No-Till Agriculture in the USA

Jared Margulies

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

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

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

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

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

1 Introduction

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

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

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

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

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

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

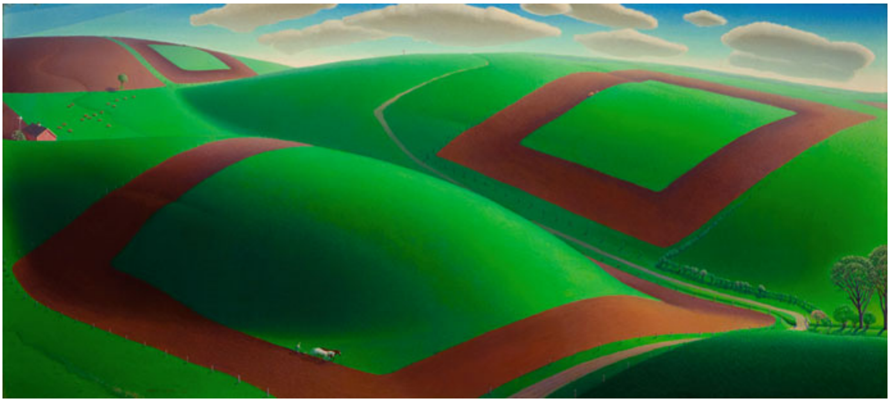

Fig. 2 Persistent iconic imagery of American agricultural landscapes shaped by the moldboard plow. Grant Wood, 'Spring Turning' (1936) (Courtesy of Reynolda House Museum of American Art, Winston-Salem, North Carolina. Art © Figge Art Museum, successors to the Estate of Nan Wood Graham/Licensed by VAGA,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

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

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

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

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

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

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

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

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

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

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

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

3 Modern No-Till Agriculture: Land and Water Impacts

3.1 Soil Erosion by Wind and Water

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

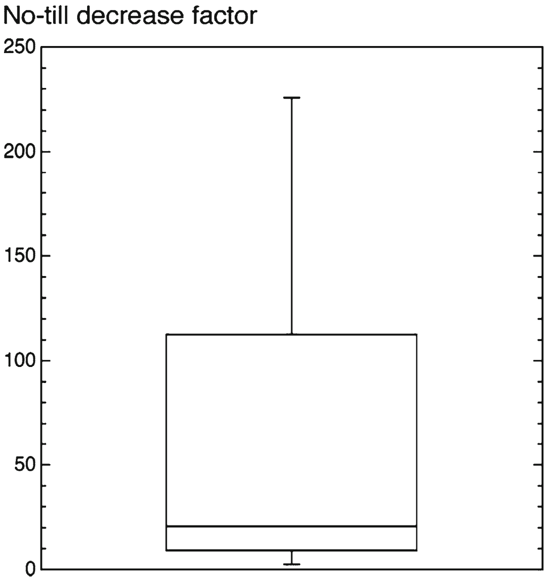

Fig. 4 Box-and-whiskers plot showing the range of reported decreases in erosion rate for studies reporting direct comparisons of conventional tillage and no-till practices for comparable settings ($n = 39$, median = 20, mean = 488, minimum = 2.5, maximum = 7,620). Data include studies that reported both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

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

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

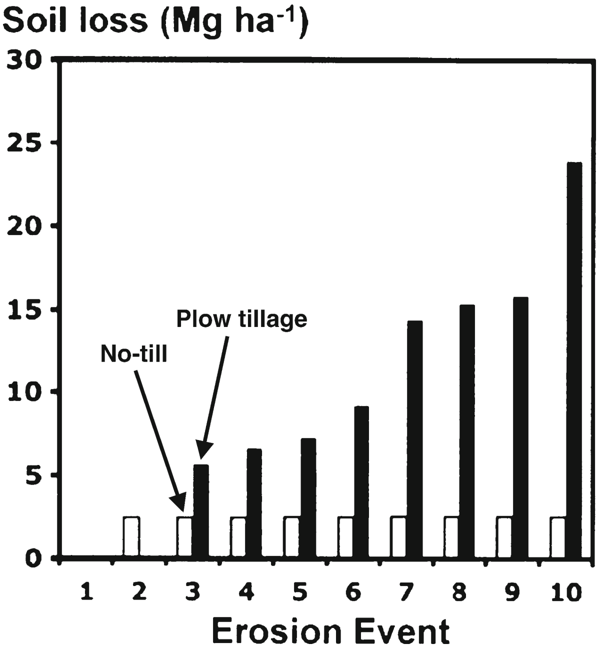

Fig. 5 Cumulative soil loss from no-till and plow tillage watersheds at Coshocton, OH, for the years of 1970–1973. The erosion events are all rainfall events that produced runoff and erosion during this time period. To visualize the no-till values, they were multiplied by ten before being plotted in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

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

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

3.2 Soil Physical and Biological Properties

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

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

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

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

3.3 Soil Carbon Sequestration and Greenhouse Gas Emissions

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

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

3.4 Water Quality

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

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

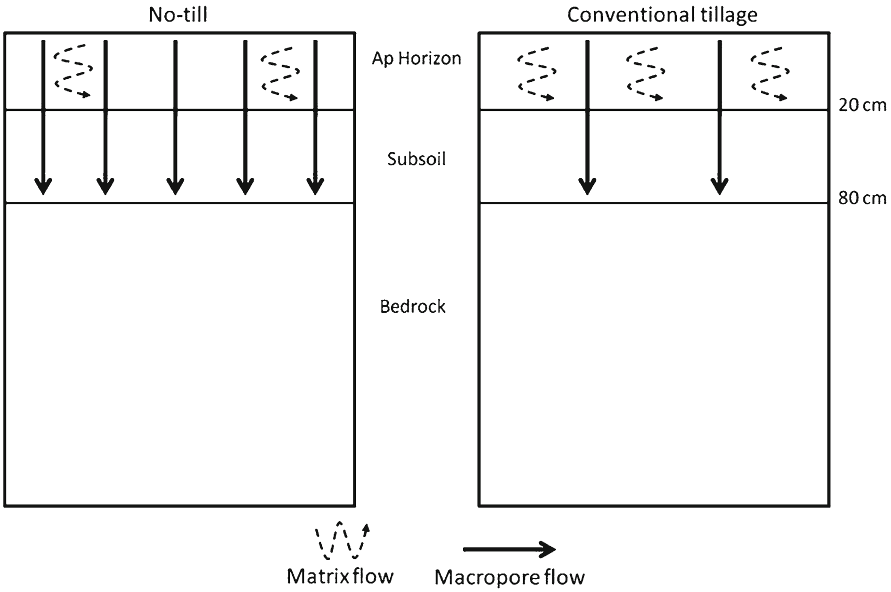

Fig. 6 Illustrative depiction of subsurface water flow under (**a**) no-till and (**b**) conventional tillage systems during the growing season. Earthworm burrow preservation under no-till creates a preferential flow of water via macropores under no-till systems compared to conventional tillage (Adapted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

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

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

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

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

4 Problems in No-Till

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

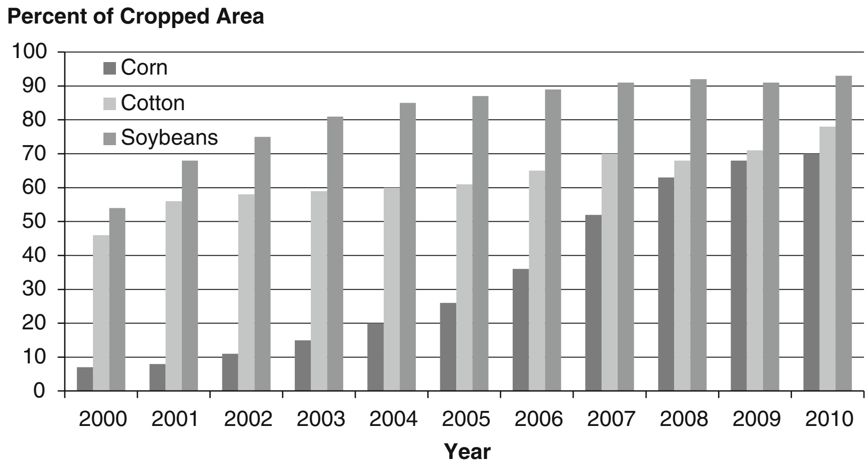

Fig. 7 Herbicide-tolerant crops as a percentage of total cropped area. Percentages are totaled from herbicide-tolerant only crops and herbicide-tolerant and insect resistant (Bt) crops (stacked varieties) (Data from USDA ERS 2011)

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

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

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

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

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

5 Discussion

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

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

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

5.2 A Different Future for No-Till?

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

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

6 Conclusion

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

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