatives. The oils of different crops include fatty acids with C_{16} to C_{22} chains with one, two, or three double bonds. Within various crop species and individual varieties, biotypes may be characterized by increased or reduced content of typical fatty acids. These features are inherited so individual variability is the basis of selection to increase the concentrations of some fatty acids and decrease concentrations of others and, within each variety, we find various phenotypes that differ in features like oil content and quality (Temirbekova et al. 2018).

Oil quality can be enhanced by increasing the content of the main fatty acids (oleic and linoleic). The variability in the content of linoleic acid in different growing seasons is probably due to an extended flowering period and the late maturing of certain cultures. It is known that environmental conditions influence the accumulation

Table 23.1 Safflower var. *Krasa Stupinskaya* oil percentage, 2012–2014

Indicator	Sample					
	Rostov region, 2012	Rostov region, 2013	Rostov region, 2014	Moscow region, 2012	Moscow region, 2013	Moscow region, 2014
Oil content (fat mass fraction), %	14.50	19.02	23.70	22.92	6.40	30.20

of oleic and linoleic acids and, in all sunflower varieties, intensive accumulation of linoleic acid has been observed in more northerly areas compared with the south (71.7–72.0% and 53.7–59.0%, respectively); high linoleic acid content is associated with a low concentration of oleic acid (16.9–17.9% and 29.0–36%, respectively).

In the case of safflower, oil accumulation depends on the rainfall or wet soil conditions during flowering and ripening phase (Table 23.1). We noticed that the oil content depends not only on rainfall but, also, temperature. Oil formation benefits from moderate rainfall and temperatures above 18 °C during flowering and ripening. In the atypical weather conditions of 2013, the oil content of safflower seed grown in the Rostov region was 12.6% higher than that in safflower grown in the Moscow region (6.4%). In 2014, the oil content in the Moscow region was 30.2%, 6.5% higher than in Rostov region (23.7%). Table 23.2 highlights the influence of the weather on the oil content of safflower seeds in contrasting years. The growing season in 2010 was warm (18.8 °C compared with the long-term mean of 15.1 °C) as well as dry (154.4 mm) and the oil content of the seed was 31.2%. In 2011, rainfall was

Table 23.2 Influence of agro-biological factors on oil content in var. *Krasa Stupinskaya*, 2010–2015

№	Sample	Oil content (fat mass fraction) (%)	Precipitation (mm)		Temperature (°C)	
			Multi-year mean	Growing season	Multi-year mean	Growing season
1	Moscow region 2010	31.2	264	154.4	15.1	18.8
2	Moscow region 2011	29.0	264	285.5	15.1	17.8
3	Moscow region 2012	22.3	264	245.8	15.1	17.8
4	Moscow region 2013	6.4	264	335.8	15.1	18.4
5	Moscow region 2014	30.2	264	184.1	15.1	16.4
6	Moscow region 2015	30.9	264	348.4	15.1	18.9
7	Central Tajikistan 2015	34.3	510	306.8	16.8	20.5

Table 23.3 Fatty acid composition of safflower oil in 2013–2014

Fatty acids	Mass fraction of fatty acids, % of total fatty acids			
	Mahalli 260 (Tajikistan), 2013	*Krasa Stupinskaya* 2013	*Krasa Stupinskaya* 2014	Norms according to GOST 30,623–98
$C_{14:0}$ Myristic	0.1	0.1	0.1	<1.0
$C_{16:0}$ Palmitic	7.6	7.7	9.9	2.0–10.0
$C_{16:1}$ Palmitoleic	0.2	0.1	0.6	< 0.5
$C_{18:0}$ Stearic	2.6	2.0	2.5	1.0–10.0
$C_{18:1}$ Oleic	13.2	13.6	16.9	7.0–42.0
$C_{18:2}$ Linoleic	75.6	75.7	65.9	55.0–81.0
$C_{18:3}$ Linolenic	0.2	0.1	–	<1.0
$C_{20:0}$ Arachidic	0.3	0.4	–	<0.5
$C_{20:1}$ Gondoic	0.2	0.3	–	<0.5

285.5 mm and the temperature 17.8 °C, 2012 had optimal warmth (17.8 °C) and less humidity (245.8 mm) and the oil content was 29.0 and 22.3, respectively. In 2013, rainfall was 335.8 mm, temperature18.4 °C, and the oil content only 6.4%. In 2014, rainfall was 184.1 mm and temperature 16.4 °C, and the oil content 30.2%. In 2015, the oil content was 34.3% in Central Tajikistan and 30.9% in the Central region of the Russian Federation.

Weather conditions also influenced the oil content in the new variety *Pamyati Kapiton Novozhilov* in 2019: rainfall during the growing season was 385 mm, air temperature was 19–22 °C; the oil content in the seeds was only 7.3%; and the crop suffered enzyme-mycotic depletion of the seeds (Figs. 24.6–24.9).

Safflower varieties differ in the fatty acids ratio of their oil (Table 23.3).

Judged by the content of linoleic acid (which is not synthesized in the human body), *Krasa Stupinskaya* is equal to the southern variety *Mahalli 260*, famous for its good oil content; and judged by the content of oleic acid, responsible for preserving the freshness of the oil over a long period, *Krasa Stupinskaya* exceeds other varieties. In the Central region of Russia, the oil yield of *Krasa Stupinskaya* is 240 kg/ha at plant density of 250–300 thousand/ha and the seed yield is 0.8t/ha; in warm Central Tajikistan, its oil yield is near 940 kg/ha at plant density of 160 thousand/ha and the seed yield 1.7 t/ha.

Place in Crop Rotation and Tillage

Productivity and product quality depend on farm practice. It is necessary to take account of the crop's agronomic needs and characteristics and match these with complex actual soil patterns and hydrothermal regimes. Technical equipment, financial condition, and agronomic management also matter, so the potential yield and economic effect of the introduction of a new culture will depend on timely use of cultivation technology adapted to local conditions, taking into account all these factors.

The best precursors of safflower are demanding crops like potatoes. Safflower itself is undemanding: it does well even on poor, sod-podzolic soils in Moscow region; seedlings can withstand 3–5 degrees of frost and the crop needs only enough heat in the phase of flowering and ripening; but the oil content in the seeds depends on temperature. Under optimum rainfall during the growing season (255-265 m) and moderate temperatures (15–18.2 °C), the oil content may attain 30.5%. However in cold, cloudy, wet conditions (not typical for the region), the yield and oil content in seeds is low and enzyme-mycotic exhaustion causes many empty seeds.

Cultivation

The stubble of the previous crop was disked to a depth of 8–10 cm July. In the Central region and in Privolzhskiy region of the Russian Federation, the soil for safflower was prepared in the fall by ploughing to a depth of 20–25 cm; in the North Caucasus region, around Rostov, and in Central Tajikistan the soil was ploughed to 25–27 cm. Deep ploughing suppresses root rot and other pathogens and promotes robust growth of safflower in the following year but it accelerates the loss of soil organic matter. In the spring, the soil was harrowed in two–three tracks to a depth of 8–10 cm and 6–8 cm before sowing.

Seed Preparation and Sowing

The productivity and oil content of *Krasa Stupinskaya* is highly dependent on the seed quality. Seeds for sowing must be aligned, large, and have a purity of 95–100% for better than 90% germination (Fig. 23.4).

Sowing is in early spring: in Rostov and Saratov regions, this is at the end of April and beginning of May. In Central Tajikistan, two sowing periods are possible: winter (December) and spring (March–April). The yield of safflower is very dependent on the sowing date; delay shortens the growing season. Seeding depth is 5–6 cm; the seed rate is 12–15 kg or 300–350 thousand/ha (250–300 thousand/ha in the Moscow region). After planting, the field should be rolled. Shoots appear 7–10 days after seeding but, in sod-podzolic soil, a hard crust may prevent seedling emergence. In this case, light pre-emergence harrowing is needed within 5–7 days and again when the second pair of true leaves appear. Plant density in the phase of full shoots is 20–30 pcs/m^2; weediness ranges from 50 to 200 pcs/m^2. Flowering begins after 60–75 days and lasts 1–1.5 months. From flowering to ripening is 38–45 days. The growing season across the four regions is 89–115 days.

Fig. 23.4 Safflower seeds for sowing

In wet years, both *Krasa Stupinskaya* and *Pamyati Kapitona Novozhilova* were afflicted by enzyme-mycotic exhaustion seeds (EMIS) (Figs. 23.5, 23.6, 23.7, 23.8 and 23.9), a biological injury on the vine during seed formation that causes cracking of the seed coat, invasion of pathogens, mass seed destruction by *Alternaria, Fusarium, Botrytis* and *Sclerotinia* and, eventually, poor-quality seed. Pests of safflower include wireworms and cutworms; specific pests include sage scoop and safflower fly but, at

healthy seed	cracks (trauma) low degree	split (injuries) strongly + settling alternaria	settling alternaria + grey mould

Fig. 23.5 Development of enzyme and mycotic stage of EMIS

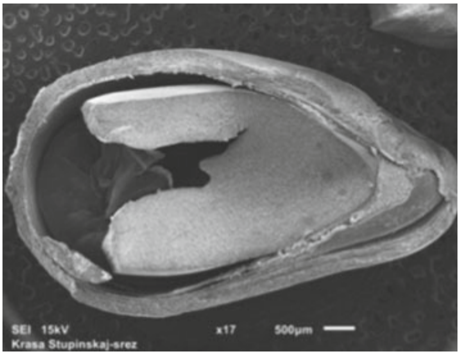

Fig. 23.6 Longitudinal section, healthy seed (×17)

Fig. 23.7 Biological injury followed by infection with *Alternaria carthami* (×16)

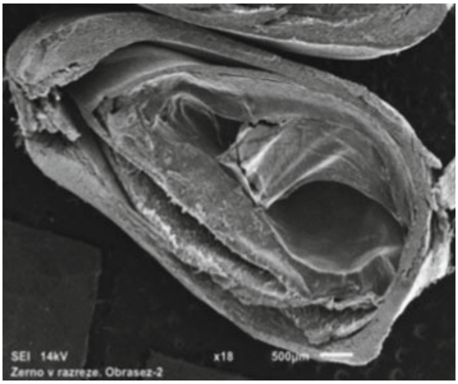

Fig. 23.8 Leakage of biopolymers decomposed by hydrolysis enzymes from safflower seeds of variety *Pamyati Kapiton Novozhilov* (×16)—hollow (hidden biological trauma)

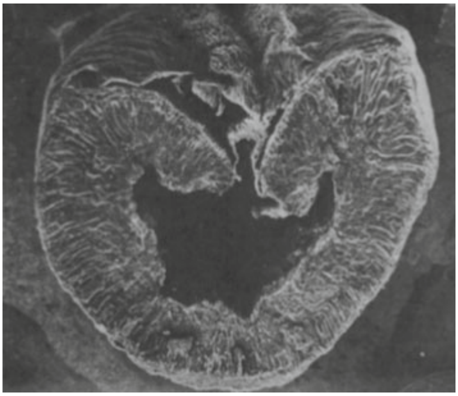

Fig. 23.9 Leakage of biopolymers of wheat grain under the influence of the enzyme stage EMIS—hollow (×145)

present, they are absent in the Central region. In its native habitat, safflower is subject to rust, which has not yet appeared in the Central and North Caucasus regions, and *ramulyarioz* which is manifest as yellow–brown spotting on leaves.

Pollination

To make good seed, pollination by bees is recommended. Hives should be placed near or in the crops at the rate of 1 swarm of bees/ha.

Harvesting

Maturation is almost simultaneous. This completely stops photosynthesis and the leaves wither. The seed doesn't shatter and, if the weather is dry, it is necessary to wait for complete drying before threshing when the moisture content of the seed is about 8–12%. Harvesting is by a conventional combine harvester set for a high cut, but not higher than 10 cm from the lowest productive branch. After threshing, the seeds are cleaned and stored with humidity no higher than 10–12%, otherwise pathogens reduce germination. Crop residue may be used to feed livestock.

Conclusions

1. The new safflower cultivar *Krasa Stupinskaya* quickly adapts to contrasting soil and climatic conditions in several regions of the Russian Federation. It is a first-class break crop and green manure.
2. Safflower is a promising source of high-value edible oil. It matures almost a month earlier than sunflower so it facilitates uninterrupted delivery of raw materials to the mills.
3. In India, which is the world leader in safflower production, the flowers rather than the seeds are collected for use in dyeing textiles and, also, as a food colourant.
4. The honey and flowers of safflower are of special value: in both China and Kazakhstan, the flowers are used as herbal medicine for hypertension, coronary heart disease, and stroke.

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Chapter 24
Agronomic Benefits of Perennial Crops and Farmyard Manure in Crop Rotations

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Abstract Specialization and concentration of agricultural production have neglected the benefits of perennial crops and farmyard manure in the crop rotation. Historically, integration of cropping and livestock was the main tool for restoration of soil fertility, and it increased the production from both sectors. Current market-driven intensification through specialisation has been accompanied by soil degradation and pollution of the environment. The advantages of a crop rotation that includes perennial grasses and legumes together with the application of farmyard manure are proven by data obtained in a long-term poly-factorial experiment with different crop rotations, systems of soil tillage and systems of soil fertilization, but without using pesticides. Inclusion of perennial legumes in diverse crop rotation together with the application of manure cuts the need for mineral fertilizers and the plough and increases the stocks of soil organic matter.

Keywords Crop rotation · Tillage · Soil fertilization · Perennial legumes and grasses · Soil organic matter

Introduction

The industrial model of agricultural intensification that evolved in the mid-twentieth century increased crop yields and the productivity of labour by specialisation, simplification, industrial inputs and exploitation of fossil fuels. Local, renewable sources of energy and on-farm nutrient cycling were neglected. Production increased four-fold; the prices paid by the consumer fell; but the price paid by the planet has been soil degradation and, pollution of air, water and soil; loss of biodiversity; global heating; social consequences that are harder to measure (Boincean and Dent 2019; Gliessman 2000; Magdoff and Weiln 2004; Whalen and Sampedro 2010). If we accept that things cannot go on like this, we must find an alternative. However, most agronomic recommendations are based on the results of experiments where each factor of intensification is studied separately, and our study seeks to establish not

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only the direct actions, but also the interactions between the main components of the farming system: alternation of crops, systems of soil tillage and fertilization.

Experimental Site and Methods

The Selectia long-term poly-factorial field experiment on *Typical Chernozem* heavy loam was established in 1996. The sequences of crops in the two rotations are:

I	II
1. Lucerne + ryegrass	1. Maize silage
2. Winter wheat	2. Winter wheat
3. Sugar beet	3. Sugar beet
4. Corn-for-grain	4. Corn-for-grain
5. Winter barley	5. Winter barley
6. Maize for green mass under-sown with lucerne and rye grass	6. Peas-for-grain
7. Lucerne + rye grass	7. Sunflower

Tillage is by (1) alternation of the mouldboard plough with ploughless tillage or (2) entirely ploughless tillage. The systems of fertilization are: (1) the control (without fertilization), (2) composted farmyard manure and (3) farmyard manure + mineral fertilizers. For crop rotation I, the average application of organic and mineral fertilizers per ha of crop rotation is 10t/ha farmyard manure + $N_{12.8}$ $P_{21.4}$ $K_{24.2}$ kg a.i/ha; for crop rotation II, 10 t/ha farmyard manure + $N_{38.6}$ $P_{24.2}$ $K_{24.2}$ kg a.i/ha. No chemicals are applied to control weeds, pests and diseases. There are three replicates. Each plot is 264 m^2 making a total experimental area of 8.7 ha. Simultaneously, trials have been conducted with continuous cropping of winter wheat, winter barley, sugar beet, corn-for-grain and sunflower under the same conditions but without replication. Here, we report only the results obtained during the last five years in the same crop rotation link for both crop rotations: winter wheat—sugar beet—corn-for-grain.

Table 24.1 summarizes the weather for 2015–2019. The annual average temperature was 1.7 °C higher than the long-term mean; spring and summer temperatures higher by 2.6 and 2.2 °C, respectively, autumn and winter temperatures higher by 0.8 and 1.1 °C, respectively. Annual precipitation was 15.1 mm higher than the long-term mean; precipitation in spring exceeded the long-term mean by 63.6 mm; precipitation in autumn was 39.3 mm lower than the long-term mean, which is problematic for sowing winter cereals. During the last two years, winter cereals have germinated late, even in mid-winter when the fate of the crop depends on the early spring weather.

Table 24.1 Precipitation and air temperature for agricultural years 2015–2019, Selectia RIFC, Bălţi

Months	Average temperature, °C			Precipitation, mm		
	Monthly	Multi-annual	± from multi-annual	monthly	Multi-annual	± from multi-annual
September	17.3	15.8	+1.5	16.8	36.0	−19.3
October	12.2	9.7	+2.5	2.0	33.0	−31.0
November	2.4	4.0	−1.6	45.0	34.0	+11.0
Autumn	10.6	9.8	+0.8	63.8	103.0	−39.3
December	−1.3	−1.0	−0.3	19.8	27.0	−7.3
January	−3.6	−3.4	−0.2	37.8	22.0	+15.8
February	1.8	−1.9	+3.7	14.5	22.0	−7.5
Winter	−1.0	−2.1	+1.1	72.0	71.0	+1.0
March	9.7	2.8	+6.9	16.5	22.0	−5.5
April	10.2	10.3	−0.1	79.3	31.0	+48.3
May	17.1	16.1	+1.0	69.8	49.0	+20.8
Spring	12.3	9.7	+2.6	165.6	102.0	+63.6
June	24.8	19.5	+5.3	77.0	62.0	+15.0
July	20.6	21.2	−0.6	50.8	58.0	−7.3
August	22.5	20.6	+1.9	31.0	49.0	−18.0
Summer	22.7	20.4	+2.2	158.8	169.0	−10.3
Annual	11.2	9.5	+1.7	460.1	445.0	+15.1

Results and Discussion

Tables 24.2a and b present the yields of crops in two crop rotation links under different systems of fertilization and tillage, and the extra yields resulting from including the mixture of perennial legumes and grasses in the rotation. The *extra yields* from including the mixture of perennial legumes and grasses in crop rotation on plots cultivated with a combination of mouldboard plough and ploughless tillage were:

For Winter Wheat

- Control, without fertilization +2.2 t/ha or 48%
- With farmyard manure +1.4 t/ha or 30%
- With farmyard manure + NPK +0.2 t/ha or 4%.

For Sugar Beet

- Control, without fertilization +5.0 t/ha or 17%
- With farmyard manure −1.2 t/ha or 4%
- With farmyard manure + NPK −1.6 t/ha or 5%.

Table 24.2 Crop yields in rotations with and without perennial legumes and grasses 2015–2019, t/ha/%

Crops	Crop rotation with perennial legumes and grasses			Crop rotation without perennial legumes and grasses			Extra yields from perennial crops		
	Unfertilized control	Farmyard manure	Farmyard manure + NPK	Farmyard manure	Unfertilized control	Farmyard manure + NPK	Unfertilized control	Farmyard manure	Farmyard manure + NPK
(a) *Combination of mouldboard plough and ploughless tillage*									
Winter wheat	4.64	4.65 4.65	4.73	2.44	3.26	4.53	+2.2/48%	+1.40/30%	+0.20/4%
Sugar beet	29.56	33.3	34.1	24.54	34.52	35.70	+5.02/17%	−1.22/4%	−1.60/5%
Corn-for-grain	5.70	5.77	5.62	4.51	4.95	5.40	+1.19/21%	+0.82/14%	+0.22/49%
(b) *Ploughless tillage*									
Winter wheat	4.25	4.50	4.64	2.43	3.36	4.42	+1.83/43%	+1.14/25%	+0.22/5%
Sugar beet	29.2	32.74	31.74	24.62	35.0	33.22	+4.60/16%	−2.26/7%	−1.48/5%
Corn-for-grain	6.15	6.0	5.92	4.70	5.18	5.24	+1.47/24%	+0.81/14%	+0.68/12%
± *from combination of mould board plough and ploughless tillage*									
Winter wheat	+0.39/8%	+0.15/3%	+0.09/2%	+0.01/0.4%	−0.10/3%	+0.11/2%	–	–	–
Sugar beet	+0.36/1%	+0.56/2%	+2.36/7%	−0.08/0.3%	−0.48/1%	+2.48/7%	–	–	– –
Corn-for-grain	−0.46/8%	−0.23/4%	−0.30/5%	−0.19/4%	−0.23/5%	+0.16/3%	–	–	–

For Corn-for-Grain

- Control, without fertilization +1.19 t/ha or 21%
- With farmyard manure +0.82 t/ha or 14%
- With farmyard manure + NPK +0.22 t/ha 4%.

The greatest increase in yields was achieved on unfertilized plots. Application of farmyard manure to sugar beet negates the benefit of perennial legumes and grasses in the rotation and reduces any residual effect on the following grain crops. Supplementing the farmyard manure with mineral fertilizers quite eliminates the benefit of including perennial legumes and grasses in the rotation.

With only ploughless tillage, the extra yields from including the mixture of perennial legumes and grasses in crop rotation were:

For Winter Wheat

- Control, without fertilization +1.83 t/ha or 43%
- With farmyard manure +1.14 t/ha or 25%
- With farmyard manure + NPK +0.22 t/ha or 5%.

For Sugar Beet

- Control, without fertilization + 4.6 t/ha or 16%
- With farmyard manure −2.26 t/ha or 7%
- With farmyard manure + NPK −1.48 t/ha or 5%.

For Corn-for-Grain

- Control, without fertilization +1.47 t/ha or 24%.
- With farmyard manure +0.81 t/ha or 14%
- With farmyard manure + NPK +0.68 t/ha or 12%.

The system of soil tillage has a negligible effect on crop yields. In general, fertilization considerably reduces the benefit of the mixture of perennial legumes and grasses in crop rotation. Fertilizer efficiency is greater in the crop rotation without the mixture of perennial legumes and grasses (Table 24.3).

Under the combination of the mouldboard plough and ploughless tillage, the extra yields from application of farmyard manure and farmyard manure + NPK were:

For Winter Wheat

- In rotation with the mixture of perennial legumes and grasses: 0.02 and 0.09 t/ha (0.4 and 2%), respectively
- In rotation without perennial legumes and grasses: 0.82 and 2.09 t/ha (33 and 86%), respectively.

Table 24.3 Extra yields from fertilization in crop rotation with and without perennial legumes and grasses, 2015–2019

Crops	Rotation with perennial legumes and grasses		Rotation without perennial legumes and grasses	
	Farmyard manure (%)	Farmyard manure + NPK (%)	Farmyard manure (%)	Farmyard manure + NPK (%)
(a) *Combination of mouldboard plough and ploughless tillage*				
Winter wheat	+0.02/0.4	+0.09/2	+0.82/34	+2.09/86
Sugar beet	+3.74/13	+4.52/15	+10.0/41	+11.16/46
Corn-for-grain	+0.07/1	−0.08/1	+0.44/10	+0.89/20
(b) *Ploughless tillage*				
Winter wheat	+0.24/10	+0.40/17	+0.93/38	+2.0/82
Sugar beet	+3.02/12	+2.74/11	+9.8/40	+8.7/35
Corn-for-grain	+0.43/9	−0.37/8	+1.07/23	+0.50/11

For Sugar Beet

- In rotation with the mixture of perennial legumes and grasses: 3.74 and 4.52 t/ha (13 and 15%), respectively
- In rotation without perennial legumes and grasses: 10 and 11.16 t/ha (41 and 46%), respectively.

For Corn-for-Grain

- In rotation with the mixture of perennial legumes and grasses: 0.07 and −0.08 t/ha (1 and −1%), respectively
- In rotation without perennial legumes and grasses: 0.44 and 0.89 t/ha (10 and 20%), respectively.

Under ploughless tillage, the extra yields from application of farmyard manure and farmyard manure + NPK were:

For Winter Wheat

- In rotation with the mixture of perennial legumes and grasses: 0.24 and 0.4 t/ha (10 and 17%), respectively
- In rotation without perennial legumes and grasses: 0.93 and 2.0 t/ha (38 and 82%), respectively.

For Sugar Beet

- In rotation with the mixture of perennial legumes and grasses: 3.02 and 2.74 t/ha (12 and 11%), respectively.
- In rotation without perennial legumes and grasses: 9.8 and 87 t/ha (40 and 35%), respectively.

For Corn-for-Grain

- In rotation with the mixture of perennial legumes and grasses: 0.43 and −0.37 t/ha (9 and −8%), respectively
- In rotation without the mixture of perennial legumes and grasses: 1.07 and 0.5 t/ha (23 and 11%), respectively.

The experimental data demonstrate that, in crop rotation after the mixture of perennial legumes and grasses, fertilization of winter wheat brings no greater yield. The effect of fertilization, especially supplementary mineral fertilizers, is greater in the crop rotation without the mixture of perennial legumes and grasses. The effect of fertilization is somewhat greater under ploughless tillage.

Sugar beet is more responsive to fertilization in both crop rotations, but the extra yields from fertilization are significantly higher in the rotation without the mixture of perennial legumes and grasses. However, sugar beet does not respond to supplementary mineral fertilizer.

Corn-for-grain does not respond to fertilization in crop rotation with the mixture of perennial legumes and grasses but the effect of fertilization is increases significantly in the rotation without mixture of perennial legumes and grasses.

Conclusions

1. On unfertilized plots, inclusion of a mixture of perennial legumes and grasses in the crop rotation increases the yields for the following crops.
2. Fertilization much reduces the benefit of the mixture of perennial legumes and grasses in the crop rotation.
3. The effect of fertilization is greater in crop rotation without mixture of perennial legumes and grasses, regardless of the systems of soil tillage in crop rotation.
4. Tillage has a negligible effect on yield formation, regardless of the system of fertilization.
5. At the margins, a reduced intensity of tillage increases the benefit of including perennial herbaceous crops in the crop rotation.

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Chapter 25
No-till for Cereal Crops on the Bălţi Steppe of Moldova

Dorin Cebanu, Boris Boincean, Marin Cebotari, and David Dent

Abstract Agriculture across the Steppes faces many challenges. No-till is a promising option for transition to more sustainable farming systems. However, simple replacement of the plough by a ploughless system does not cut the Gordian knot of problems related to crop productivity and soil fertility. Extending Conservation Agriculture requires an holistic approach to farm management oriented towards regenerating soil health that simultaneously cuts the need for soil tillage, synthetic fertilizers, and chemical control of weeds, pests and diseases. Observance of crop rotation is mandatory for adoption of no-till, together with other measures for building soil fertility. Zero tillage of winter cereals after late-harvested predecessors doubles the accumulation of soil moisture during the autumn–winter-spring period relative to conventionally cultivated, early-harvested predecessors, not to mention black fallow.

Keywords No-till · Crop rotation · Field crops · Soil fertility · Soil water stocks

Introduction

Debate about tillage is eternal: How often? How deep? Mouldboard plough, chisel plough, or disc harrow? Why do it all? Liebig (1863) could find no good argument for soil tillage, he thought it useless; and Edward Faulkner (1943) reckoned that the plough had caused more damage to humanity than all wars put together. Ploughing uses more than half of all the time, energy and expense of agriculture to uproot and bury weeds to give annual crops an equal chance in competing against them. The development of desiccant herbicides (paraquat in 1961, glyphosate a decade later) made zero tillage a viable proposition. It now encompasses about 15% of the world's arable (Kassam et al. 2018), embracing not just zero tillage but, just as important, crop rotations that afford continuous protective cover of the soil surface—if not by

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crops then by a mulch of crop residues. But it remains very much a farmers' initiative. When problems have arisen, research has been lagging.

Research has also lagged in Moldova. Our programme could only begin in 2015 thanks to the generosity of Lincolnshire farmer Tony Reynolds who presented us with a Moore Uni-drill, made in Northern Ireland. Indeed, no-till farmers have been ahead of the science everywhere but our intention is to have a national programme of in-field research, conducted in cooperation with the farmers. This direction is much needed considering the increasing frequency of droughts, the increased danger of soil erosion, and the need to cut costs because farm-gate prices for agricultural commodities are not matching the soaring costs of fuel, fertilizers and equipment.

Experimental Site and Methods

The Bălţi long-term field experiments on crop rotation were established in 1962; crops grown in continuous monoculture were added in 1965. The soil is *Typical chernozem* heavy loam. There are eight crop rotations with different proportions of row crops, from 40% up to 70%. The proportion of winter wheat in each rotation is 30% but it is sown after different predecessors: in one field after early-harvested predecessors, in the second after maize silage, in the third after corn-for-grain (Boincean et al. 2021). A long-term experiment on ecological agriculture was added in 1989; the three crop rotations include one without perennial crops and two that include a mixture of lucerne and ryegrass, one of which receives supplementary wheat and barley chaff and maize stover. The four fertilization systems are: (1) unfertilized control, (2) farmyard manure, (3) farmyard manure + PK, and (4) farmyard manure + NPK (Boincean 1999). All these experiments have been carried out with conventional tillage, according to local and regional practice. Direct-drilled winter wheat and winter barley were added in 2015, following corn-for-grain in six crop rotations and in two crop rotations after early-harvested predecessors—field peas and mixture of vetch-and-oats for green mass, respectively. In addition to a base dressing of farmyard manure to the rotation, the cereals receive supplementary $N_{90}P_{30}K_{30}$ a.i./ha. None of the crops is sprayed with herbicide, we depend on crop rotation to control weeds.

Results and Discussion

Table 25.1 presents data for no-till winter wheat and winter barley, averaged for 2015–2019.

Winter barley is more productive than winter wheat in all crop rotations. The *effect of fertilization* is high for both crops: 94–121% extra yield, irrespective of predecessors. In order to distinguish between the residual action of the farmyard manure applied earlier in the rotation and the effect of directly applied mineral fertilizers, we may use data from an adjacent long-term field experiment on ecological agriculture

Table 25.1 Yields of no-till winter cereals in a 10-field rotation with different predecessors and fertilization, 2015–2019

Crop rotations	Predecessors	Fertilization	Winter wheat		Winter barley	
			t/ha	Increase from fertilizers/%	t/ha	Increase from fertilizers/%
7	Corn-for-grain	Unfertilized	1.85	–	2.24	–
3	Corn-for-grain	Manure + NPK	3.64	1.79/97	4.94	2.70/121
2	Peas-for-grain	Manure + NPK	3.82	1.97/107	4.68	2.44/109
4	Corn-for- grain	Manure + NPK	3.73	1.88/102	4.87	2.63/117
5	Corn-for-grain	Manure + NPK	3.59	1.74/94	4.73	2.49/111
8	Vetch-and-oats for green mass	Manure + NPK	4.00	2.15/116	4.76	2.52/113
Dl_{05}			0.18		0.16	

where there are plots with different systems of fertilization in crop rotation, including post-action of farmyard manure for winter cereals; in this rotation, winter wheat is sown after vetch-and-oats for green mass and winter barley follows corn-for-grain (Tables 25.2 and 25.3).

Taking the average yields for 2015–19, the residual action of farmyard manure accounts for an extra 1.16 t/ha yield of winter wheat (30%) but supplementary mineral fertilizers made no significant difference. The extra yield of winter barley was 2.11 t/ha (81%) but supplementary mineral fertilizers actually reduced the yield by 1.99 t/ha (77%). It is clear that the productivity of both winter cereals is determined by the residual action of farmyard manure applied earlier in the crop rotation. Direct application of mineral fertilizers offers no advantage to cereal crops in the rotation. *This also applies under no-till* unless there is a lot of straw after harvest, in which case about 3 kg/ha ammonium nitrate or a commercial bio-decomposer may be applied to avoid temporary nitrogen starvation of the following crop while the soil microorganisms get to work on the stubble. We emphasize this because farmers

Table 25.2 Yields of winter wheat and winter barley in 7-field crop rotation under different systems of fertilization, 2015–2019

Fertilization	Winter wheat after vetch-and-oats		Winter barley after corn-for- grain	
	t/ha	±from fertilizers	t/ha	±from fertilizers
Unfertilized	3.90	–	2.60	–
Farmyard manure	5.06	+1.16/30%	4.71	+2.11/81%
Farmyard manure + NPK	5.07	+1.17/30%	4.59	+1.99/77%

Table 25.3 Effect of crop rotation for winter wheat after early-harvested and late-harvested predecessors, 2015–2019

Crop rotation		Continuous cropping		Effect of crop rotation		Effect of fertilization	
(a) *After vetch-and-oats for green mass*							
Unfertilized	Fertilized	Unfertilized	Fertilized	Unfertilized	Fertilized	In crop rotation	Continuous wheat
3.90	5.07	1.94	3.56	+1.96/101%	+1.51/42%	+1.17/30%	+1.62/84%
(b) After corn-for- grain							
Unfertilized	Fertilized	Unfertilized	Fertilized	Unfertilized	Fertilized	In crop rotation	Continuous wheat
1.85	3.64	1.94	3.56	−0.09	+0.08/2%	+1.79/97%	+1.62/84%

commonly believe that no-till should be accompanied by higher rates of mineral fertilizers as well as herbicide to control weeds. Dependence on mineral fertilizers and herbicides is likely to increase if the plough is replaced by no-till without respecting crop rotation but, otherwise, fertilizers are only appropriate for impoverished soils.

This contention comes from our experimental data. The *effect of crop rotation* (the difference in yields between crop rotation and continuous cropping) is tremendous. For winter wheat sown after vetch-and-oats, the extra yield is 1.96 t/ha or 101% on unfertilized plots, and 1.51 t/ha or 42% on fertilized plots. Remarkably, it disappears when wheat follows corn-for-grain. The *effect of fertilization* for winter wheat sown after vetch-and-oats is 1.17 t/ha or 30%; for winter wheat sown after corn-for-grain in crop rotation it is 1.79 t/ha or 97%; but for continuous wheat, it is 1.62 t/ha or 84% (Table 25.4). For winter barley sown after corn-for-grain in the 7-field rotation, the effect of crop rotation was 1.25 t/ha or 93% on unfertilized plots and 1.02 t/ha or 29% on fertilized plots, respectively (Table 25.5). The effect of fertilization was significantly higher in the 10-field rotation than in the 7-field rotation: 2.7 t/ha or 121% and 1.99 t/ha or 77%, respectively.

Except for corn-for-grain, supplementary fertilizers return a greater extra yield from continuous monocrops than from crop rotations. The general conclusion is that, with a good crop rotation, supplementary mineral fertilizers (and pesticides) are not

Table 25.4 Yields of winter wheat after different predecessors and from continuous wheat, 2015–2019, t/ha

	Predecessors	Fertilization		Effect of fertilization, t/ha/ %	Reduction of yield relative to early-harvested predecessors, t/ha/%	
		Unfertilized	Fertilized		Unfertilized	Fertilized
Crop rotation	Vetch-and-oats	4.16	5.18	+1.02/25	–	–
	Maize silage	3.09	4.87	+1.78/58	−1.07/26	−0.31/6
	Corn-for-grain	1.85	3.64	+1.79/97	−2.31/56	−1.54/30
Continuous wheat	Winter wheat	1.94	3.56	+1.62/84	−2.22/53	−1.62/31

Table 25.5 Effects of crop rotation and fertilization for winter barley sown after corn-for-grain, t/ha and %

Crop rotation		Continuous barley		Effect of crop rotation		Effect of fertilization	
(a) *7-field crop rotation*							
Unfertilized	Fertilized	Unfertilized	Fertilized	Unfertilized	Fertilized	In crop rotation	Continuous barley
2.60	4.59	1.35	3.57	+1.25/93%	+1.02/29%	+1.99/77%	+2.22/164%
(b) *10-field crop rotation*							
Unfertilized	Fertilized	Unfertilized	Fertilized	Unfertilized	Fertilized	In crop rotation	Continuous barley
2.24	4.94	1.35	3.57	+0.89/67%	+1.37/38%	+2.7/121%	+2.22/164%

necessary. This means that no-till cropping should respect crop rotation, especially an alternation of crops that ensures sowing crops after the best predecessor.

We have always considered the best predecessors for winter cereals to be early-harvested crops. However, we find that no-till that maintains a continuous ground cover of crop residues after harvest has the capacity to accumulate more soil water after late-harvested predecessors than conventionally cultivated crops after early-harvested predecessors (Tables 25.6 and 25.7). This demands re-thinking of the opinion that early-harvested predecessors, of themselves, promote accumulation of soil water. We are reminded of the conclusions of Izmailsky (1937), writing in the 1880s, and Dokuchaev (1948) in response to the great drought of 1892, who reasoned that repeated drought and *black storms* were not brought on by climate change but by degradation of the Chernozem following breaking of the sod—in particular, the loss of its protective surface felt of plant residues and degradation of its granular structure—so that it could no longer make the best use of whatever rain came its way. Certainly, systematic research is needed on the role of a surface mulch of crop residues in cutting evaporation from the soil surface and the transmissivity of the soil profile under the plough and under no-till.

Water consumption from both the 0–100 cm and 0–200 cm soil layers was greater after early-harvested predecessors, because the yields were higher, but water-use efficiency was similar in crop rotation $N2$ (444.2–457.6 tonne water per tonne grain), and better in crop rotations $N4$ and $N5$ after early-harvested predecessors: 430.1 and 425.9 t/t. The share of the 0–100 cm soil layer in the total water consumption was 41% after early-harvested predecessors and 50% after late-harvested predecessors.

In five years of trials of no-till winter cereals, we find no significant difference in yields between no-till and conventional tillage, certainly no difference that is not made good by the savings in fuel and labour; the accumulation of soil water during the autumn-winter-spring periods is much greater under no-till than under conventional tillage (Tables 25.8 and 25.9); and we should take account of the other consequences of conventional soil tillage that make it unsustainable in the longer term.

It is worthy of note that the least accumulation of soil water was under black fallow and the amount of soil water accumulated in the first metre of soil after black fallow (rotation N2) was only half of that after the mixture of winter vetch and winter rye for green mass (rotation N4) or lucerne in the third year after first cut (N5). Black fallow has the least capacity to accumulate soil water because of its physical deterioration. There are at least two factors in operation. If we compare the pore space distribution of native grassland with arable cultivated for at least a century and with 50-year continuous black fallow on *Typical chernozem* at Kursk, Russia (Table 25.10) we see a smooth and uninterrupted gradation of pore space in virgin steppe but an abrupt closing down of pore space in and below the plough layer of arable and black fallow. And these data do not reveal the even more significant interruption of the macropores created by roots and burrows, which interferes with infiltration and transmission of rain and snowmelt. The other factor is the development of a sun-baked, water-repellent layer at the soil surface. This is most extreme in black fallow, whereas the adoption of zero tillage and protection of the soil surface by a mulch of crop residues brings us back closer to the hydrological state of the virgin

Table 25.6 Water-use efficiency of no-till winter wheat after late-harvested predecessors (tonne soil water use per tonne grain) yield) 2016–2019

Crop rotation	Predecessor	Soil water stocks (mm)				Soil water consumption (mm)		Share of 0-100 cm soil layer (%)	Yield t/ha	Water-use efficiency t/t
		Spring		At harvest		0–100	0–200			
		0–100	0–200	0–100	0–200					
2	Peas-for- grain	155.7	336.7	84.0	159.9	71.7	176.8	41	3.98	444.2
4	Corn-for-grain	164.5	323.7	82.1	145.0	82.4	178.7	46	3.74	477.8
5	Corn-for-grain	160.7	307.7	81.3	143.9	79.4	163.8	49	3.58	457.5

Table 25.7 Water-use efficiency by conventionally tilled winter wheat after early-harvested predecessors (t/t) 2016–2019

Crop rotation	Predecessors	Soil water stocks (mm)				Soil water consumption (mm)		Share of 0–100 cm soil layer (%)	Yield (t/ha)	Water-use efficiency (t/t)
		Spring		At harvest		0–100	0–200			
		0–100	0–200	0–100	0–200					
2	Black fallow	156.1	340.3	56.5	112.4	99.6	227.9	44	4.98	457.6
4	Winter vetch-and-rye	157.7	323.2	53.8	113.3	103.9	209.9	50	4.88	430.1
5	Lucerne	157.8	320.7	57.4	109.9	100.4	210.8	48	4.95	425.9

Table 25.8 Soil water accumulation during autumn–winter–spring by no-till and conventionally tilled winter wheat, average for 2015–2019 but excluding 2016, mm

Crop rotation	No-till after late-harvested predecessors				Conventional tillage after early-harvested predecessors			
	Soil layers (cm)		Share of 0–100 cm (%)	Yield (t/ha)	Soil layers (cm)		Share of 0–100 cm (%)	Yield (t/ha)
	0–100	0–200			0–100	0–200		
2	69.1	143.9	48.0	3.82	38.8	76.1	51.0	4.95
4	124.9	245.9	50.8	3.69	112.0	185.1	60.5	4.95
5	123.4	220.5	56.0	3.57	97.3	187.3	51.9	4.80

Table 25.9 Soil water accumulation during autumn–winter–spring under continuous black fallow, meadow, winter wheat and corn-for-grain, average for 2015–2018, mm

Variants	Unfertilized			Fertilized		
	Soil layers (cm)		Share of 0–100 cm layer (%)	Soil layers (cm)		Share of 0–100 cm layer (%)
	0–100	0–200		0–100	0–200	
Black fallow	52.8	67.7	78	35.5	45.8	78
Meadow[a]	98.2	142.6	69	104.0	192.9	54
Continuous winter wheat	94.2	151.8	62	102.0	203.8	50
Continuous corn-for-grain	50.5	73.9	68	85.4	169.2	51

[a] Average for 3 years

Table 25.10 Comparison of pore space under virgin steppe, arable and black fallow in *Typical chernozem,* Kursk, Russia (after Mikhailova et al. 2000)

Steppe depth (cm)	Steppe bulk density (t/m^3)	Steppe pore space (%)	Arable depth (cm)	Arable bulk density (t/m^3)	Arable pore space (%)	Fallow depth (cm)	Fallow bulk density (t/m^3)	Fallow pore space (%)
0–14.6	0.80	69.9	0–10	1.17	55.9	0–10.7	1.09	58.8
14.6–27.1	0.94	64.5	10–19.5	1.24	54.7	10.7–20	1.26	52.4
27.1–39.5	0.94	64.5	19.5–28.9	1.24	54.7	20–30	1.26	52.4
39.5–51.5	1.01	61.5	28.9–39	1.2	53.2	30–40	1.21	54.3
51.5–63.2	1.06	60.0	39–49.3	1.21	54.3	40–50	1.24	53.2
63.2–73.2	1.08	59.3	49.3–59.3	1.06	60.0	50–60	1.06	60.0
73.2–82.8	1.11	58.1	59.3–68	1.08	59.3	60–70	1.08	59.3
82.8–92.8	1.11	58.1	68–78	1.11	58.1	70–80	1.11	58.4
92.8–102.6	1.11	58.1	78–88	1.09	58.9	80–90	1.09	58.9
102.6–112.2	1.15	56.6	88–98	1.11	58.1	90–100	1.11	58.1
112.2–121.7	1.16	56.2	98–108	1.15	56.6	100–110	1.15	56.6
121.7–131.4	1.2	54.7	108–118	1.16	56.2	110–120	1.16	56.2

steppe observed by Izmailsky and Dokuchaev. Improved infiltration and water storage under no-till is a substantial potential benefit, provided that all the other factors of production can be optimized.

Conclusions

1. Winter wheat and winter barley in rotation after late-harvested predecessors respond strongly to the residual action of farmyard manure but supplementary mineral fertilizers bring no agronomic or economic benefit.
2. The effect of crop rotation on winter cereals is lower after late-harvested predecessors and higher after early-harvested predecessors. The effect of fertilization is the opposite: higher for late-harvested predecessors and lower for early-harvested predecessors.
3. Observance of crop rotation is mandatory for adoption of no-till, together with other measures for building soil fertility.
4. No-tillage for winter cereal crops after late-harvested predecessors doubles the accumulation of soil water during the fall-winter-spring period relative to conventionally cultivated early-harvested predecessors.

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Chapter 26
Long-Term Irrigation and Fertilization of *Typical Chernozem* on the Bălţi Steppe of Moldova

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Abstract Irrigation and fertilization are key factors of agricultural intensification. Their influence on crop yield and soil fertility has been studied in an experimental six-field crop rotation on *Typical chernozem* at Selectia Research Institute of Field Crops on the Bălţi Steppe begun in 1968. The yields of both winter wheat and sugar beet are increased by application of farmyard manure and mineral fertilizers and, also, by irrigation. But, in the case of winter wheat, the extra yield does not cover the extra costs. Corn-for-grain does not respond to irrigation or to fertilization. Without addition of farmyard manure and mineral fertilizers, even a crop rotation that includes 50% of perennial legumes cannot compensate for the annual losses of soil organic matter by mineralization. Irrigation increases these losses and, at the same time, changes the quality of soil organic matter.

Keywords Irrigation · Fertilization · Cost recovery · Soil organic matter · Total nitrogen · C/N ratio

Introduction

Drought has always stalked the steppes so intensification of agriculture has been allied with the extension of irrigation. Now, a climatic shift is apparent and the appeal of irrigation is all the greater. Over the last five years, mean annual precipitation on the Bălţi Steppe was 460.1, 15.1 mm above the 50-year mean and distributed as 63.8 mm (14%) in autumn, 72 mm (16%) in winter, 165.6 mm (36%) in spring, and 158.8 mm (35%) in summer. This compares with seasonal means of 103 mm (23%), 71 mm (16%), 102 mm (23%), and 169 mm (38%), respectively. Less rain in autumn accompanied by higher temperatures (+0.8 °C) is problematic for germination of winter cereals and their success is determined by the weather during winter and spring. Under these conditions, autumn irrigation induces timely germination. Somewhat increased annual precipitation has been accompanied by a 1.7 °C increase in annual

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temperature. Compared with the 50-year mean, springs are warmer by 2.6 °C so the greater spring rainfall is cancelled out by greater evaporation; summer heat and drought have become normal with a 2.2 °C increase in temperature accompanied by 10.3 mm less rainfall.

Intensification has also relied upon synthetic fertilizers but, on Chernozem soils, the effect of irrigation and fertilization on crop yields is not the same as their effect on soil fertility (Kovda and Samoilova 1983; Krupenikov 2008; Boincean et al. 2014; Boincean and Dent 2019). Actual farm practice rarely respects crop rotation, let alone including perennial legumes and grasses so, without enough farmyard manure, irrigation, and fertilization have driven a dramatic decline in soil fertility—which depends on soil organic matter. This is highlighted by the long-term field experiment with irrigation on the *Typical chernozem* of the Bălţi Steppe. Even with a crop rotation that includes perennial legumes, yields have not increased in spite of the regular introduction of potentially more productive crop varieties and hybrids.

Transition to a more sustainable farming system is impossible without knowing the negative effects of irrigation and mineral fertilizers on inherent soil fertility. The transition requires reorientation of the whole farming system towards soil regeneration, as an alternative to irrigation.

Experimental Site and Method

The long-term field experiment, begun in 1968, employs a six-field crop rotation: three years of lucerne—winter wheat—sugar beet—corn-for-grain. Each field is 3 ha, each experimental plot 200–400 m^2 with 50–100 m^2 sampled for yield measurements, and with four replicates. Three systems of fertilization have been compared: an unfertilized control, farmyard manure applied at 80t/ha prior to the sugar beet crop, and farmyard manure plus mineral fertilizers ($N_{60}P_{90}K_{40}$ for winter wheat and $N_{70}P_{90}K_{60}$ kg a.i./ha for sugar beet). However, for the last 7 years, mineral fertilizers have not been applied to winter wheat and sugar beet because of their negative impact, mainly caused by a higher level of diseases. Water for irrigation is pumped from a semi-artesian well. During the growing season, the soil water content is maintained at 50–80% of field capacity. For winter wheat, irrigation is applied before and after sowing and during critical periods of development. For sugar beet, irrigation is scheduled for the three main periods of development, at 300–900m^3/ha. Different irrigation regimes maintain soil water at 60, 70, and 80 % of field capacity. The content of soil organic matter was determined for different soil layers to a depth of 1 m at the beginning of the experiment in 1968 and, again, in 2019 using Tiurin's method. To calculate the recovery of the costs of irrigation and fertilization by the resulting extra yields, the following costs ($US) have been used:

- Fuel: 0.872/l
- Electric power: 0.156/kWh
- Amofos (N 10%, P 50%): 566.58/t

- Ammonium nitrate: 363.33/t
- Potassium chloride: 484.51/t
- Winter wheat grain: 133.88/t
- Sugar beet roots: 92.41/t.

Results and Discussion

Agronomic Response

Winter wheat responds to both fertilization and irrigation (Table 26.1).

The residual action of manure was much the same on both rainfed and irrigated plots: 0.50 t/ha and 0.59 t/ha, respectively (about 11%). Supplementary mineral fertilizers or, over the last 7 years, the residual action of previously applied fertilizers gave no increase in yield compared with separately applied manure: 0.42 t/ha (9%) and 0.59 t/ha (11%), respectively. On average for 2015–2019, the extra yield from irrigation on unfertilized plots was 0.65 t/ha and, for plots receiving manure, the extra yield was much the same—0.74 t/ha (about 14%).

Sugar beet is very responsive to fertilization, especially with irrigation (Table 26.2). The extra yields from farmyard manure on plots without irrigation and with irrigation were 27.5 t/ha (138%) and 42.2 t/ha (245%), respectively. Supplementary mineral fertilizers or their residual action produced no extra yield compared with manure alone. Irrigated unfertilized plots yielded 2.8 t/ha (14%) less than rainfed unfertilized plots. However, the extra yields from fertilization were much greater on irrigated plots, especially on plots receiving supplementary mineral fertilizers: 22.8 t/ha (71%) compared with 11.9 t/ha (25%) on plots receiving only manure, so irrigation increased the residual action of previously applied mineral fertilizers.

Corn-for-grain in crop rotation does not respond to fertilization or irrigation (Table 26.3).

Cost Recovery

Table 26.4 shows the extent to which extra yields recoup the costs of irrigation and fertilization.

It does not pay to apply mineral fertilizers and irrigation to winter wheat, whereas the rainfed variant receiving only farmyard manure and yielding an extra 0.5 t/ha, accrues $US66.9/ha. Application of irrigation together with mineral fertilizers reduces the cost recovery by $US0.2–0.3 per tonne of grain; irrigation without fertilizer increases the cost recovery by $US0.5–0.6 per tonne of grain; even so, the extra yield does not repay the investment—except in a drought year like 2019 when irrigated yields were 1.5–2.0 times the rainfed yields.

Table 26.1 Mean yields of winter wheat in rotation under fertilization and irrigation, 2015–2019, Selectia RIFC

Indices	Without irrigation			With irrigation			Extra yields from fertilization				Extra yields from irrigation		
	Not fertilized	Fertilized		Not fertilized	Fertilized		Without irrigation		With irrigation		Not fertilized	Fertilized	
		1	2		1	2	1	2	1	2		1	2
Yield t/ha/%	4.66	5.16	5.08	5.31	5.90	5.89	+0.50/11%	+0.42/9%	+0.59/11%	+0.58/11%	+0.65/14%	+0.74/14%	+0.81/16%

Legend 1—Composted farmyard manure, 2—Composted farmyard manure + NPK, $DL_{05} = 0.31$ t/ha

Table 26.2 Mean yields of sugar beet in rotation under fertilization and irrigation, 2015–2019, Selectia RIFC

Indices	Without irrigation			With irrigation			Extra yields from fertilization				Extra yields from irrigation		
	Not fertilized	Fertilized		Not fertilized	Fertilized		Without irrigation		With irrigation		Not fertilized	Fertilized	
		1	2		1	2	1	2	1	2		1	2
Yield t/ha/%	20.0	47.5	32.0	17.2	59.4	54.8	+27.5/138%	+12.0/60%	42.2/245%	37.6/219%	−2.8/14%	11.9/25%	22.8/71%

Legend 1—Composted farmyard manure, 2—Composted farmyard manure + NPK, $DL_{05} = 0.31$ t/ha

Table 26.3 Mean yields of corn-for-grain under fertilization and irrigation, 2015–2019, Selectia RIFC

Indices	Without irrigation			With irrigation			Extra yields from fertilization				Extra yields from irrigation		
	Not fertilized	Fertilized		Not fertilized	Fertilized		Without irrigation		With irrigation		Not fertilized	Fertilized	
		1	2		1	2	1	2	1	2		1	2
Yield (t/ha)	6.2	6.8	6.0	6.4	6.7	6.2	0.6	0.2	0.3	0.2	0.2	0.1	0.2

Legend 1—Composted farmyard manure, 2—Composted farmyard manure + NPK, $DL_{05} = 0.56$ t/ha

Table 26.4 Recovery of costs of fertilization and irrigation by extra yields of winter wheat and sugar beet, 2015–2019 average, $US per tonne of production

Crops	Extra yield from fertilization (t/ha)				Cost of fertilization and irrigation				Extra yield from irrigation			Cost of fertilization and irrigation		
	Without irrigation		With irrigation		Without irrigation		With irrigation		Not fertilized	fertilized		Not fertilized	fertilized	
	1	2	1	2	1	2	1	2		1	2		1	2
Winter wheat	0.50	0.42	0.59	0.58	–	206.4	154.5	360.9	0.65	0.74	0.81	154.5	154.5	360.9
	Value of extra yield				Cost recovery by extra yield				Value of extra yield			Cost recovery by extra yield		
	66.9	56.2	79.0	77.8	66.9	0.3	0.5	0.2	87.0	99.1	108.4	0.6	0.6	0.3
Sugar beet	27.5	12.0	42.2	37.6	419.2	636.1	573.6	790.6	−2.8	11.9	22.8	154.5	573.7	790.6
	Value of extra yield				Cost recovery by extra yield				Value of extra yield			Cost recovery by extra yield		
	891.4	389.0	1367.7	1218.6	2.1	0.6	2.4	1.5	–	385.78	739.0	–	0.7	0.9

Legend 1—Composted farmyard manure, 2—Composted farmyard manure + NPK

In general, sowing winter wheat in rotation after lucerne enables the soil to accumulate enough nutrients and water to yield well without irrigation or mineral fertilizers. Rainfed sugar beet repays the cost of fertilization with farmyard manure alone. With irrigation, the cost of manure + NPK fertilizer is also recovered but, without irrigation, it does not pay to apply supplementary mineral fertilizer.

Soil Organic Matter Stocks

Intensive agricultural systems employ irrigation and fertilizers to increase crop yields but they have been so employed without regard to their impact on soil fertility. Tables 26.5 and 26.6 present data on the changes in stocks of soil organic carbon (SOC) and total nitrogen to a depth of 1 m from the outset of the long-term field experiment with irrigation and fertilization in 1968.

Even under a crop rotation that includes 50%lucerne, the stock of soil organic matter is maintained only under rainfed crops receiving farmyard manure together with mineral fertilizers. Under this combination, there was a gain of 31.96 tC/ha in the 40–100 cm soil layer. Without farmyard manure, the rainfed rotation lost 23.3 tC/ha or 10% of the initial stocks of the uppermost metre of the soil, an annual loss of 0.2 tC/ha. In other words, a crop rotation with 50% of perennial legumes cannot maintain the carbon stocks of Chernozem soils without the input of farmyard manure. Irrigation contributed to losses of SOC from fertilized and, especially, unfertilized plots: 33.5 and 47.5 tC/ha, respectively (21 and 15% of the initial stocks) or annual losses of 0.42 and 0.29 tC/h. Of this loss, almost 80% was from the 0–60 cm layer.

Experimental data from a crop rotation on the same *Typical chernozem* with 50% of perennial legumes and annual application of 13.3 tonne of manure per 1 ha of crop rotation reveal an annual loss of 0.29 tC/ha, and a loss of 0.42 tC/ha on unfertilized plots. In real production conditions, SOC losses will be much greater because perennial legumes no longer feature in the crop rotation and soils have seen no farmyard manure for thirty years.

We see the same pattern in the stocks of total nitrogen for the topmost metre of the soil profile (Table 26.6). From unfertilized rainfed plots, the loss of total nitrogen from the 0 to 100 cm soil layer over 51 years was 4.91 t/ha (19% of the initial stocks) or 0.38 tN/ha/year. Fertilized rainfed plots gained 0.99 tN/ha (4% relative to initial stocks) or 0.08 tN/ha/year. Unfertilized irrigated plots lost 5.91 tN/ha (23% of the initial stocks) or 0.46 tN/ha/year. Fertilized irrigated plots lost 4.41 tN/ha (17% of the initial stocks of nitrogen) or 0.34 tN/ha/year.

Changes in the C:N ratio of soil organic matter (Table 26.7) indicate a greater degree of transformation of soil organic matter under irrigation, especially on fertilized plots: from 9.5 to 9.7 on rainfed plots to 8.9 on unfertilized irrigated plots and 8.4 on fertilized irrigated plots, respectively. We may suppose that the capacity of soils to provide nitrogen from the labile fraction of soil organic matter is lower on irrigated plots, especially without fertilization, and is increasing on plots without irrigation,

Table 26.5 SOC stocks under long-term irrigation and fertilization, mean of 3 replicates, Selectia RIFC

Soil layers (cm)	SOC stocks 1968 (tC/ha)	SOC stocks 2019 (tC/ha)				Changes in SOC stocks (t/ha)			
		Without irrigation		With irrigation		Without irrigation		With irrigation	
		Not fertilized	Fertilized	Not fertilized	Fertilized	Not fertilized	Fertilized	Not fertilized	Fertilized
0–20	70.1	57.12	63.84	55.92	67.2	−12.98	−6.26	−14.18	−2.90
20–40	58.8	56.16	65.78	51.48	49.92	−2.64	+6.96	−7.32	−8.88
40–60	46.3	40.30	56.42	30.42	34.06	−6.00	+10.12	−15.88	−12.24
60–80	28.8	28.28	40.04	23.80	24.08	−0.52	+11.24	−5.0	−4.72
80–100	20.2	19.04	30.80	15.12	15.40	−1.16	+10.6	−5.08	−4.80
0–100	224.2	200.9	256.9	176.7	190.7	−23.3	+32.7	−47.5	−33.5
% change						−10.4	+14.6	−21.2	−14.9
± tC/ha/year						−0.20	+0.29	−0.42	−0.29

Table 26.6 Stocks of total nitrogen (t/ha) under long-term irrigation and fertilization, mean of 3 replicates

Soil layers (cm)	Total N stocks 1968 (tN/ha)	Stocks of total nitrogen 2019 (tN/ha)				Changes in the stocks of total nitrogen (tN/ha)			
		Without irrigation		With irrigation		Without irrigation		With irrigation	
		Not fertilized	Fertilized	Not fertilized	Fertilized	Not fertilized	Fertilized	Not fertilized	Fertilized
0–20	6.36	5.28	6.00	5.28	6.24	−1.08	−0.36	−1.08	−0.12
20–40	6.01	5.20	6.24	4.68	4.94	−0.81	+0.23	−1.33	−1.07
40–60	5.32	3.90	5.46	3.90	3.90	−1.42	+0.14	−1.42	−1.42
60–80	4.42	3.36	4.76	3.08	3.36	−1.06	+0.34	−1.34	−1.06
80–100	3.30	2.80	3.92	2.52	2.52	−0.50	+0.62	−0.78	−0.78
0–100	25.41	20.5	26.4	19.50	21.0	−4.91	+0.99	−5.91	−4.41
% of initial stocks						19.3	3.9	23.3	17.4
±tN/ha/year						0.38	0.08	0.46	0.34

Table 26.7 Changes of C:N ratio under long-term irrigation and fertilization, mean of 3 replicates, Selectia RIFC

Soil layers (cm)	1968	2019			
		Without irrigation		With irrigation	
		Unfertilized	With fertilization	Without fertilization	With fertilization
0–20	11.0	10.8	10.6	10.6	10.4
20–40	9.8	10.9	10.6	11.0	10.1
40–60	8.7	10.5	10.2	8.5	8.4
60–80	6.5	8.3	9.1	8.3	7.3
80–100	6.1	6.8	8.0	6.0	5.7
Average	8.4	9.5	9.7	8.9	8.4

especially when fertilized with farmyard manure—which is why there is less need for supplementary mineral fertilizers on soils fertilized with farmyard manure.

Conclusions

- Winter wheat and sugar beet respond to irrigation and fertilization. However, the cost of irrigation is repaid only by sugar beet. On sugar beet, supplementary mineral fertilizers do not pay unless irrigation is also provided. For winter wheat, respecting crop rotation and following early harvested predecessors, in particular by following after lucerne, make irrigation and supplementary mineral fertilizers unnecessary.
- In crop rotation, corn-for-grain does not respond to either irrigation or fertilization.
- Over 51 years under rainfed conditions, a crop rotation with 50% perennial legumes fertilized with farmyard manure (13.3 t/ha/year over the rotation) and mineral fertilizers *increased* SOC stocks in the topmost metre of soil by 32.7 or 0.29 t/ha annually. However, a rotation with 50% of perennial legumes without supplementary application of farmyard manure and mineral fertilizers cannot maintain the initial stocks of soil organic matter.
- Any gains in soil organic matter occur in the deeper soil layers: depletion of stocks is greatest in the upper soil layers.
- Irrigation increases losses of SOC from both fertilized and unfertilized plots, increases losses of total nitrogen, and accelerates the transformation of soil organic matter—with losses from the labile fraction in particular.
- The argument for irrigation as a saviour from increasing droughts is questionable. Irrigation as practised, without perennial legumes and grasses in the crop rotation and without enough farmyard manure, is dramatically depleting soil fertility. This is unsustainable. Agriculture needs restructuring—especially in irrigated areas.

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Chapter 27
Post-irrigation State of Black Soils in South-Western Ukraine

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Abstract Large-scale irrigation of Southern Black Soils in south-western Ukraine in 1966–1990 increased production but, also, salinity and loss of humus. Emergence of salinity depended on the quality of irrigation water, the duration and intensity of irrigation, and agro-amelioration practices. During the last 20–25 years, there has been much less irrigation, but soil degradation processes may have been exacerbated by the former regime. Assessment of the post-irrigation evolution of, now, irregularly irrigated Black Soils and comparison with adjacent rainfed soils indicates that soils within the Lower Dniester Irrigation System, which were irrigated with good-quality water (total dissolved salts 0.4–0.6 g/l), are not subject to salinity. During the post-irrigation period, their general physical properties have improved but there has been an accelerated loss of humus and increases in carbonate content and sodicity.

Keywords Black Soils · Irrigation · Soil-forming processes · Agro-amelioration state · Fertility

Introduction

Irrigation has pros and cons. In south-western Ukraine, large-scale irrigation from 1966 until 1990 increased crop production but, also, increased soil degradation. Irrigation brings new soil-forming processes into operation—their effects depending on water quality, intensity and duration of irrigation, inherent soil characteristics and management practice (Bilanchyn 2011). Black Soils in steppe landscapes are

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sensitive to the quality of irrigation water and the increased throughflow. In particular, the adsorption of Na^+ significantly changes the soil's behaviour (Balyuk et al. 2009; Bilanchyn 2003; Krasekha et al. 2016; Poznyak 1997). Over the last 20–25 years, there has been much less irrigation. Here, we assess the current state of formerly irrigated Black Soils in comparison with adjacent rainfed soils.

Materials and Methods

The study was carried out within the long-term monitoring network in the Black Soil landscape of south-western Ukraine. The climate is temperate continental with a mean annual air temperature of 10.5 °C, mean January minimum of −11.7 and mean July maximum of 24.9 °C, respectively; mean annual precipitation is 432 mm with a summer maximum; total atmospheric N deposition is 11.4 kg/ha/year (Medinets et al. 2016). The soils are *Calcic chernozem* (IUSS Working Group 2015): mycelial-calcareous Black Soils of the warm, South-European facies on the right bank of the Dniester; continental, Eastern-European facies on the left bank (Gogolev et al. 1992).

In the 1960s and 1970s, overhead irrigation was extended using good-quality water from the Danube and Dniester rivers with total dissolved salts (TDS) 0.4–0.6 g/l, and the Southern Bug (TDS 1.0–2.0 g/l), as well as water of higher mineral content from the Danube Estuary (TDS 3.0–3.5 g/l). Since 1993–1996, the greater part of landscape has been under a post-irrigation regime of rainfed grains, rapeseed and sunflower. The study sites were established in 1993–1995 on flat land that had been irrigated at varying intensity with water of different qualities, and on adjacent rainfed land. We used standard methods for soil sampling and analyses of physicochemical parameters. Statistical analyses were carried out with STATISTICA 7.0 (StatSoft Inc., USA).

Results and Discussion

Further development of irrigation systems ceased in 1993–1996 for want of money and materials; the irrigated area contracted; chemical amelioration ceased and application of manure and fertilizers decreased abruptly. Nowadays, there are few irrigated farms and the worsening condition of the soils is expressed in loss of humus and increasing sodicity. Balyuk and Medvedyev (2012) attributed the declining crop yields in recent years to soil exhaustion. Long-term studies of agro-amelioration indicators (1991–2016) and current evolution processes in formerly irrigated Black Soils show:

- The extent and severity of salinity vary depending on landscape, geochemical conditions and irrigation practice. Salt concentrations increase over summer and autumn, but salinity is hardly evident across watersheds where salts are leached from the upper soil profile during winter and spring; it is more prominent in lower landscape positions where the water table lies at a depth of 3–5 m and where irrigation water had higher mineral content (TDS > 1.5–2.0 g/l). Even 20–25 years after cessation of irrigation, the ratio of water-soluble Ca^{2+}/Na^+ remains narrow (range: 0.3–0.7). It appears that salinity has shifted from the upper soil layers to deeper in the profile.

- The humus content of irrigated Black Soils was equal to and, sometimes, higher than adjacent rainfed soils. Loss of soil organic matter, with and without irrigation, can be attributed to cropping grains and sunflower without applying enough manure and fertilizer; only under the second or third year under lucerne does the stock of humus increase or even stabilize. The dynamics of humus in the post-irrigation period may be illustrated by the Vinogradivska Irrigation System (VIS) under a rotation representative of the arable of south-west Odesa Region. The system was irrigated during 1970–1995 with water of high mineral content (TDS 2–3.5 g/l) from Yalpug Lake. Figure 27.1 shows that, for the period 1994–2016, the humus content declined faster in post-irrigated plot ($R^2 = 0.67$, $p < 0.05$) compared to rainfed plot ($R^2 = 0.88$, $p < 0.01$)—although inter-annual variation of humus content was also related to agro-climatic parameters and management practice (data not shown here).
- Under irrigation, the composition of soil adsorption complex (SAC) and content of adsorbed Na^+ in the upper layers of Black Soil was practically unchanged but Na^+ increased with depth, increasing the thickness of salinized horizon. Once irrigation ceased, natural leaching resumed; water-soluble and adsorbed Na^+ decreased in the upper soil layers; and there has been some increase in the share of Ca^{2+} in the SAC. However, the content of water-soluble Na^+ remained high with narrow ratio

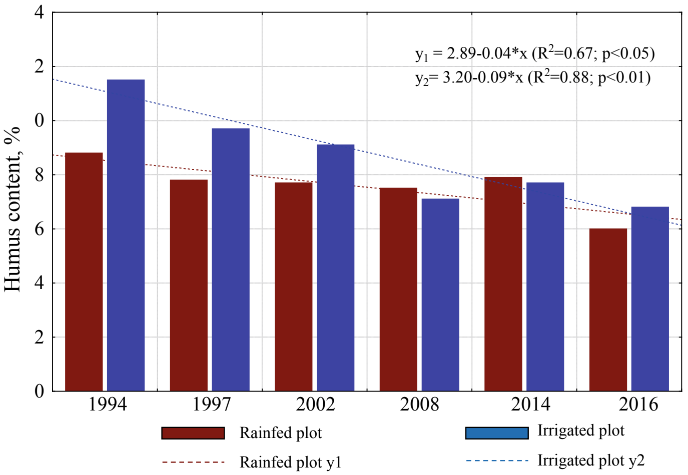

Fig. 27.1 Humus content in post-irrigated and rainfed Black Soil in the Vinogradivska Irrigation System

of Ca^{2+}/Na^+ (0.3–0.7) in the deeper layers, especially in plots previously irrigated with mineralized water.

- Agro-physical parameters (density, structure, water and physical properties) changed significantly under the influence of irrigation—usually for the worse, especially when irrigation water had high mineral content. Following the cessation of irrigation 20–25 years ago, leaching under the influence of rainfall and snowmelt has somewhat improved the agro-physical condition. Soils that were previously irrigated with water having higher TDS value (>1.5 g/l) have recovered better; this recovery has been accelerated by application of manure and ameliorants containing soluble Ca^{2+}, and by growing perennial legumes and grasses (Bilanchyn 2011; Krasekha et al. 2016).
- The loss of soil organic matter has been aggravated during recent decades by failure to apply enough manure and fertilizer. Agriculture is mining N from the soil organic matter (Boincean and Dent 2019; Krupenikov et al. 2011; Tsurkan et al. 2021).

Table 27.1 summarizes results of a long-term study (1990–2015) of changes in physicochemical composition and properties of *Calcic chernozem* within the Lower Dniester Irrigation System under sprinkler irrigation (1970–1993) and, subsequently, periodic irrigation (1994–2016), largely of vegetable crops. The following changes were observed following the dramatic decrease in the intensity and frequency of irrigation and a switch to extensive management:

1. The reaction of the humus changed from neutral in both the 0–30 cm and 30–60 cm layers to mildly alkaline and alkaline, respectively.
2. Total soluble salts remained low both in upper and lower layers (0.03–0.04 and 0.07–0.09%, respectively). By this assessment, these soils are not saline. They were leached of soluble salts but, post-irrigation, the ratio of water-soluble Ca^{2+}/Na^+ in the topsoil increased significantly. However, the topsoil Ca^{2+}/Na^+ ratio was lower for the post-irrigated soils (systematically irrigated before 1994) than for consistently rainfed soils. In the subsoil, the post-irrigation soils showed both a narrowing of the Ca^{2+}/Na^+ ratio and an increase in carbonates: the depth at which the soil effervesced with 10% HCl rose from 76 cm in the soils systematically irrigated in 1970–1994 to 57 cm at present.
3. Grishina and Orlov (1978) reported that these Black Soils had low humus content (2–4%) but a high degree of humification ($C_{HA}/C_{gen.} = 30–40$), a fulvate-humate ratio of 1–2, and a C:N ratio of 8–11. Under current management, the humus content of post-irrigation soils is still higher than comparable rainfed soils but is decreasing faster as a consequence of the cessation of manuring and the absence of perennial grasses and legumes in the crop rotation (Boincean and Dent 2019; Krasekha et al. 2016). The decrease of humus content of the plough layer between 1990 and 2016 amounts to 58 t/ha or 0.1%, which is in line with other data in the literature.
4. Post-irrigation, under extensive management, compaction of the topsoil and loss of soil structure are tangible.

Table 27.1 Physicochemical parameters of rainfed and formerly irrigated Black Soils, 1976–2016

Transects	Depth (cm)	pH water	Total soluble salts %	Ca^{2+}/Na^{+}_{aq}	$CaCO_3$ %	Humus (%)	Total adsorbed bases *M* eq/100 g	Na^+ + K^+ from total adsorbed bases %	Bulk density (g/cm^3)	Particle-size distribution (by fraction) %			*К*[a]	Ка[b]	Pc[c]
										>0.05 mm	<0.01 mm	<0.001 mm			
Rainfed (1990–2016)	0–29	8.6	0.051	6.0	0	2.1	31.35	1.8	1.36	13.5	42.4	24.4	10.3	60.8	39.3
	29–59	8.4	0.063	1.6	0	2.1	29.31	1.7	1.39	9.4	47.1	26.3	3.2	75.6	40.9
	59–84	8.8	0.071	1.1	15.7	0.6	21.79	2.7	1.54	12.8	51.7	30.0	15.3	58.7	52.4
	84–155	8.8	0.079	2.4	17.0	0.4	23.91	1.3	n/a	7.3	56.8	33.4	6.3	75.5	56.3
Systematically irrigated (1976–1994)	0–32	6.8	0.048	1.5	0	3.4	26.47	1.4	1.42	1.3	58.0	33.4	5.1	97.2	51.1
	32–44	6.7	0.040	1.1	0	3.1	26.20	1.2	1.50	6.7	59.2	37.0	6.5	80.4	65.8
	44–57	6.7	0.053	1.8	0	2.3	25.45	1.4	1.56	18.7	57.0	36.2	8.8	68.9	65.2
	57–69	7.6	0.085	2.4	0.4	1.7	24.86	3.1	1.56	5.0	59.4	36.9	8.7	78.4	63.4
	69–79	7.7	0.094	2.7	3.8	1.4	23.82	0.9	1.55	28.4	60.5	38.9	8.5	65.1	73.5
	79–130	7.8	0.106	4.1	9.4	0.8	23.80	0.8	1.58	34.0	62.2	40.8	12.3	42.3	90.3
	130–150	7.9	0.071	2.2	10.8	0.4	23.31	0.9	1.58	9.9	64.1	41.8	4.1	60.2	73.1
Periodically irrigated (1994–2016)	0–25	8.2	0.039	3.6	0	3.3	30.81	2.9	1.49	12.4	47	27.5	7.7	66.1	45.8
	25–55	8.3	0.033	2.4	0	2.6	30.52	2.4	1.61	7.6	50.1	29.3	2.9	71.9	46.4
	55–68	8.5	0.063	2.1	1.8	2.0	30.16	1.9	1.47	6.5	53.7	31.7	2.7	80.7	51.3
	68–87	8.7	0.071	2.7	9.6	0.6	25.42	1.7	1.57	8.0	52.5	32.3	3.9	81.6	54.1
	87–123	8.7	0.068	1.4	15.7	0.4	26.22	1.6	1.59	16.0	60.1	37.8	5.6	65.8	81.8
	123–160	8.8	0.085	1.3	8.7	0.3	24.73	2.1	1.61	9.7	56.1	34.2	3.7	52.1	61.0

[a] *К*—Kachinskiy dispersion factor
[b] Ка—Beiver aggregation degree
[c] Pc—Vadyunina particle-size pedality index

5. The clay content of formerly irrigated soils has decreased; values of the Kachinskiy dispersion factor increased in the topsoil but decreased below; and there has been a general decrease in the Beiver aggregation degree (Shein and Karpachevskiy 2007), water stability and potential structure formation capacity according to Vadyunina particle-size pedality index (Medvedyev et al. 2018).

Conclusions

Black Soils are sensitive to irrigation water quality, especially under overhead or surface irrigation. The leaching of salts, nutrients and, even, carbonates from root zone is intensified; and exchangeable Na^+ increases—leading to deterioration of soil structure, bulk density, porosity and water permeability.

Irrigation-induced salinity depends, to a large extent, on water quality, irrigation intensity and agro-amelioration practice. The lower horizons of Black Soils previously irrigated with water having a high salt content (TDS > 1.5 g/l) still show the effects of salinity, but during the 20–25 year post-irrigation period, the soils' general physical properties have improved—apart from significant loss of soil organic matter. The agro-physical parameters of Black Soils irrigated in 1970–1994 are different from the respective parameters of non-irrigated (rainfed) soils in the region but these differences are not great.

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Chapter 28
Effects of Drip Irrigation on the Composition and Fertility of Black Soils in Odesa Region

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Abstract Drip irrigation technology is in demand across the Steppes for efficient use of scarce water resources, especially in the south of Odesa Region. However, it may aggravate salinity and sodicity. Under drip irrigation, leaching of calcium carbonate and a decrease in adsorbed Ca^{2+}/Na^{+} were observed in both the 0–30 and 30–60 cm layers of Southern Black Soil. Two growing seasons under rainfed spring barley did not restore the initial values; raised values of sulphate and sodium persisted and total carbonate was lower than that in the rainfed control.

Keywords Southern Black Soils · Fertigation · Salinity · Carbonates

Introduction

The steppes of Ukraine are characterized by capricious and, for most agricultural crops, insufficient rainfall. Therefore, drip irrigation is in demand as a resource-efficient, power-saving method of applying supplementary water to vegetables, potatoes, perennial fruit and berry crops (Balyuk et al. 2009; Romaschenko et al. 2012). Surface and overhead irrigation use significantly more water, which changes soil morphology, composition and behaviour; and surplus water drains to the groundwater (Bilanchyn et al. 2021; Poznyak 1997; Tsurkan et al. 2018). By comparison, drip irrigation is supposed to cause minimal environmental impact while ensuring optimal yield and quality—so it is generally considered to be the best technology

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in terms of efficient use of water and conservation of soil and landscape (Krasekha et al. 2016; Shatkovskiy 2016).

Irrigation may lead to the accumulation of soluble salts and changes in the soil's adsorption complex, triggering salinity and sodicity (Balyuk et al. 2009; Krasekha et al. 2016) depending on water quality, amount and timing of application, as well as rainfall in the autumn–winter period (Shatkovskiy 2016; Tsurkan and Bilanchyn 2018). In Ukraine, irrigation water is of variable quality, depending on its source. Here, we investigate how drip irrigation influences physicochemical composition and fertility of Black Soils in Odesa Region in the south west of the country.

Materials and Methods

The study was undertaken in croplands of the Dobra Gorodyna farming enterprise near Petrodolinskoye Atmospheric Research Monitoring Station in Odesa region. The climate is temperate continental, with a mean annual temperature (2000–2014) of 10.5 °C, mean January minimum and mean July maximum of -11.7 °C and 24.9 °C, respectively. Mean annual precipitation is 432 mm with a summer maximum. Drip irrigation has been used for vegetable production since 1996–1997; the crop rotation is tomatoes—sweet pepper—onions (2 years)—spring barley (2 years). Bicarbonate-calcium water with a total soluble salt (TSS) content < 0.5 g/l and p_H7.5–7.8 is drawn from the River Dniester; NPK fertilizer and microelements are applied through the drippers and, during the growing season, soil water content is maintained at 70–85% of field capacity, depending on the crop's development phase.

To study soil dynamics under drip irrigation, in particular the local character of soil wetting, soil was sampled from in-row positions under drippers and inter-row spaces (Medinets et al. 2016). Samples were taken during the irrigation period, during the post-irrigation period and, to assess the impact of drip irrigation in the medium term, samples were also taken during the 2nd year after harvest of the spring barley crop. Irrigation water and soil samples were analysed according to ISOs adopted in Ukraine (Medinets et al. 2016). Statistical analyses were carried out with STATISTICA 7.0 (StatSoft Inc.).

Results and Discussion

The impact of drip irrigation on physicochemical parameters may be estimated with variation coefficients (VCs); according to Rozhkov (2018), VC magnitudes greater than 30% indicate significant changes. Table 28.1 summarizes the spatial and vertical variability encountered. We observe that the local inflow of water and nutrients directly into the root zone has changed the salt distribution, nutrient status and carbonate regime of the soils, especially at the in-row position. Variability of carbonate content in the zone of intensive water penetration (30–70 cm depth)

Table 28.1 VC (%) of agrochemical parameters in drip-irrigated Southern Black Soils, 2011–2013

Observation period	Cl^-	$SO_4{}^{2-}$	Na^+	$N\text{-}NO_3{}^-$	$N\text{-}NH_4$	P_2O_5	$CaCO_3$
0–30 cm							
Jun 2011	102.9	44.9	62.3	40.2	108.0	13.3	0
Nov 2011	53.7	38.4	30.5	49.9	28.2	31.5	0
Jun 2012	57.4	26.5	20.4	74.9	42.1	32.6	0
Apr 2013	65.2	27.2	70.9	74.5	26.8	31.8	0
Jul 2013	115.4	46.6	14.4	24.0	15.3	17.0	0
Nov 2013	61.9	30.1	7.9	40.0	40.7	7.8	0
30–50 cm							
Jun 2011	48.1	28.7	36.9	62.8	17.2	64.9	143.0
Nov 2011	54.4	36.1	27.4	51.4	65.5	145.9	85.1
Jun 2012	59.6	23.1	18.6	73.8	35.5	62.7	97.4
Apr 2013	48.2	22.8	42.6	51.8	27.7	36.8	199.2
Jul 2013	98.4	14.2	37.6	49.1	22.9	101.1	50.2
Nov 2013	36.9	13.4	14.0	138.5	48.1	8.0	67.7
50–70 cm							
Jun 2011	43.0	41.9	31.3	42.4	14.9	31.7	39.3
Nov 2011	48.7	27.8	25.8	38.7	77.6	192.4	25.2
Jun 2012	41.2	19.8	19.5	114.2	40.6	38.2	45.6
Apr 2013	32.4	17.3	75.7	52.6	11.2	83.0	52.8
Jul 2013	35.1	14.8	67.1	18.6	30.3	49.7	44.4
Nov 2013	58.9	20.9	5.9	112.3	49.5	0	19.5
70–100 cm							
Jun 2011	57.7	36.1	79.2	10.8	57.7	41.5	17.1
Nov 2011	49.0	33.3	21.0	32.6	71.2	19.4	7.0
Jun 2012	47.5	28.9	17.3	117.4	37.1	30.5	12.1
Apr 2013	36.4	25.8	48.8	40.4	22.1	26.9	10.9
Jul 2013	59.1	21.4	47.3	38.3	51.3	177.2	7.5
Nov 2013	45.5	11.4	14.4	114.4	0	2.4	5.0

depended on the steady supply of water and active biological processes both during and after the irrigation period: VC exceeded 30% to a depth of 70 cm in the rows and 50 cm between rows, while down the profile VC varied in a range of 5–17% indicating lateral wetting (Afanasyev 2008; Krasekha et al. 2016).

Southern Black Soil is generally not saline but, under fertigation, we observe accumulation of salts in topsoil and subsurface horizons, both in the rows and inter-row spaces, both during irrigation and in the post-irrigation period (Table 28.2). Within the rows, total soluble salts (TSS) increased significantly ($p < 0.05$) in both upper (0–30 cm) and deeper (70–100 cm) soil layers compared to the rainfed control.

Table 28.2 Mean and std. error of parameters of Southern Black Soil under drip irrigation, 2011–2016 ($n = 8$)

Sampling area/period		Depth (cm)	pH_{water}	Total salts × 10^{-3}%	Ca^{2+} /Na^{+} in water extract	Na^{+} + K^{+} % of total adsorbed bases	CaCO_3%
Rainfed control		0–10	7.0	18	13.7	2.9	0
		10–20	6.9	14	3.1	1.8	0
		20–30	6.8	15	3.7	1.7	0
		30–40	7.0	19	3.8	1.6	0
		40–50	7.7	52	8.0	1.5	2.3
		50–70	7.9	51	8.6	1.5	13.6
		70–90	7.9	49	5.2	1.5	14.5
		90–120	7.9	51	4.3	1.6	14.3
Irrigated growing period	In-row	0–30	7.0 ± 0.1	59 ± 5.5	3.2 ± 0.3	2.7 ± 0.2	0
		30–50	6.9 ± 0.1	36 ± 4.7	1.8 ± 0.2	1.9 ± 0.1	0
		50–70	7.6 ± 0.0	57 ± 1.5	2.9 ± 0.2	1.7 ± 0.1	7.7 ± 1.3
		70–100	7.7 ± 0.0	63 ± 1.0	2.2 ± 0.1	1.6 ± 0.1	9.3 ± 1.1
	Inter-row space	0–30	7.2 ± 0.1	39 ± 3.0	2.6 ± 0.3	2.8 ± 0.2	0
		30–50	7.4 ± 0.2	48 ± 4.3	3.4 ± 0.4	1.6 ± 0.1	3.0 ± 0.8
		50–70	7.6 ± 0.0	51 ± 1.5	4.0 ± 0.3	1.5 ± 0.1	13.9 ± 0.6
		70–100	7.7 ± 0.0	53 ± 1.1	3.2 ± 0.2	1.3 ± 0.1	15.2 ± 0.2
Post-irrigation period	In-row	0–30	6.8 ± 0.1	34 ± 3.6	1.7 ± 0.2	3.3 ± 0.1	0
		30–50	7.3 ± 0.2	44 ± 7.2	2.5 ± 0.4	2.2 ± 0.1	1.6 ± 0.6
		50–70	7.7 ± 0.0	59 ± 1.9	3.2 ± 0.3	2.0 ± 0.1	11.0 ± 1.1
		70–100	7.9 ± 0.1	54 ± 1.7	2.5 ± 0.3	2.1 ± 0.1	14.6 ± 0.7
	Inter-row space	0–30	7.0 ± 0.1	25 ± 1.6	1.6 ± 0.2	3.1 ± 0.1	0
		30–50	7.6 ± 0.0	54 ± 3.9	3.7 ± 0.4	2.1 ± 0.1	4.0 ± 0.9
		50–70	7.8 ± 0.1	55 ± 2.3	3.1 ± 0.3	2.1 ± 0.1	12.7 ± 1.0
		70–100	8.1 ± 0.1	50 ± 3.0	2.4 ± 0.2	2.1 ± 0.0	13.7 ± 0.3
Non-irrigation period, 2 years spring barley		0–30	7.6	47	2.6	3.3	0
		30–46	7.5	38	2.5	2.1	0
		46–64	7.8	59	4.6	2.2	9.3
		64–91	7.9	59	2.9	1.9	8.8
		91–120	7.9	59	1.7	2.0	6.6

Continuous influx of irrigation water enriched with dissolved NPK fertilizers (at depth of ~ 10 cm) resulted in TSS increase in topsoil. However, during the growing season, ions were actively taken up by the crops, which led to decrease of TSS concentration in root zone (30–70 cm) where no significant difference with non-irrigated control plot was found. Between the rows, TSS increased from 0.04 to 0.05% in the top 50 cm of the soil profile.

Following irrigation, a salt haze appeared on the surface and on soil aggregates, drawn to evaporating surfaces along with soil water (TSS $\cong$ 0.3%). In the post-irrigation period, TSS in the 0–50 cm layer remained higher than in the rainfed control; the biggest differences in salt content and composition between soil samples taken from the rows and between the rows were observed down to a depth of 70 cm, beyond which the differences gradually equalized.

Soluble salts in the root zone (30–50 cm) comprised mainly calcium bicarbonate, magnesium chloride and sodium sulphate; and down profile, magnesium sulphate. During irrigation, concentrations of sulphate, chloride, calcium and magnesium increased in the rows (Fig. 28.1) and significant differences between the rows and inter-row spaces persisted in the case of sulphate and TSS ($p < 0.01$). After two years under barley without irrigation, statistically significant differences in salt content and composition were registered between non-irrigated soils and the rainfed control, mainly for the topsoil; sulphate and sodium concentrations were slightly higher ($p < 0.05$) than in the underlying layer.

Under drip irrigation, the Ca^{2+}/Na^{+} ratio tends to decrease and the ratio of $Na^{+} + K^{+}$ to total adsorbed bases tends to increase to the extent that the ratio Ca^{2+}/Na^{+} was below 2.5 in the 0–30 cm soil layer during the post-irrigation period and in 70–100 cm layer during the growing season under irrigation. Moreover, increase in p_H was observed both in and between rows within the 0–30 cm soil layer during the irrigated growing season compared with the control. The raised p_H persisted down to 70 cm. Under these circumstances, we might think that these Black Soils are threatened by salinity. However, in the post-irrigation period, the sodicity (alkalinity) of the topsoil was low ($(Na^{+} + K^{+})/\Sigma_{ads.bases} > 3.0\%$) and, during the two years under rainfed barley, there was a tendency towards increase of Ca^{2+}/Na^{+} and $(Na^{+} + K^{+})/\Sigma_{ads.bases}$ ratios. We conclude that there is little likelihood of irrigation-induced salinity under application of Dniester water.

Previous studies (e.g. Poznyak 1997; Zhantalay 1990) showed migration of calcium carbonate under irrigation. We too observed that carbonate distribution under drip irrigation differed significantly from the control (Table 28.2; Fig. 28.1). In the control, a small amount (2.3%) of $CaCO_3$ was registered at a depth of 40 cm and carbonate content increases markedly down profile, reaching 14.5% in the calcic horizon. Irrigation brought about migration of carbonates down profile in the rows: we detected carbonates only within the 50–70 cm soil layer, but already at an increased concentration (7.7%), but not in the inter-row spaces. Due to the low solubility of $CaCO_3$ and low concentrations of CO_2 in soil air and soil solution during the dry post-irrigation period, carbonates are drawn up to 30 cm from soil surface, depositing as fibrous efflorescent lublinite.

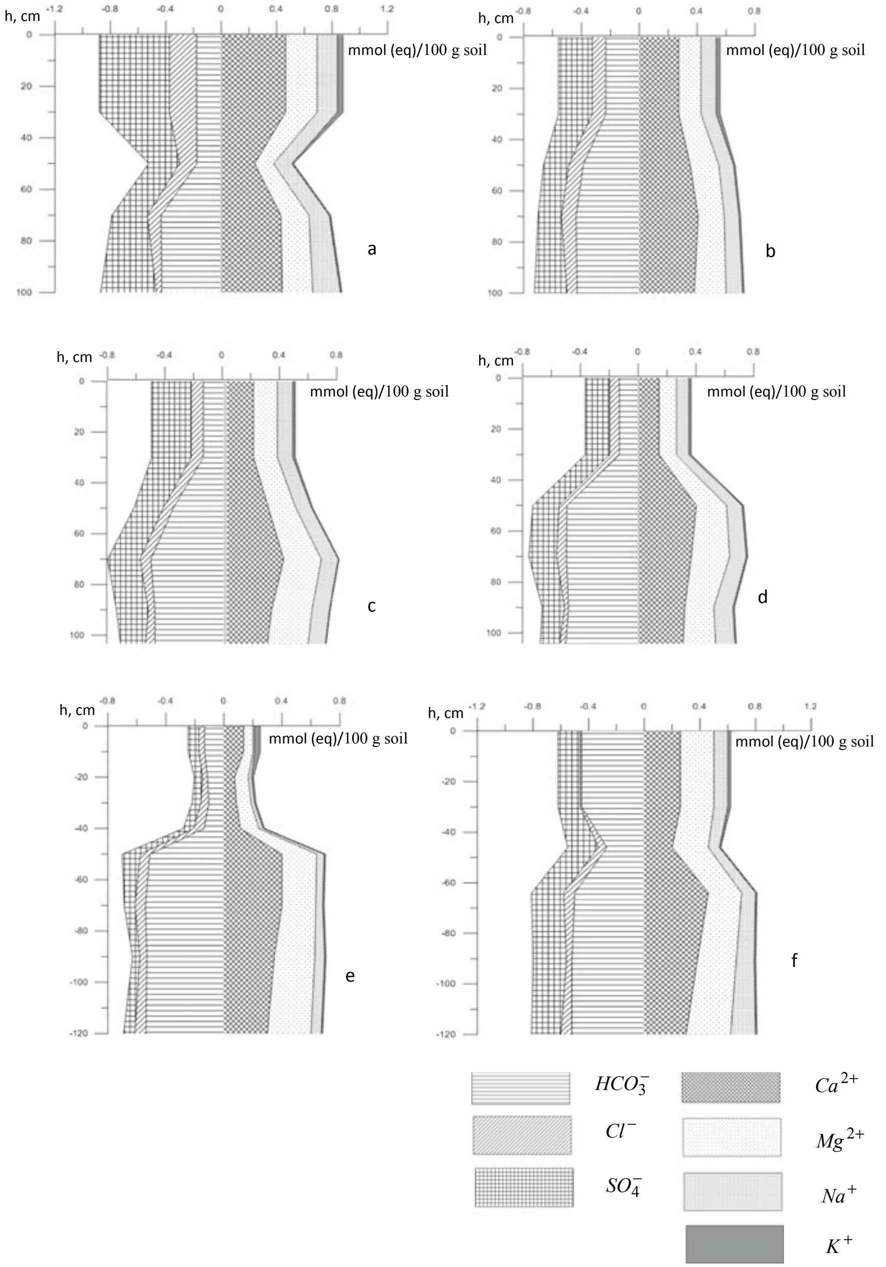

Fig. 28.1 Salt profiles of Southern Black Soils under different irrigation conditions: during the growing season in the rows (**a**) and between rows (**b**), during the post-irrigation period in the rows (**c**) and between the rows (**d**), during the non-irrigation period under spring barley (**f**), and rainfed control (**e**)

Because drip irrigation may impose salinity and/or sodicity, a break of crop should be included in the rotation. We noticed that, in the first year of the break, the spring barley was taller and with bigger ears along the lines of the former irrigated rows.

Conclusions

Long-term application of drip irrigation/fertigation aggravates salinity and sodicity in Southern Black Soils and introduces variability in some indicators of fertility in the zone of intensive wetting. In these soils, salinity is characterized by seasonal pulses associated irrigation and periodic flushing.

Soluble salts accumulate in topsoil and subsoil horizons both in the irrigated rows and between them, both during irrigated growing seasons and between them. The Ca^{2+}/Na^{+} ratio decreased; the $Na^{+} + K^{+}$ to total adsorbed bases increased; and $CaCO_3$ was leached from upper layers (0–50 cm) down the soil profile.

The health of the irrigated Black Soils is not significantly improved by a two year break under rainfed barley. Targeted studies are required to better understand biogeochemical processes and plant–microbe interactions in Black Soils under fertigation so as to develop irrigation-smart regionally specific options to sustain soil fertility.

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Chapter 29
Verification of the Wind Erosion Equation on the Ukrainian Steppe

Sergiy Chornyy and Oleg Pismenniy

Abstract As a basis for the design of anti-deflationary measures, the Wind Erosion Equation has been verified for the steppe zone of Ukraine. Soils may be classified in eight Wind Erodibility Groups (WEG) according to their resistance to deflation, with the lowest potential annual loss (I-factor) zero and the highest 766 t/ha. Generalization of the data on the anti-deflationary stability of soils showed that most soils of loamy and clay texture fall into Group 7 with an I-factor of 94 t/ha/year; the sandy soils of the Oleshkovsky Sands area can be assigned to groups 1 and 5. Study of intra-annual fluctuations of the I-factor, as well as the effect of soil erosion, irrigation, and various kinds of tillage showed that, in most cases, these factors have little effect on the classification of soils by WEG groups. At the same time, slaking of the soil during unstable winter weather conditions can lead to a short-term increase in the I-factor in spring.

Keywords Soil erosion · Wind erosion equation · Wind erodability groups · Chernozem

Introduction

Deflation decimates soil fertility in Ukraine. Its extreme manifestations are *black storms* that cover hundreds of square kilometers. These were first recorded at the beginning of the nineteenth century when the steppes were converted to arable land. Nowadays, with ploughland at its maximum extent, the area vulnerable to deflation across Ukraine is estimated at about 20million hectares, including 16–18 million ha of the steppe (Chornyy 2018). Local outbreaks of wind erosion are observed almost every year and regional or trans-continental dust storms occur every 5–10 years. In the 20th century, trans-continental dust storms swept the steppes from the Altai to the Carpathians—in 1928, 1960, 1968, 1969, 1972, 1974, and 1984. In this century, the catastrophic black storm of March 23/24, 2007, covered much of the Odesa region, the whole of Mykolayiv, Kherson and Zaporizhzhia regions, the north of Crimea,

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the southern regions of the Kirovograd and Dnipropetrovsk regions, and the western regions of Donetsk—an area of about 125 thousand km^2, about 20% of the country and half of the entire steppe zone; soil losses amounted to 50–400 t/ha (Chornyy et al. 2008).

An objective, quantitative basis is needed to design effective anti-deflationary measures; in particular, a mathematical model to quantify the potential soil loss. These values can be compared with the permissible norm to arrive at a scientifically sound system of soil protection for a particular territory—which should include legal, agricultural, and forest reclamation measures. Equations of wind erosion (Wind Erosion Equation—WEQ) were worked out in the USA in the 1950s–90s for the conditions of the Prairie states of the Mid-West (Woodruff and Siddoway 1965; Skidmore and Woodruff 1968; USDA 2011) with the aim of predicting long-term average annual soil losses from a specific agricultural landscape that has certain plant and soil characteristics, roughness, a specific intra-annual distribution of strong winds, specific farming practices, etc. A modified version (RWEQ) was used in the USA until replaced by the new WEPS (Wind Erosion Prediction System) (Wagner 2013). Given the cost of creating our own national system for quantifying wind erosion, and current financial and scientific constraints, it seems reasonable to adapt this well-proven system for the conditions of the Ukrainian steppe, as scientists from Austria, Hungary, Canada, and the Czech Republic have done for theirs (Klik 2004; Mezosi et al. 2015; Huang et al. 2017; Kozlovsky Dufková et al. 2019).

Results and Discussion

By the end of the 1980s, the WEQ equation had acquired a more-or-less complete form (USDA 2011) and made it possible to calculate annual soil losses (E, tonne per acre) according to the formula:

$$E = I \cdot K \cdot C \cdot L \cdot V \tag{29.1}$$

where

I is the indicator of soil wind-erodibility.
C is the climatic parameter of wind erosion.
K is an indicator of the roughness of the soil surface.
L is the value of the *unprotected distance.*
V is an indicator of soil-protective effectiveness of vegetation cover.

The I-index (or I-factor) is the conditional average annual deflationary soil loss in tons per acre/tonne per ha, provided that this section is:

- isolated from external deflation; i.e. there is no input saltation of soil particles from outside
- absolutely flat

- in the territory where the value of the C (climatic) parameter is 100
- without barriers that inhibit the wind (shelter belts etc.)
- without vegetation
- without a soil crust.

As part of the verification of Eq. (29.1) in the United States, the entire list of soils of the sub-humid and semi-arid regions of the United States was classified by wind erodibility groups (WEG) and the I-factor was determined for each group of soils. This grouping is based on the macrostructure, the content of organic matter and carbonates, and the mineralogical composition of the topsoil. Eight classes of soils were determined by their susceptibility or resistance to deflation (1, 2, 3, 4, 4L, 5, 6, 7, and 8) with the lowest I-factor 0 and the highest I-factor of 310 tons per acre per year (766t/ha/year). The current version of WEG is published in the National Soil Survey Handbook (NRCS 2019). According to Chepil (1958), the value of the I-factor is closely related to the content of the aggregates on the soil surface greater than 0.84 mm diameter under dry dispersion conditions. This size fraction is commonly used as an independent indicator of anti-deflation stability, for example in the spatial hazard assessment of wind erosion in Western Europe developed by Borrelli and others (2014). An analagous *lumpiness* indicator (fraction greater than 1 mm) is widely used in deflation studies in Ukraine and a substantial database on *soil loosening* has been accumulated in the steppe zone (Chornyy and Pismenniy 2006, 2008; Chornyy and others 2012; Chornyy and Voloshenyuk 2017). Recalculation of this indicator, i.e. the content of aggregates of more than 1 mm to the content of fraction in the soil of greater than 0.84 mm is a purely arithmetic issue.

The determination of the soil susceptibility to deflation (I-factor) is obtained either by the method in the National Handbook or by the formula:

$$I = 766.78 \cdot \exp(-0.049 \cdot g) \tag{29.2}$$

where g is the fraction content of greater than 0.84 mm with dry soil dispersion.

Generalization of data on steppe soils of Ukraine (Table 29.1) was made only taking into account the content of fractions greater than 0.84 mm. Most soils of loamy and clay texture fall into WEG 7 although the mineralogy of our soils is different from that of US soils in that group. For this WEG group, the I-factor is 94 t/ha/year. Two samples (10 and 11 of Table 29.1) taken in the Oleshkovsky Sands area (the left-bank part of Kherson), loose and cohesive sands according to NRCS (2019), are assigned to WEG 1 ($I = 310$ t/ha/year) and WEG5 ($I = 766$ t/ha/year). It should be noted that two samples with sandy particle size distribution (12 and 13 of Table 29.1) fell into group 7. In the first case, long-term irrigation with mineralized water affects the content of aggregates greater than 1 mm (and greater than 0.84 m) when the saturation of the cation exchange complex with Na^+ and Mg^{2+} ions promote micro- and macro-units that become stronger when dried. In the second case, the formation of windshield aggregates was probably positively affected by the beneficial accumulation of humus in the upper soil layer associated with a high proportion of legumes in crop rotation and the introduction of organic

Table 29.1 Soil resistance parameters against wind erosion

№.	Coordinates at the middle of the site		Soils	Soil texture	Land use	Aggregate content %		*I* (t/ha/year)	WEG
	Latitude (N)	Longitude (E)				<1 mm	<0.84 mm		
1	47° 51.050	31° 34.467	*Ordinary chernozem*	Light clay	Arable	68.8	72.0	22.5	7
2	47° 53.429	31º 33.819	*Ordinary chernozem*	Light clay	Arable	56.5	59.2	42.2	7
3	47° 51.050	31º 34.467	*Ordinary chernozem*	Light clay	Grassland	83.2	87.1	10.7	7
4	47º 53.431	31° 33.000	*Ordinary chernozem*	Light clay	Grassland	78.1	81.8	13.9	7
5	46° 50.766	32º 13.183	*Dark chestnut*	Heavy loam	Arable	69.4	72.7	21.8	7
6	46° 58.702	32º 10.118	*Southern chernozem*	Heavy loam	Arable	62.4	65.3	31.2	7
7	46º 53.966	31º 40.877	*Southern chernozem*	Heavy loam	Grassland	80.2	84.0	12.5	7
8	46° 56.441	31º 40.348	*Southern chernozem*	Heavy loam	Arable	76.5	80.1	15.1	7
9	46º 53.821	31º 39.905	*Southern chernozem*	Heavy loam	Arable	57.4	60.1	40.3	7
10	46° 31.606	32º 58.026	Sandy	Coarse sand	Fallow forest	1.4	1.5	713.6	1
11	46° 31.571	32º 57.220	Sandy	Sandy clay loam	Fallow	32.8	34.3	142.5	5
12	46º 31,453	32º 56.928	Sod- sandy	Sandy clay loam	Irrigated crops	54.7	57.3	46.3	7

(continued)

Table 29.1 (continued)

№.	Coordinates at the middle of the site		Soils	Soil texture	Land use	Aggregate content %		*I* (t/ha/year)	WEG
	Latitude (N)	Longitude (E)				<1 mm	<0.84 mm		
13	46° 24.817	33° 02.355	*Dark chestnut*	Sandy loam	Arable	76.7	80.3	15.0	7
14	46° 23.774	33° 06.191	*Dark chestnut*	Light loam	Arable	80.6	84.4	12.3	7
15	46° 41.189	31° 52.421	*Dark chestnut*	Medium loam	Arable	54.9	57.5	45.9	7

fertilizers. The humus content in these soils was about 1% whereas it is only 0.5% in the sandy parent material.

Given that the sampling was carried out in spring and early summer (March-June), it is necessary to determine how representative the obtained I-factor values are in the local verification of the WEQ equation. Specific local soil conditions can affect the soil deflation resistance, for instance, soil erosion and changing agricultural practices, especially cultivation and irrigation systems, Fig. 29.1 shows the annual fluctuations of the I-factor in the area of lat. 46º 53.821, 31º 39.905 with non-eroded, weakly eroded, and moderately eroded *Southern chernozem*. These fluctuations hardly depend on the soil erosion factor but are determined by other factors—in particular by a sharp drop in the fraction cover greater than 0.84 mm so the growth of the I-factor in spring is associated with the number of freeze–thaw cycles during the winter months. If the number of cycles approaches 50–70, then almost complete destruction of large aggregates is observed.

In other cases, when the winter is persistently cold or warm, there is no such slaking of the soil surface. From the point of view of soil classification in the context of model verification, despite a sharp decrease in the ability of the soil to resist wind erosion in the spring of 2008, *Southern chernozem* were the most wind-resistant over the whole period of observation. Analysis of the I-factor in *Southern chernozem* with irrigation at lat. 46º 56.504, long. 31º 40.607 (Fig. 29.2) shows that the anti-deflation stability

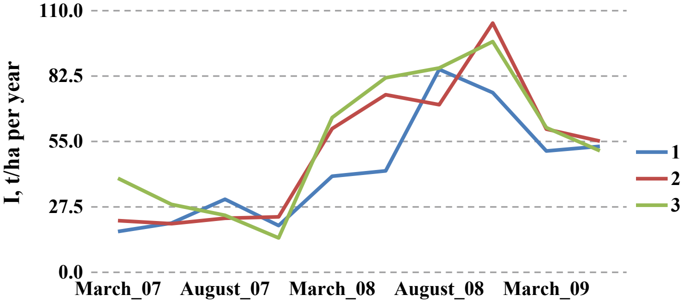

Fig. 29.1 Impact of extant soil erosion on wind-erosion susceptibility (1 non-eroded, 2 weakly eroded, 3 moderately eroded)

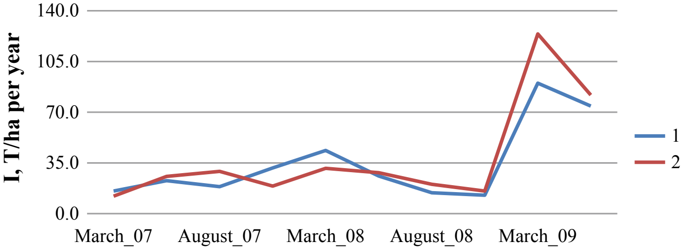

Fig. 29.2 Impact of irrigation on wind erosion susceptibility (1 irrigated soil, 2 non-irrigated soil)

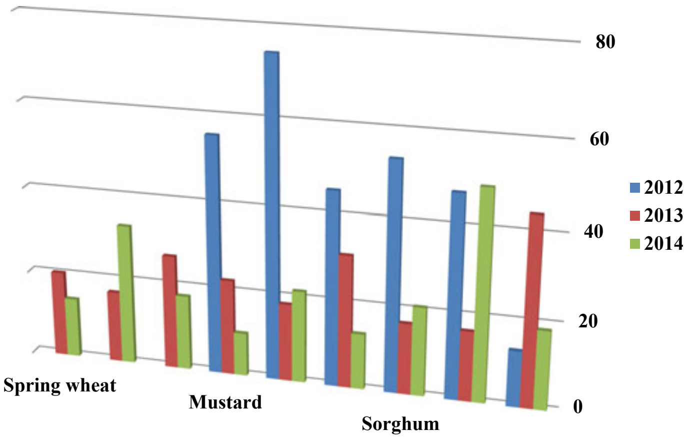

Fig. 29.3 Impact of tillage on wind-erosion susceptibility (left to right: traditional tillage, minimum tillage, no-till)

of these soils does not go beyond WEG 7; the difference of the macrostructure in unstable, short-term winter conditions resulted in an I-factor of 120 t/ha in March 2009 which would indicate WEG 6.

A study of the effect of tillage on the ability of the soil to withstand blowing was carried out 2012–2014 in Askania-Nova, the most erosion-prone part of Ukraine, at lat. 46.549249, long. 33.813563. Chornyy and others (2012) and Chornyy and Voloshenyuk (2017) have shown that under standard and minimal tillage and no-till spring wheat, mustard, and sorghum, the resilience of *Southern chernozem* to wind erosion, determined by the I-factor in the spring, fluctuates between 15 and 65 t/ha per year (Fig. 29.3). These fluctuations are determined not so much by the direct influence of tillage as by the degree of protection of the soil surface by crop residues. In particular, under no-till with the soil surface mulched by crop residues during winter and early spring, the number freeze–thaw cycles is much reduced, so the destruction of structural aggregates on the soil surface is less intense.

Conclusions

1. The design of effective anti-deflation measures is possible only on an objective, quantitative basis. The well-established WEQ technology predicts long-term average annual soil losses while accounting for soil parameters, surface roughness, intra-annual distribution of strong winds, and the effects of agricultural machinery, growing crops, etc.
2. Generalization of the data on the anti-deflation stability of the soils of the region showed that most loamy and clayey soils fall into the WEG group 7 (the I-factor

is 94 t/ha/y). Some sandy soils of the Oleshkovsky Sands region can be assigned to group 1 ($I = 310$ t/ha per year) and group 5 ($I = 766$ t/ha per year).

3. Study of intra-annual fluctuations of the I-factor, as well as the effect of soil erosion, irrigation, and various tillage system reveals no strong relationship with WEG groups. However, there is a clear relationship between susceptibility to blowing and soil cover and structural stability, for instance when unstable winter weather slakes the soil surface causing a short-term increase in the I-factor in spring.

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Chapter 30
Promoting Agroforestry Within the Agricultural Competitiveness Project in Moldova

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Abstract Moldova faces big challenges from soil and land degradation and climate change, especially in the south of the country. Agroforestry practices are effective remedies for soil degradation and have been implemented within the Support for Rehabilitation of Forest Protection component of the Moldova Agricultural Competitiveness Project. The network of 2.2 thousand ha of shelter belts in the south of the country has been rehabilitated, protecting a tract of 63 thousand ha. Additional carbon sequestration amounts to 7.9 tCO_2eq/ha/year, a net carbon capture of 70,000 tCO_2eq and, as a by-product, the Moldsilva Agency undertaking the works delivered 13,000 m^3 of firewood to the local authorities.

Keywords Agroforestry · Shelterbelt · Climate change · Carbon sequestration

Introduction

Several international agencies have drawn attention to global, regional, and local crises and conflicts arising from a nexus of food, water, energy, environmental, climatic, social, and political issues (amongst others UNEP 2007; IPCC 2014, 2019). Everywhere, problems of economic and social development demand urgent protection and conservation of soil, water, forests, and wetlands. Soil is the natural wealth of Moldova. It underpins the economy and the welfare of the people, and it is the best buffer against climate change that is already showing itself in rising temperatures and a change in the character of the rainfall that brings increasing drought, floods and landslides (Ciubotaru 2000). Harmonious, integrated management of soil and land resources is an imperative and, of course, not only in Moldova.

Adaptation to climate change requires the creation of optimal conditions for agriculture and forestry (Government of Moldova 2008), which means adopting new practices for soil management and crop husbandry. Agroforestry occupies a special place where arable crops, grassland, fruit, and forest trees, livestock, natural habitat

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and biological diversity share the same space. By design, agroforestry systems regenerate soil, water, and biological resources and thus ensure benefits not only to farmers but, also, to the environment (Galupa et al. 2017a). Depending on the purpose, location, and local soil and climate, some or all of the following practices may be appropriate:

- afforestation of degraded lands
- multipurpose trees and shrubs within farmland
- shelter belts
- alley cropping between tree rows
- cover crops in place of fallow
- productive, protective fences.

The Moldova Agriculture Competitiveness Project (MACP) aims to boost the agricultural sector and local products by integrating ecological agriculture and sustainable land management (Andreev et al. 2017). The Support for Rehabilitation of Forest Belts sub-component, implemented during 2012–2017, has made good a quarter of a century of neglect by rehabilitating 2200 ha of shelterbelts (*forest protection belts* in Romanian) in the south of the country. The shelterbelt network protects the land from various harmful factors, ameliorates local climate and, indeed, enhances the landscape (Paladiychuk 1986) by:

(a) Improving the microclimate through modifying albedo, moderating air temperature, cutting wind speed, retaining snow, cutting unproductive evaporation, and increasing humidity. The diurnal amplitude of the air temperature may be reduced by 1–4 °C and the annual range by 1–2 °C; wind speed is reduced by 31–55% in the shelter belt itself and by 10–15% across the protected areas; unproductive evaporation is reduced by as much as 30%; and humidity at ground level is increased by 3–5%. All this improves the growing conditions of crops to a distance of 20–30 times the height of the shelterbelt downwind and 5–12 times its height upwind.
(b) Improving soil and water conservation by cutting runoff, increasing infiltration, increasing accumulation of organic matter, and arresting erosion by wind.
(c) Increasing biodiversity by creating favorable conditions for wildlife
(d) Remodelling the landscape.

At present, the total area of shelterbelts in the country is 30.7 thousand ha (Government of Moldova 2018), of which 5.7 thousand ha is under State management, 24.9 thousand ha under local authorities, and only one hundred ha in private hands. Their original purpose was to arrest soil erosion but, also, to obtain valuable food products (Bordyug et al. 1972) which determined their composition:

- walnut 38%
- acacia 36%
- oak 9%
- other species (elm, ash, sophora, cherry, poplar, etc.) 17%.

Overall, shelterbelts occupy 1.7% of the arable but, taking account of recommendations in respect of relief, soils and climate the quota should be greater than 4% (Ungureanu et al. 2006), which would be an increase of about 40 thousand ha.

Results and Discussion

Agroforestry Practices Applied

During MACP implementation, specialists of Forestry Research and Management Institute (FRMI) evaluated the agroforestry practices applied in each of the 12 administrative districts encompassed by the project (Galupa et al. 2017b, Table 30.1). About 45% of the country's shelterbelts are situated in the project area.

Complex measures are needed to protect agricultural land but, for a start, another 22,000 ha of shelterbelts are needed to reach the 4% threshold in the south of the country which is suffering alarming soil degradation. MACP has supported community-level activities to reverse the atrophy of the existing shelterbelt network; no less than 75 local authorities are responsible for the 2428 ha of shelterbelts. Rehabilitation was carried out by 9 forestry enterprises under the Moldsilva Agency: Forestry Enterprise (FE) Iargara, FE Silva-Sud, FE Comrat, FE Cimislia, FE Hancesti-Silva, FE Tighina, FE Chisinau, FE Manta-V, FE Sil-Razeni. FRMI provided technical assistance through:

- Public presentation of agroforestry practices currently applied in the south of the country and recommended technical measures for rehabilitation of shelterbelts
- Developing technical guidelines, including cost estimation for recommended activities
- Consultancy on formal approvals needed for work on the ground
- Determining measurable indicators for each rehabilitation activity, and monitoring or supervising the works
- Consultancy on planting trees and shrubs on degraded land and arable land to comply with technical norms and project requirements.

Rehabilitation began as soon as the local authorities transferred their management responsibilities to the forestry enterprises. In some cases, three or four technical solutions were combined (Table 30.2): often, clear felling was chosen (1197 ha or 54%), otherwise pruning (315 ha or 14%) or reconstruction (253 ha or 11%). At the outset, fire breaks were identified as a key element in the integrity of shelter belts around cropland; stubble burning causes a lot of damage to the environment, especially to shelterbelts.

About 23.3 million MDL (1.2 million Euro) or an average of 10.4 thousand MDL/ha from the state budget was invested in shelterbelt rehabilitation during MACP implementation. The greatest costs were for reconstruction works (26.2 thousand

Table 30.1 Agroforestry in the MACP project area

Administrative district	Area of district, thousand (ha)	Farmland, thousand (ha)	Forest plantations, thousand (ha)				Proportion of shelterbelts within agricultural land (%)
			Total	Including			
				Forest land	Of which		
					Forest vegetation	Shelterbelts	
Basarabeasca	31.8	23.0	3.1	2.5	0.6	0.6	2.6
Cahul	154.5	84.6	18.1	15.7	2.4	2.1	2.5
Cimislia	102.6	71.1	12.9	11.5	1.4	1.3	1.9
UTA Gagauzia	184.8	147.0	17.7	14.7	3.0	2.7	1.8
Leova	76.5	57.2	11.8	9.6	2.2	0.9	1.5
Anenii Noi	88.8	65.9	12.2	11.0	1.4	0.7	1.1
Hancesti	147.2	92.7	39.0	36.7	2.3	0.9	1.0
Ialoveni	78.4	52.4	14.8	13.6	1.2	0.6	1.1
Cantemir	86.8	64.4	12.7	11.5	1.2	0.9	1.4
Causeni	131.1	102.1	16.1	14.6	1.4	1.1	1.1
Stefan-Voda	99.8	78.5	9.6	8.5	1.1	0.9	1.1
Taraclia	67.4	54.7	5.7	4.3	1.4	1.1	2.0
Total	1249.7	893.6	173.6	154.0	19.6	13.7	1.5
Proportion (%)	*100*	*71.5*	*14*	*12*	*2*	*1*	

Table 30.2 Areas rehabilitated by different technical solutions

No.	Technical solutions	Area (ha)	Percentage
I	Reconstruction works, total	253	11.3
1.1	Replanting	253	11.3
II	Stimulation of natural regeneration, total	20	0.9
2.1	Coppicing	4	0.2
2.2	Completion/tree planting	15	0.7
III	Forestry treatments, total	252	11.2
3.1	Extraction of pre-existing trees	210	9.4
3.2	Tree planting	64	2.9
3.3	Coppicing	156	6.9
IV	Tending activities, total	1197	53.4
4.1	Tending coppice in young plantations	760	33.9
4.2	Thinning	239	10.7
4.3	Removing dead and diseased wood	198	8.8
V	Pruning	315	14.0
VI	Crown and canopy thinning	66	2.9
VII	Tending undergrowth	12	0.6
VIII	Creation and maintenance of fire breaks	127	5.7
Total		2242	100

MDL/ha), and the least for stimulation of natural regeneration of acacia (0.3 thousand MDL/ha).

After completion of the rehabilitation works, the shelterbelts were returned to the local authorities, which can request any necessary technical and advisory support from FRMI and/or the local forestry enterprises. For the post-project stage, FRMI specialists have developed technical recommendations to improve the quality and functionality of the shelterbelts, in particular, to guard against grazing and illicit logging, and the creation and maintenance of fire breaks.

Area of Farmland Protected by Shelter Belts Rehabilitated Within MACP

A conservative estimate of the area of farmland protected was made according to the structure, composition, number of component rows of the rehabilitated shelterbelts (Galupa 2017b; Zaytsev 1965; Romashov 1958). The most effective structure comprises 3–9 rows of deciduous trees which protects, on average, 35 ha per hectare of shelterbelt. However, many existing shelterbelts composed of only one or two rows of common walnut planted at 4–8 m intervals along the rows and with 6–12 m spacing

Table 30.3 Species present in the rehabilitated shelterbelts

Main species (Romanian)	Area (ha)	%
Walnut (Nuc/NU)	560	25
Acacia (Salcam/SC)	1016	46
Ash (Frasin/FR)	146	7
Elm (Ulm de camp/ULC)	118	5
Plane (Paltin/PA)	79	4
Oak (Cvercinee/ST)	74	3
Honey locust (Gladita/GL)	52	2
Sophora (Sofora/SF)	38	2
Cherry (Cires/CI)	24	1
Poplar (Plop/PL)	22	1
Others (Alte specii/AS)	70	3
Total	2200	100

between the rows have a much smaller radius of influence: on average 12 ha/1 ha for a single row of walnut, 15 ha/1 ha of shelter belt for a double row, and 20 ha/1 ha for a double row of other deciduous species. Table 30.3 lists the main species present.

Thanks to the rehabilitation of the 2200 ha of shelterbelts, 63 thousand hectares of farmland have been protected (Table 30.4). The greatest protection is afforded by shelterbelts comprising 3–9 rows (50 thousand ha or 79%); those consisting mainly of acacia protect about 34 thousand ha of farmland (54% of the total protected area).

Estimation of Benefits

Agricultural Production

Table 30.5 summarises the agronomic benefits arising from the rehabilitation of shelterbelts based on the average cost of shelterbelt establishment (34.9 thousand MDL/ha), the yields of the main crops in southern part of the country (winter wheat, maize, sunflower, soya) according to agricultural statistics (Valcov et al. 2018), the yield increase attributable to the shelter, the average field size (43 ha), and the total area of the bordering shelterbelt (4.14 ha). It demonstrates a positive cost–benefit balance of shelterbelts of 8.2–9.5%. This benefit is more pronounced in dry years. The shelterbelts ensure that the soil stays where it belongs so this production can continue indefinitely; and the relatively small cost of maintenance of the shelterbelts is, self-evidently, a very good investment.

Table 30.4 Area of farmland protected by rehabilitated shelterbelts

Main species	Number of rows								Total	
	1		2		3–9		≥ 10			
	Area (ha)	Protected area (ha)	Area (ha)	Protected area (ha)	Area (ha)	Protected area (ha)	Area (ha)	Protected area (ha)	Area (ha)	Protected area (ha)
SC	0	0	6	112	874	30,578	137	3423	1016	34,112
NU	139	1667	360	5394	62	2153	0	0	560	9215
FR	0	0	7	147	121	4242	17	432	146	4821
ULC	1	8	13	255	85	2976	19	485	118	3724
PA	0.6	7	6	123	73	2542	0	0	79	2672
ST	0.2	3	4	79	70	2457	0	0	74	2539
GL	3	35	8	159	41	1446	0	0	52	1639
SF	0	0	0	0	38	1338	0	0	38	1338
CI	7	80	17	340	0.6	20	0	0	24	440
PL	12	144	9	175	0.9	30	0	0	22	349
AS	3	34	5	108	62	2168	0.0	0.0	70	2311
Total	165	1978	435	6892	1427	49,950	174	4340	2200	63,159
%	*8*	*3*	*20*	*11*	*659*	*79*	*8*	*7*	*100*	*100*

Table 30.5 Benefit: cost analysis of the use of shelterbelts in agricultural practice

Indicator	Measurement unit	Agricultural crops				
		Maize grain	Winter wheat	Soy	Sunflower	Average
Yield	t/ha	5.5	3.1	2.3	2.2	3.3
Cost of agricultural production	lei/t	2278.0	2493.0	5609.0	5050.0	3857.5
Value of agricultural production	1000 MDL/ha	12.6	7.8	13.1	11.0	11.1
Value of agricultural production for a 43 ha field	1000 MDL	539.7	336.6	564.4	473.4	478.5
Increase of production from shelterbelt influence (17.5%)	1000 MDL	94.5	58.9	98.8	82.8	83.7
Income from the wood	1000 MDL	46.6	46.6	46.6	46.6	46.6
Income from non-wood products and other	1000 MDL	20.3	20.3	20.3	20.3	20.3
Total complementary income	1000 MDL	161.3	125.8	165.6	149.7	150.6
Cost of shelterbelt creation (7/3 rows; 4.14 ha/2 fields)	1000 MDL	72.2	72.2	72.2	72.2	72.2
Cost of tending and maintenance works for shelterbelts	1000 MDL	5.8	5.8	5.8	5.8	5.8
Loss of farmland to shelterbelts (6% from total agricultural production)	1000 MDL	32.4	20.2	33.9	28.4	28.7
Total costs	1000 MDL	110.4	98.2	111.9	106.4	106.7
Balance of cost and income	1000 MDL	+50.9	+27.5	+53.7	+43.3	+43.9

(continued)

Table 30.5 (continued)

Indicator	Measurement unit	Agricultural crops				
		Maize grain	Winter wheat	Soy	Sunflower	Average
Percentage from the total production	%	+9.4	+8.2	+9.5	+9.1	+9.1

Carbon Capture

Carbon stocks in the standing vegetation were estimated before and after rehabilitation using AR-AM0002 methodology approved by the Clean Development Mechanism of the UNFCC Kyoto Protocol, (Forest Agency Moldsilva and GFA Terrasystems Winrock International 2009) taking account of the initial carbon stock in 2014, changes in the carbon stock immediately after the rehabilitation works in 2016, and changes in carbon stock post-implementation in 2019 (Galupa et al. 2019). Sample plots were established and measurements carried out according to:

- Main species: oak, acacia, walnut
- Type of rehabilitation work: *reconstruction* (includes reconstruction works, stimulation of natural regeneration, forest treatments), *tending* (spacing, thinning, etc.), *tending of tree stands and undergrowth* (pruning, crown, and canopy thinning, tending works applied for undergrowth).

To ensure continuity and comparison of results, the same stratification was applied over the three periods, constituting 28 sample plots representing eight relatively homogeneous strata over the initial project area of 2200 ha (Table 30.6).

Table 30.6 Sample size for the estimation of carbon in biomass

Strata	Name of strata	Area (ha)	Number of sample plots
Stratum 1	Oak, replanting	127	3
Stratum 2	Oak, tending trees	262	3
Stratum 3	Oak, tending trees and undergrowth	235	2
Stratum 4	Acacia, replanting	206	5
Stratum 5	Acacia, tending trees	810	10
Stratum 6	Walnut, replanting	114	2
Stratum 7	Walnut, tending trees	232	2
Stratum 8	Walnut, tending trees and undergrowth	214	1
Total		2200	28

Table 30.7 Carbon stock in plots rehabilitated within MACP

Project stage	Carbon in tree and bush biomass (tC)	Carbon stock in litter (tC)	Carbon stock in soil (tC)	Total carbon stock in MACP (tC)
Initial, 2014	39,774	7458	166,844	214,769
After rehabilitation, 2016	59,962	21,066	144,787	225,815
Post-implementation, 2019	72,883	12,594	147,524	233,001
Difference (%)	+83	+69	−12	+9

Plots for estimating soil carbon were stratified according to the soil quality score that indicates the amount of humus in the topsoil. The assessment of the initial state of the shelter belts suitable for inclusion in the MACP did not foresee a soil study so statistical data were used to estimate soil carbon. Two strata were established within which 15 sample plots were used to calculate soil carbon:

- Poor soils (humus < 2%)—1715.3 ha (13 sample plots)
- Rich soils (humus > 2%)—484.7 ha (2 sample plots).

Table 30.7 lists the carbon stocks arrived at from the field measurements and calculation of carbon stock in all sinks (trees, bushes, litter, and soil). According to the measurements from 2019, it was found that the MACP plots contain 233 thousand tonne of carbon (standing biomass, litter, soil) or 105.9 tC/ha, equivalent to 854 thousand tonne of CO_2.

The beneficial effects of shelter belt rehabilitation includes an increase of above-ground and below-ground biomass and an increase of litter which immediately affects the carbon stock in soil. At the same time, the differences between 2016 and 2019 are smaller compared to those between 2014 and 2016, which confirms the stabilization of carbon reservoirs after cutting and extraction of old and dead trees, soil disturbance, etc. To estimate net cumulative carbon sequestration (tree biomass, litter, soil), the difference between the stock *ex ante* (2014) and the *ex post* (2019) was calculated (Table 30.8): a gain of 7.89 tCO_2eq/ha/year or a cumulative value of 69 392 tCO_2eq.

Table 30.8 Net carbon/GHG reductions on the plots rehabilitated under the MACP

Element	Actual net carbon stock, *ex post* (tC)	Net carbon stock, *ex ante* (tC)	Net carbon stock change (tC)	Total net GHG drawdown from the atmosphere (tCO_2eq)	Net GHG drawdown by sinks (tCO_2eq/ha/year)
Total	233 001	214 076	+18 925	69 392	7.89

Conclusions

Rehabilitation of the shelterbelt network yields many and various social and economic benefits in rural areas. In addition to creating temporary and permanent jobs replanting and tending, guarding, and harvesting the trees, 12,500 m^3 of wood was harvested and handed over to the local authorities to supply firewood to socially vulnerable families.

Environmental benefits become apparent within 3–6 years of establishment or rehabilitation of shelterbelts, culminating within 10–12 years. Shelterbelts increase crop yields by 15–20%, which yields a positive cost–benefit balance, and the estimated value of the complementary production (wood, non-wood forest products, etc.) constitutes about 10% of the total production of the adjacent farmland. And, finally, the capacity of the shelter belts to capture carbon dioxide is significantly increased. An increase of the above-ground and below-ground biomass of the trees and shrubs and, the increase of the quantity of litter has a direct impact on the amount of carbon stored in the soil. The shelterbelts rehabilitated within the MACP have achieved net carbon capture of 7.9 tCO_2eq/ha/year, or a cumulative gain of 69,392 tCO_2eq.

Another important aspect is the testing and modeling of the technical solutions that have contributed to the efficiency of the rehabilitation process and the performance of the shelterbelt network. These technical solutions and improvements will be used in the rehabilitation of the entire network of shelter belts across the country to protect farmland from wind, runoff, and soil erosion; improve infiltration, storage and utilization of rainfall and snowmelt; increase soil organic matter; and increase biodiversity.

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Chapter 31

An Investable Proposal for Regenerative Agriculture Across the Steppes

David Dent and Boris Boincean

Abstract Farmers are responsible for one-third of greenhouse gas emissions and there is no plan to deal with this; their impact on land and water resources, floods, droughts, and the global extinction of species also cries out for attention. Half of the humus that makes the Black Earth what it is has been pumped into the air and, with it, the soil's capacity to receive rainfall, supply water to crops, and recharge streams and groundwater is diminished. Since 1970, soil carbon across the steppes has been run down by 2.4–3.8/tC/ha/yr (5 times more where the soil has been eroded). Taking the least of these figures, mineralization of soil organic carbon (SOC) has emitted 195 Gt or 25 ppm of atmospheric CO_2. Adoption of Conservation Agriculture that includes a diverse crop rotation with perennial legumes and grasses offers *carbon capture* of 0.5–1 Gt/yr, arrest of soil erosion, and bigger crops. At present, there is no market for the perennial grasses and legumes needed to put the organic matter back into the soil. The old-fashioned answer is to integrate crops and livestock – farmyard manure doubles the benefit of crop rotation, integrating crops and livestock will regenerate rural communities, and the extra production will make space to restore degraded land for wildlife, water resources, and amenity. But the people and skills needed for livestock enterprises are now hard to come by. Alternatively, the green biomass can be converted to biogas: a ready market for all the green biomass that can be grown would transform farming systems. This would be a strategic investment that can easily be funded through Green Bonds.

Keywords Mitigating climate change · Carbon capture · Integrating crops and livestock · Biogas · Green Bonds

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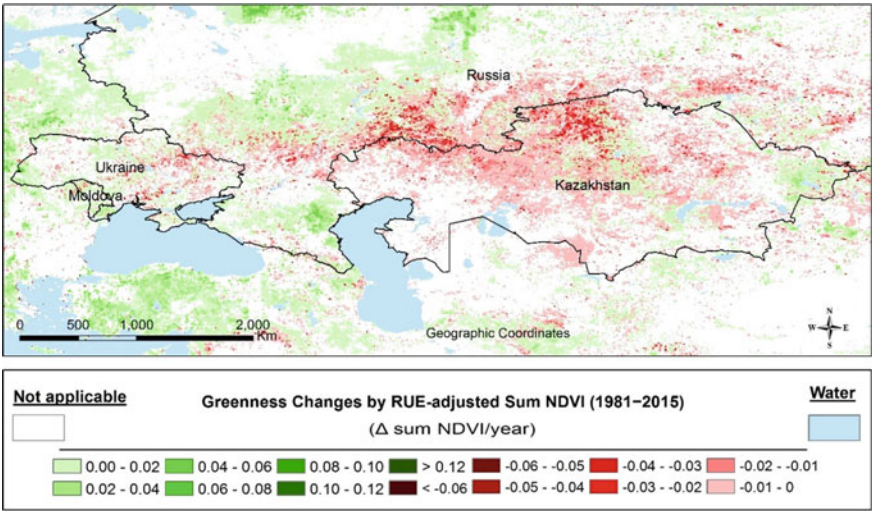

Fig. 31.1 Trends of normalized difference vegetation index across the Steppes, after Bai et al. 2015)

Context

Soil holds more carbon than the atmosphere and all standing vegetation put together; it is the biggest brake on global heating. But farmers have been burning off soil organic matter for 12 thousand years and have run up a carbon debt of not less than 133 billion tonnes; the biggest debts on the best soils (Sanderman et al. 2017). The best thing they could do for the planet is to put it back again—and the best place to start is the breadbasket—the Black Earth of the Steppes and Prairies that produces more than half of all the grain traded internationally.

Over the last century, half of the humus that makes the Black Earth what it is has been pumped into the air and, with it, the soil's capacity to receive rainfall, supply water to crops, and recharge streams and groundwater. Thirty five years of satellite measurements of the normalized difference vegetation index (NDVI) that equates to carbon-capture capacity, reveals a dramatic decline across the Steppes (Fig. 31.1). The best soil in the world is the worst example of land degradation. And not for the first time—in the 1930s, three-quarters of the topsoil and three and a half million Americans and left the Dust Bowl of Great Plains.

Conservation Agriculture

After the Dust Bowl, soil conservation measures were developed: contour bunds, terraces, grassed waterways, and the like. They were never popular because their cost and continual upkeep are not recouped; and they don't deal with the root cause of soil erosion—*bare soil*. Annual crops give scant protection against the elements and ploughing accelerates the loss of humus that brings about the collapse of soil structure, erosive runoff, and loss of topsoil in dust clouds. Conservation Agriculture (CA) is a different paradigm embracing *zero tillage, continuous ground cover* by crops or crop residues, and *crop diversification* through rotations that control weeds, pests, and diseases. It works everywhere for the simple reason that it eliminates destructive tillage and the daily attacks of sun, wind, and rain. The purpose of ploughing is to kill weeds: desiccant herbicides made zero tillage a viable proposition—offering arrest of soil erosion, drought proofing, more reliable yields, more planting days, less outlay on farm machinery, a simpler operation to manage, and 70% less fuel consumption and labour.

Greenhouse Gas Emissions and Potential Extra Grain Yield

The pre-industrial concentration of CO_2 in the atmosphere was 280 ppm: land-use change and burning fossil fuels have boosted it beyond 400 ppm. This is forcing global heating. To hold global temperatures within 1.5 °C of the pre-industrial level, emissions must be halved by 2030, eliminated by 2050 and, then, the excess greenhouse gases must be hauled back (IPCC 2019).

Agriculture is responsible for one-third of greenhouse gas emissions *and there is no plan to deal with this.* Instead of absorbing CO_2, agriculture is pumping it out: *more soil organic carbon (SOC) is being lost by mineralization than is being put back with fresh organic matter*. Across the Steppes, SOC has been run down by 2.4–3.8/tC/ha/yr since 1963–5 times more where the soil is eroded (Boincean and Dent 2019). Taking the least of these figures and Liu's estimate of the area of Black soils across the Eurasian steppes (4.85 million km^2, Liu et al. 2012), and assuming two-thirds of this area is under the plough, mineralization of SOC has emitted 195 Gt or 25 ppm of atmospheric CO_2 since 1970. Table 31.1 presents the situation in Russia, Ukraine, Kazakhstan and Moldova; in the table, Black Earths encompass Chernozem and Phaeozem.

These emissions can be halved, simply by eliminating black fallow. The whole CA package offers *carbon capture* of 0.7–1.5 tC/ha/yr, arrest of soil erosion, and bigger crops. Current commercial yields are about 2 t/ha; the effect of crop rotation, about one tonne/ha increase in the yield of winter wheat, will make up for the loss of one-third of the sown area of cereals, making room for the perennial grasses and legumes that we need to put the organic matter back into the soil.

Each hectare of lucerne will fix at least 50kgN from the atmosphere (our data suggest 100 kg/ha) so we can cover at least half if not all the cost of nitrogen fertilizers which are, themselves, a significant contributor to global heating. The problem is that there's no market for perennial grasses and legumes. Coke of Norfolk's answer, in 1776, was to integrate crops and livestock that turn them into meat, milk, wool, and manure—and we know that farmyard manure doubles the benefit of crop rotation. Under this system, the four countries could produce 40million tonnes of wheat more

Table 31.1 Potential of CA to cut atmospheric CO_2 and raise crop yields

Country	Total area (K km^2)	Area of Black Earth (K km^2)	Arable Black Earth (K km^2)	Area of Chestnut Earth K km^2	Arable Chestnut Earth (K km^2)	CO_2 emissions 1970–2020 Gt (ppm)	Double cereal yield from 0.66 area (million t)	Area under CA in 2015/6 (K km^2)
Russia	17,098	1348	1078	394	177	75.9 (9.7)	+27.3	50
Ukraine[a]	603	265	233	13	11	14.8 (1.9)	+9.1	7
Kazakhstan[b]	2725	212	126	855	132	15.6 (2.0)	+4.2	27
Moldova	34	27	22	Nil	Nil	1.3 (0.2)	+0.6	0.6

1 Gt = 1000 million tonne; 1 ppm atmospheric CO_2 = 7.8G t

[a] Baliuk et al. (2015)

[b] Govt Kazakhstan (2019)

than now; integrating crops and livestock will regenerate rural communities; and the extra production will make space for restoration of degraded land for wildlife, water resources, and amenity. But the people and skills needed for livestock enterprises are now hard to come by.

Alternatively, the biomass can be converted into biogas. In Moldova, two-years-in-six under perennial legumes and grasses would transform annual emissions of 1.2 $GtCO_2$ to *annual carbon capture* of 7.3 million tonnes *and* produce all the nitrogen needed for optimum crop yields—with huge savings in the energy-cost of nitrogen fertilizers. The digestate from biogas production is first-class organic fertilizer that will recycle all the plant nutrients and a goodly portion of the organic matter. Assuming that we re-introduce 666,000 ha of lucerne, the annual crop of green biomass will be 21.6 million tonnes and that will yield 2 371 million m^3 of biogas.[1] This can be injected into the gas grid or be used on site to generate 23.7 million MWh of electricity valued at $15/MWh and an equivalent amount of heat. To produce this electricity requires an installed generating capacity of 3180 MW; that is about double Moldova's present actually used generating capacity and nearly the position of Germany that, in 2015 had 8726 methane plants in place with a total capacity of 3905 MW—achieved by building more than one thousand biogas plants a year for several years (Zorg Biogas Ukraine Ltd. 2020; Triboi and Triboi-Blondel 2021).

Our simplistic calculation assumes large commercial biogas installations of about 500 kW capacity that require efficient logistics to feed the digesters and, in the other direction, distribute the spent organic matter back to the land as organic fertilizer. The alternative is many more farm-scale operations centred on plants of about 125 kw capacity working with about 10t/day of silage or green press cake or 40 t/day of livestock slurry. With smaller-scale operations, a greater proportion of crop residues can be utilized, transport costs much reduced, and power generation would become a transformative farm enterprise.

Opportunities for Green Bonds

CA will go a long way to meeting the commitments of the Paris Accord on climate change (UN 2015). It will immediately save more than half the farmers' annual fuel costs and achieve a better rate of return than present farming systems. CA has already been adopted over more than 200 million ha (15% of all cropland but 60% in Brazil and 75% in Australia). In the four steppe countries, 10 million ha are under CA *but uptake is not equal to the scale and urgency of the challenge*. Kazakhstan is a priority (Fehér and Fieldsand 2019) it is strategic within China's Belt and Road initiative and, with 2.5 million ha already under CA, farmers have developed viable

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[1] In 1990 within the Soviet Union, Moldova devoted 300,000 ha to rotational forage crops, producing 9.8 million tonne of green mass; all this was abandoned along with most of the livestock. Conversion of green press cake (80% water) is 110m^3 gas per/tonne. 100 tonne biomass/day generates 1 MW.

crop rotations. At the same time, it is at the dry end of the Steppes with a lot more land degradation than improvement. Russia and Ukraine are lagging. Moldova has hardly begun. Investment in know-how and infrastructure could speed things up but the task is so great that a new means of finance is needed.

The Paris Agreement was forced on governments by the world's bankers, insurers, and pension funds: the alternative is global bankruptcy. Corporate reporting on how companies are accounting for climate change reveals risks assessed in $trillions—and matching finance has been lined up to counter these risks (Carney 2019): $trillion this year, $120 trillion by 2030. The cheapest source of finance for governments or municipalities that have the capacity to undertake the work is to issue Green Bonds (Green Finance Taskforce 2018). Every bond offered has been oversubscribed; what is lacking are investable proposals, so here is an investable proposal that can be adapted to each of the four countries. It will be necessary to aggregate many farm-scale projects (little projects cannot be financed because of the substantial issuance costs) but direct returns on this investment that will easily repay the bond include the potential for more than doubling exports of grain, new livestock industries, and self-sufficiency in renewable energy. And a more diverse rural economy will bring profound social benefits.

National Action Plans for Transition to Sustainable Agriculture

Action to achieve sustainability within 5 years:

1. *Stop ploughing*
2. *Don't fallow.* Instead, sow annual medic or under-sow the main crop with a mixture of perennial legumes and grasses.
3. *Adopt a diverse cropping system.* This is crucial. Only crop rotations that include perennial legumes and grasses generate enough root mass to replace the humus lost by mineralization; legumes fix nitrogen that replaces costly fertilizer; and break crops control weeds, pests, and diseases without resort to toxic chemicals.
4. *Integrate crops and livestock.* The problem with diverse rotations is how to turn the green mass into cash. The Norfolk 4-course rotation depended on integration of crops with livestock but livestock require daily attention and a skilled workforce, and a livestock industry requires investment in infrastructure. *Alternatively, green crops can feed biogas plants* – proven technology that offers energy self-sufficiency and, as a by-product, organic fertilizer.
5. *Plant windbreaks* against a drying climate. Greater biodiversity will redress the balance between pests and allies and cut the need for chemical sprays and seed dressings.

Costs: Re-equipment costs are manageable given that the costs of replacing machinery come around all too often and *less power will be needed.* Countrywide adoption of no-till in Kazakhstan will require new machinery costing some $4.5 billion; Moldova will need $450 million.

Windbreaks should make up 4% of the arable. For Moldova, this means an additional 40,000 ha at a cost of $80 million. For Kazakhstan, 2 million ha will be needed at a cost of about $4 billion—a big job but more than 2 million ha was planted between 1949 and 1953 under Stalin's Plan for the Transformation of Nature.

Short-term cover against farm losses in transition to CA: If it were done all at once, countrywide adoption of a diverse crop rotation in Kazakhstan might forego 10million tonne grain worth $1.2 billion in the first year or $222 million annually spread over five years; say one tenth of this for Moldova. Alternatively, incentives may be offered in the shape of payments for environmental services, such as carbon credits and green water credits.

Infrastructure: CA depends on crop rotation to control weeds, pests and diseases, and perennial grasses and legumes to regenerate soil fertility. Infrastructure for a livestock industry includes housing, water supply, processing, transport, and marketing. Given the market demand, this should be self-financing. *Biogas would be a strategic investment for Moldova and Ukraine and the creation of a market for biomass would obviate the need for other incentives.* In Moldova, the annual production of green mass would provide enough biogas to meet the country's power requirements; in Ukraine, biogas production could replace all the existing coal-fired power stations; as energy exporters, Russia and Kazakhstan face more-nuanced decisions. If we take a 500 kW biogas plant as a standard unit, the installed cost of each one will be about $2 million so for Moldova to replace its present coal-fired generating capacity will need 3200 × 500 kW plants at total cost $6.4 billion; to make use of all the projected biomass will require 6360 × 500 kW plants, costing $12.7 billion at today's prices. For Ukraine to phase out its present coal-fired generating capacity of 24 GW, which has to be done in any case, will need 48 thousand 500 kW plants, costing $96 billion. This is the kind of money that Green Bonds are designed for.

Smarter farmers: Farms have had to get bigger or go out of business. They have shed labor and adopted simplified farming systems that depend on ever-more-powerful machinery, more-potent pesticides and fertilizers, smarter irrigation, and new crop varieties that can take advantage of the new technology. But CA demands smarter farmers. How much are they worth? Re-skilling of agriculture needs an extension service that itself needs staff, training, facilities, communications, and transport linked with on-farm research that will yield immediately extendable results. For instance, each of the 39 Districts in Moldova needs a trained, fully equipped extension worker who will cost $500,000 annually (ten times the payroll figure); double this for national coodination and on-farm research. Kazakhastan, Ukraine and Russia would need an extension services numbered in hundreds and thousands.

The necessary finance is available for the asking. Don't think small. It is futile. Think how big it could be—and double it!

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