Do Productivity and Environmental Trade-offs Justify Periodically Cultivating No-till Cropping Systems?

A. S. Grandy,* G. P. Robertson, and K. D. Thelen

ABSTRACT

No-till management has been shown to increase soil aggregation, reduce erosion rates, and increase soil organic matter across a range of soil types, cropping systems, and climates. Few agricultural practices provide similar opportunities to deliver positive benefits for farmers, society, and the environment. The potential benefits of no-till are not being fully realized, however, in large part because no-till is rarely practiced continuously and many fields suitable for no-till are still conventionally tilled. We present here three arguments, based on recent research, in support of the agronomic and environmental benefits of continuous no-till: (i) although there exist agronomic challenges with no-till, long-term yields in these systems can equal or exceed those in tilled soils; (ii) cultivating no-till systems can decrease soil aggregation and accelerate C and N losses so rapidly that years of soil restoration can be undone within weeks to months; and (iii) over time, changes in soil structure and organic matter, coupled with producer adaptation to the need for spatially and temporally explicit chemical applications, increase plant N availability and reduce environmental N losses. At least in theory, then, continuous no-till can be widely practiced to improve the environment and maintain yields with little or no economic sacrifice by producers. In practice, however, many diverse challenges still limit no-till adoption in different regions. These challenges are surmountable, but potential solutions need to be interdisciplinary and address the ecological and especially the social and economic constraints to deploying continuous no-till.

No-till cropping has been used for decades to reduce soil erosion, improve soil physical structure, conserve soil water, and restore organic matter (Franzluebbers and Arshad, 1997; Wright and Hons, 2004; Lal et al., 2004). More recently, soil organic matter gains under no-till have been promoted as an immediate, high-impact method for partially offsetting increases in atmospheric CO_2 (Kauppi and Sedjo, 2001; Caldeira et al., 2004). Current rising energy costs combined with an expected fuel savings ranging from 33 to 53 L ha^{-1} (Kern and Johnson, 1993) provide further incentive to growers to adopt no-till. With increasing recognition by producers, researchers, and policymakers of the substantive benefits of no-till, its use has steadily increased in the U.S., and between 1994 and 2004 the percentage of total U.S. cropland in no-till rose from 13.7 to 22.6%, or 9.5 million ha (CTIC, 2004).

The deployment of no-till, however, continues to be far below its potential. Many fields suitable for no-till are still managed using conventional plowing methods. Moreover, only a fraction of no-till cropping systems are permanent no-till. In the U.S. Midwest, for example, many farmers rotate conventionally cultivated corn (*Zea mays* L.) with no-till soybean [*Glycine max* (L.) Merr.]. In the western U.S., periodic plowing is used to control downy brome (*Bromus tectorum* L.) and other winter annual grasses (Wicks, 1997; Kettler et al., 2000). Soils that are restored through set-aside programs such as the Conservation Reserve Program (CRP) gain no-till attributes even faster than no-till cropping (CAST, 2004) but are routinely converted back to conventional tillage (Zheng et al., 2004). Reasons for periodically cultivating no-till soils are both agronomic—e.g., to mineralize stored soil N, interrupt pest cycles, incorporate manure, and alleviate compaction and associated problems, particularly in soils with high clay contents—and economic—e.g., to reduce production costs associated with increased herbicide use (Rice et al., 1986; Yiridoe et al., 2000; Martens, 2001).

At the W.K. Kellogg Biological Station (KBS) Long-Term Ecological Research (LTER) site in southwest Michigan, we examined the effects of 14 yr of no-till corn–soybean–wheat (*Triticum aestivum* L.) cropping on yields and N cycling. Our objectives are to determine whether soil N concentrations, N_2O fluxes, and yields are similar in long-term till and no-till cropping systems. Producers, researchers, and policymakers need to weigh potential changes in yields and N cycling in long-term no-till soils against the immediate and short-term consequences of cultivating soils in long-term no-till. We therefore also performed a series of experiments in a previously uncultivated grassland soil to determine the potential for tillage to immediately alter soil aggregation, organic matter dynamics, N cycling, and CO_2 and N_2O fluxes. The results from these and other experiments, in addition to recent advances in evaluating ecosystem services, demonstrate the importance—and feasibility—of deploying continuous no-till.

CROP YIELDS AND SOIL PROPERTIES IN LONG-TERM NO-TILL

The KBS is located in the northern portion of the midwestern Corn Belt in southwest Michigan. Soils at the KBS LTER are co-occurring Kalamazoo fine loam and Oshtemo coarse loam (Crum and Collins, 1995). Although the clay content in these soils is typically between 15 and 20%, the silt content is high (≈ 40%). Because of its location and soil type, field-crop systems at the KBS LTER are potentially susceptible to many of the

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Abbreviations: CRP, Conservation Reserve Program; KBS, W.K. Kellogg Biological Station; LF, light fraction organic matter; LTER, Long-Term Ecological Research Project; MWD, aggregate mean weight diameter.

problems previously reported in no-till systems including increased bulk density and compaction (Afyuni and Wagger, 2006; Singh and Malhi, 2006), slower plant growth (Vyn and Raimbault, 1993; Halvorson et al., 2006), and reduced N availability (Rice et al., 1986; Wortmann et al., 2006). In fact, growers in the area rarely use no-till because of these concerns. Despite these potential problems, however, we found that over 14 yr and three crop rotation phases (corn–soybean–wheat) that no-till never reduced yields compared with moldboard or chisel plowing (Grandy et al., 2006). In the 3 yr where there were significant differences between treatments no-till had higher yields (Grandy et al., 2006) and, when averaged over the entire experiment, no-till soybean yields were higher than those in conventional till (Fig. 1). This was in spite of indications that no-till could potentially reduce soil NO_3^- availability, particularly in corn: reductions in soil NO_3^- concentrations occurred in 3 of six corn years (Grandy et al., 2006) and the 6-yr average for NO_3^- concentrations was lower in no-till corn than in till corn (Fig. 1). Reductions in soil NO_3^- concentrations, however, did not translate into yield losses for any of the crops in the rotation, as indicated by the similar or higher yields in no-till (Fig. 1).

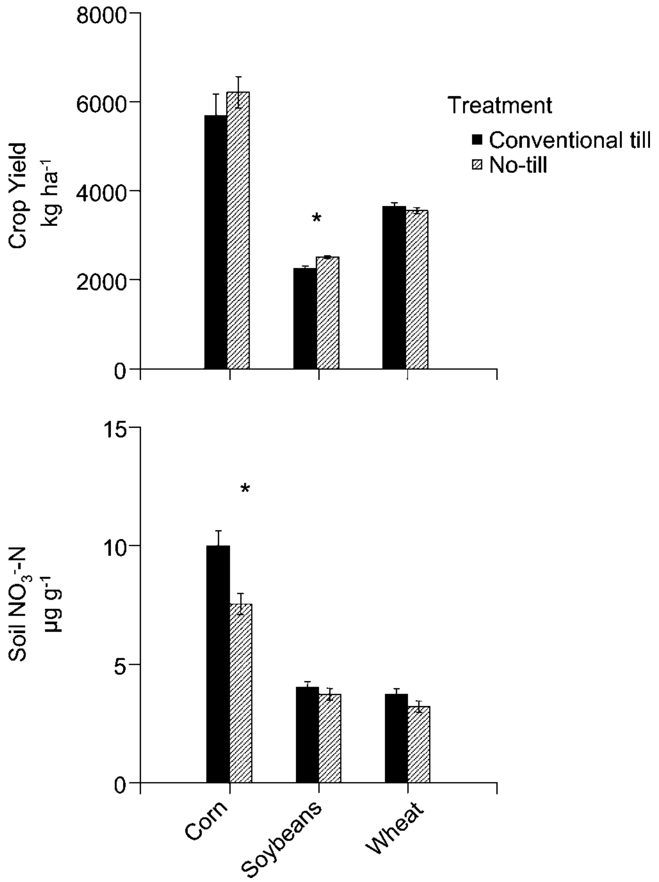

Fig. 1. Average crop yields and soil NO_3–N levels over 14 yr of conventional and no-till production at the KBS LTER site between 1989 and 2002. The crop rotation consisted of corn and soybean grown in 1:1 rotation until 1995 when the rotation was switched to corn–soybean–wheat. Corn was grown in 6 yr, soybean in 5, and wheat in 3. Asterisks indicate significant differences between tillage treatments for a particular crop ($n = 6$ replicate blocks). Data are adapted from annual crop yields presented in Grandy et al. (2006).

No-till also improved soil properties. Soil C increased from 0.69 to 1.00 kg m^{-2}, and soil aggregate mean weight diameter (MWD), a weighted index of mean aggregate size distribution, increased from 1.32 to 2.04 mm due to no-till. Higher N_2O emissions in no-till than conventionally tilled cropping systems have been reported (MacKenzie et al., 1997; Ball et al., 1999; Baggs et al., 2003), but we found no statistical difference in mean N_2O emission rates over the 12 yr for which we have measurements (Robertson et al., 2000; Grandy et al., 2006).

Other long-term studies have found that yields in long-term no-till were less than (Vyn and Raimbault, 1993; Schillinger, 2005), greater than (Anderson, 2005a; Tarkalson et al., 2006), or similar to (Dam et al., 2005; Buman et al., 2005) those in tillage-based systems. Some studies have found that no-till yields change over time relative to those in conventional till (Rice et al., 1986; Rhoton, 2000). Kravchenko et al. (2005) found yields to be more spatially variable in no-till corn following wheat than in an otherwise similar tillage-based system at KBS. Although there is some variation in relative responses to tillage systems, the potential for no-till to maintain competitive yields over time has been clearly demonstrated. Further, no-till yields can be competitive in systems very different from the one we studied here, including northern Great Plains wheat-based cropping systems (Anderson, 2005a), southern U.S. cotton (*Gossypium hirsutum* L.)-based systems (Boquet et al., 2004), and Canadian systems on heavy clay soils (Chen et al., 2004). This suggests that many agronomic solutions already exist for maintaining yields in no-till systems and that agronomic research alone will not be the catalyst for more widespread use of continuous no-till cropping.

TILLAGE EFFECTS ON LONG-TERM NO-TILL SOILS

A handful of studies have demonstrated changes in the distribution of organic matter between soil size fractions and depths following tillage of long-term no-till soils (Tiessen and Stewart, 1983; Pierce et al., 1994; VandenBygaart and Kay, 2004). Soil aggregation changes, however, have rarely been studied following this conversion. Soil aggregation may be the single best indicator of the potential agronomic and environmental effects of tillage because it influences soil structure, soil permeability, and water-holding capacity, as well as soil organic matter turnover and nutrient cycling (Jastrow et al., 1996; Grandy et al., 2002; Shaver et al., 2003).

Beginning in 2002, we moldboard-plowed a never previously cultivated grassland soil. We used moldboard plowing (Grandy and Robertson 2006a, 2006b) because it is the technique employed most commonly to put CRP and other long-term fallows back into production. We found that soil MWD, an estimate of the mean aggregate size, in the 0- to 20-cm soil layer decreased 35% (from 2.02 to 1.31 mm) within 60 d of tillage (Grandy and Robertson 2006b). Macroaggregate (>250 µm) destruction accounted for most of this decrease. Soil aggregates in the 2000- to 8000-μm size class decreased from 0.34 in no-till to 0.19 g g^{-1} in till, levels identical to those measured in adjacent agricultural fields on the same soil type cultivated for more than 50 yr. In a follow-up experiment, we found similar changes in aggregation within 31 d following tillage, suggesting that tillage per se, rather than the indirect effects of bare soils or plant community changes, destroyed soil aggregates.

Associated with declines in soil structure was an equally rapid series of changes in the physical protection of light fraction (LF) carbon, the mineralization rate of soil organic matter, and nutrient cycling. Light fraction organic matter has a more rapid turnover time than whole-soil C and is closely correlated with soil CO_2 emissions, microbial activity, and nutrient cycling (Wander et al., 1994; Swanston et al., 2002; De Gryze et al., 2004). Protection of LF organic matter within aggregate interiors can reduce its decomposition rate by half or more (Hassink, 1997; Balesdent et al., 2000; Grandy and Robertson, 2006c). We found that within 60 d of cultivation, the proportion of total LF protected within 2000- to 8000-μm aggregates decreased from 28 to 16% (Grandy and Robertson, 2006b). Releasing LF and other substrates from physical protection, coupled with increased soil temperature and other environmental changes, increased soil organic matter mineralization (Fig. 2). This increased soil NO_3^- concentrations to more than 15 μg N g^{-1} (from < 1 μg N g^{-1}) and greatly accelerated mean annual CO_2 emissions over 3 yr by 28 to 65% (1.0–1.9 g C m^{-2} d^{-1}) and N_2O emissions by 200 to 700% (Fig. 2). These changes in soil structure and function persisted until the following spring when subsequent tillage resulted in no additional declines in soil function.

The rate, magnitude, and persistence of these effects highlight the potential effect of periodic plowing in no-till soils. Climate, soil type, the duration of no-till, tillage intensity, and cropping system are all likely to influence the onset, duration, and magnitude of response. Clearly, however, tillage has an immediate and striking effect on soil processes (Calderón et al., 2001; Jackson et al., 2003), and even intermittent tillage of no-till systems may undermine efforts to restore soil physical and biological process and sequester C in these systems.

NITROGEN MANAGEMENT IN NO-TILL

Producers switch between tillage systems for different reasons, but the most widespread concerns leading to switching are related to weed competition and altered N cycling (Power and Peterson, 1998; Martens, 2001;

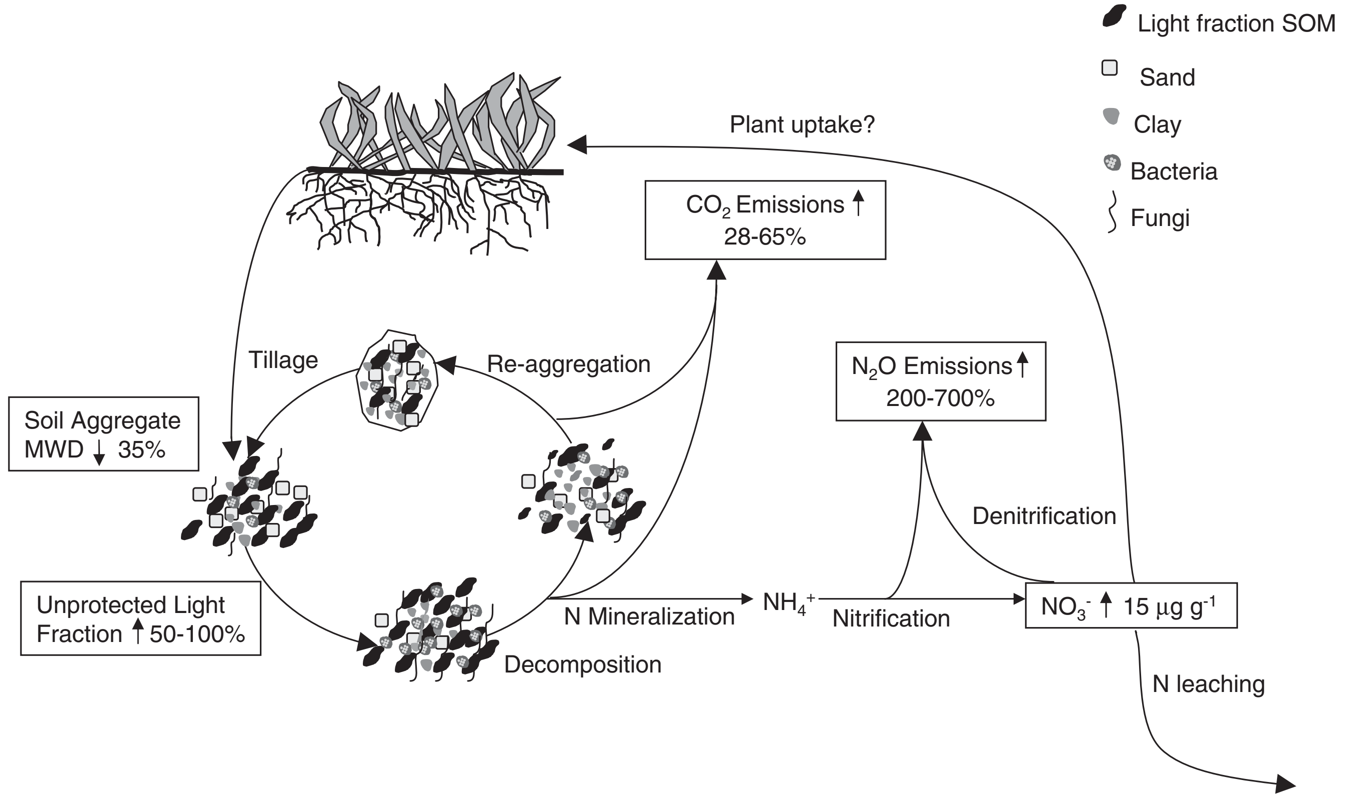

Fig. 2. A conceptual model of immediate changes in soil aggregation and organic matter availability that lead to changes in soil C dynamics, environmental nutrient losses, and substantially reduced soil structure following tillage in long-term no-till soils. Immediately following tillage is a reduction in soil aggregate mean weight diameter (MWD). The release of labile light fraction soil organic matter (SOM) from within aggregates plus the incorporation of aboveground biomass leads to increased SOM availability. Microbial activity increases, leading to accelerated CO_2 emissions and N mineralization rates. Although some of the NO_3^- produced from tillage is taken up by plants, the release of this N is often poorly synchronized with plant N needs, which usually do not peak for eight or more weeks after tillage, making it highly susceptible to loss via leaching and denitrification, including N_2O loss. Associated with these changes in aggregation and organic matter availability are increases in soil temperature and O_2 concentration that further stimulate decomposition. The process can be reversed by eliminating tillage, but the recovery of aggregates and aggregate-associated C pools takes far longer (years) than their destruction (days to weeks).

Derksen et al., 2002). Agronomic advances are now diminishing concerns about weed competition: promising ecological approaches to weed management utilize a cropping systems approach to successfully reduce competition in no-till (Derksen et al., 2002; Anderson, 2005b), and the introduction of glyphosate-tolerant soybean in 1996 has been credited with part of the increase in U.S. no-till acreage between 1994 and 2004 (CTIC, 2004). Changes in N cycling are not as readily addressed.

The development of a litter layer, changes in soil temperature and moisture, and changes in soil C distribution within the soil profile (e.g., Puget et al., 2005; Shukla and Lal, 2005) slow decomposition in no-till soils, and concomitant changes in N cycling rates have been reported to reduce yields in no-till systems (Martens, 2001). Nitrogen applied as urea ammonium nitrate (UAN) fertilizer can also be less available in no-till systems due to greater ammonia volatilization following surface application; in tilled systems, volatilization is reduced by incorporating UAN into the soil (Keller and Mengel, 1986; Fox and Piekielek, 1993). Immobilization of N in soil organic matter and concomitantly decreased N mineralization rates can also limit N availability in the no-till system (Kaspar et al., 1987; Ismail et al., 1994).

Because of these potential changes, the timing, rate, placement, and form of N fertilizer are particularly important in no-till to maximize N use efficiency (Kolberg et al., 1996; Halvorson et al., 2004; Niehues et al., 2004). Timing fertilizer N availability to coincide with plant demand can be achieved in part by using split fertilizer applications (Dinnes et al., 2002). Nitrogen is initially applied at planting and near the seed so that an adequate supply is available for crop establishment, and then an additional N application is made later in the season, corresponding with the plant's phase of rapid N uptake. Several studies have shown that starter fertilizer is critical for maintaining early-season crop growth and ultimately yields in no-till (Vetsch and Randall, 2000; Niehues et al., 2004). At the KBS LTER, starter fertilizer applications are used at a rate of about 30 kg N ha^{-1} for corn and have likely helped maintain similar soil N concentrations and yields as in the tilled soils. Presidedress N tests (PSNT; Magdoff, 1991) can provide additional information on the value of starter N for no-till corn (Jaynes et al., 2004); in another Michigan study, Kravchenko and Thelen (unpublished) used fertilization following early PSNT to maintain long-term no-till corn yield, even in the presence of heavy wheat residue. Other management strategies based on direct measurements of N availability such as the late-spring soil N test have been shown to maintain yields and attenuate N losses (Karlen et al., 2005).

Careful N fertilizer management may be necessary in the first years after no-till conversion (Rice et al., 1986; Ismail et al., 1994). During this time, no-till soils are rapidly building soil C, resulting in N immobilization, particularly in plant residues or particulate organic matter fractions at or near the soil surface, which can limit plant-available N (Schomberg et al., 1994; Burgess et al., 2002). Further, it often takes several years before soil aggregate stability increases in no-till systems. Until this occurs, compaction may limit root growth and denitrification rates may be high due to widespread occurrence of anaerobic sites (Six et al., 2004).

Over time, however, several important changes take place that can increase the productivity and environmental benefits of no-till (Fig. 3). First, soil organic matter stocks increase and potentially mineralizable N may become an important source of N in no-till systems (Ismail et al., 1994; Franzluebbers and Arshad, 1997). Second, less N is lost to denitrification and surface runoff due to increased aggregation and associated changes in water flow and storage (Six et al., 2004). These changes in soil structure also help to alleviate compaction and problems with excess water that some no-till systems, particularly those on soils with high clay contents, experience soon after the onset of no-till. Third, after several years of using no-till methods, producers will have had the opportunity to become more experienced with spatially and temporally explicit N applications that maintain N availability. That these changes over time (Fig. 3) can have measurable effects on nutrient cycling and yields needs to be articulated to growers. These changes should also provide strong incentive for researchers to study long-term dynamics in no-till systems.

THE CHALLENGE OF CONTINUOUS NO-TILL IMPLEMENTATION

Deploying permanent no-till systems will require collaboration among both private and public enterprises. Even where agronomic challenges to continuous no-till implementation are straightforward and easily overcome, it may be in the farmer's short-term economic interest to periodically till. Because of this, producers cannot be expected to shoulder alone the responsibility of permanently maintaining no-till soils.

No-till is one of few agricultural practices that can deliver services that benefit farmers, society, and the environment. Evaluation of no-till benefits, therefore, should go beyond comparing yields under different tillage systems and include benefits such as reduced erosion, C sequestration, energy conservation, and decreased N loss. Valuing services such as these for their benefits to society and creating incentive programs that reflect these benefits (Robertson and Swinton, 2005) is an important and emerging area of research with great potential for promoting no-till farming (Gutman, 2003; Robertson et al., 2004). Numerous programs have been considered that use direct payments or other incentives as a tactic for encouraging no-till, primarily because of its potential to be a low-cost and rapidly deployable means for sequestering C (Lal et al., 2004; Manly et al., 2005). Incentive programs also need to account for the potentially rapid loss of C and accelerated N_2O emissions following the resumption of tillage (Paustian et al., 2000; Grandy and Robertson, 2006b).

Even if incentive programs are put in place to facilitate adoption of no-till, no-till will need to remain financially competitive with other cropping regimes. As our research and others' demonstrate, this is already possible under a broad range of soils and cropping se-

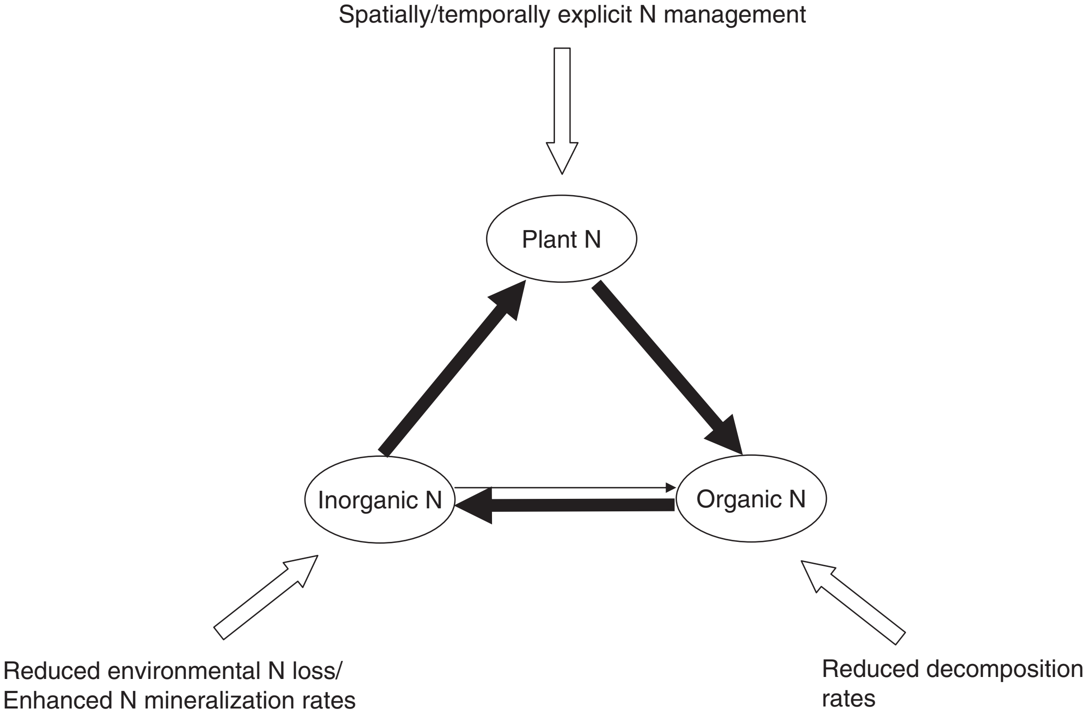

Fig. 3. Simplified N pools and pathways in long-term no-till ecosystems highlighting the changes in soil environmental conditions and management that increase plant available N over time. Organic N pools are increased by decreased decomposition rates; increased organic matter leads to greater N mineralization at a time when plants can use it, stimulated by plant growth and warmer weather rather than tillage. Inorganic N pools are maintained by N mineralization and also by reduced fertilizer N losses to the environment as changes in aggregation and porosity attenuate N losses via runoff, leaching, and denitrification. Plant available N is enhanced by increased inorganic N concentrations and by expanded producer expertise in applying appropriate N forms at times and in soil regions that maximize plant uptake, rather than environmental losses.

quences. In some systems, even if yields were to occasionally decline, no-till can still be economical because of reduced production costs (Kaval, 2004; Buman et al., 2005). Where agronomic challenges to no-till implementation still exist, identifying and overcoming these challenges should become an agricultural research priority that emphasizes an integrated systems approach and long-term dynamics. Examples include using advancements in GPS-based controlled wheel traffic technology to broaden the scope of soils and cropping sequences amenable to no-till systems. Where there are socioeconomic challenges to permanent no-till, identifying and overcoming these challenges should become a policy priority.

CONCLUSIONS

With strategic management, many no-till cropping systems can be continuously maintained without crop yield loss or ecological tradeoffs. Without permanence, many of the agronomic and environmental benefits of no-till are simply not realized. Years of soil regeneration can be lost to a single tillage event. Social and agronomic challenges, as well as current policies, continue to limit both the extent and persistence of no-till deployment. Interdisciplinary solutions are needed to address these complex problems so that no-till systems can be more extensively adopted and permanently maintained, thereby yielding their full agronomic, social, and environmental potential.

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