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Editorial

Evolution of the plow over 10,000 years and the rationale for no-till farming

Abstract

Agriculture and the plow originated 10–13 millennia ago in the Fertile Crescent of the Near East, mostly along the Tigris, Euphrates, Nile, Indus and Yangtze River valleys, and were introduced into Greece and southeastern Europe ~8000 years ago. The wooden plow, called an ard, evolved into the "Roman plow", with an iron plowshare, described by Virgil around 1 AD and was used in Europe until the fifth century. It further evolved into a soil inverting plow during the 8th to 10th century. In the U.S., a moldboard plow was designed by Thomas Jefferson in 1784, patented by Charles Newfold in 1796, and marketed in the 1830s as a cast iron plow by a blacksmith named John Deere. Use of the plow expanded rapidly with the introduction of the "steam horse" in 1910 that led to widespread severe soil erosion and environmental degradation culminating in the Dust Bowl of the 1930s. A transition from moldboard plow to various forms of conservation tillage began with the development of 2,4-D after World War II. No-till is presently practiced on about 95 million hectares globally. No-till technologies are very effective in minimizing soil and crop residue disturbance, controlling soil evaporation, minimizing erosion losses, sequestering C in soil and reducing energy needs. However, no-till is effective only with the use of crop residue as mulch, which has numerous competing uses. No-till farming can reduce yield in poorly drained, clayey soils when springtime is cold and wet. Soil-specific research is needed to enhance applicability of no-till farming by alleviating biophysical, economic, social and cultural constraints. There is a strong need to enhance sustainability of production systems while improving the environmental quality.

Keywords: Conservation tillage; No-till farming; Tillage intensity; Evolution of agriculture; Soil erosion; Dust bowl; Desertification; Tillage implements

1. Introduction

The beginning of civilization depended on agriculture for food production—so does civilization's future. At the end of the last glaciation, some humans began to take advantage of their natural landscapes in ways that their ancestors could not have imagined. The early human hunters and gatherers defined the human civilization, about 10–13 millennia ago when settled agriculture began (Cavalli-Sforza and Cavalli-Sforza, 1995; Manning, 2004). Indeed, it followed the popular saying "Where farming starts, other arts follow" (Jack, 1946). The agricultural revolution occurred across many generations, culminating into the Green Revolution in the second half of the 20th century. The agricultural revolution involved use of genetically improved varieties, supplemental irrigation where needed, soil fertility enhancing organic amendments and inorganic fertilizers, and plow-based seedbed preparation. The rise of urban societies centered in impressively wealthy cities was entirely based on the food surpluses of plow-based agriculture. By the time the industrial revolution rolled around in the 1700s, the technologies developed throughout the agricultural revolution enabled the human population to soar from a mere 4 million around 8000 BC to nearly 400 million. Moreover, average settlement size grew from a mere 200–300 people to cities with over a million people. In a few thousand years, early civilizations tackled the first environmental constraint limiting their ability to feed, clothe and shelter themselves, and in the process transformed their daily lives. The agricultural revolution transformed the landscape, ecosystems,

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vegetation, soils and water resources. These transformations had far reaching and often irreversible impact on the cycles of water and other elements (e.g., C, N, P). Human appropriation of ecosystem services and Earth's natural resources have been unprecedented since the agricultural revolution.

Over the millennia, plowing became synonymous with tillage and seedbed preparation. Yet, there is a need to revisit the scientific basis and rationale for plowing as a tool for seedbed preparation. We discuss the evolution of plow tillage from an historical perspective. The specific objective of this review is to present a historical perspective on the development of civilization and its dependence on the plow-based agriculture. The soil and environmental impacts of intensive tillage are discussed and the rationale for adopting less intensive forms of tillage with more emphasis on minimum soil disturbance, continuous crop residue cover, and diverse crop rotations are described.

2. Historical evolution of plow tillage

Settled agriculture originated in the Fertile Crescent of the Near East, mostly along the Tigris, Euphrates, Nile, Indus and Yangtze River valleys by the so-called "hydric civilizations." Some of the earliest cultivated crops included emmer (broadly, tetraploid wheat), einkorn (the most primitive wheat), barley, flax, chickpea, lentil, pea, and bitter vetch. Farming was introduced into Greece and southeast Europe from the Near East more than 8000 years ago. About 10 millennia ago, Sumerian and other civilizations developed simple tools to place and cover seed in the soil. Soil preparation through tillage has always been an important component of traditional agriculture. Tillage has been defined as the mechanical manipulation of the soil and plant residues to prepare a seedbed where crop seeds are planted to produce grain for human and animal consumption (Reicosky and Allmaras, 2003). Tillage involves seedbed preparation and post-emergent cultivation for weed control.

The on-set of settled agriculture led to the development of ancient civilizations in the fertile alluvial plains of Mesopotamia, the Nile Valley and other rivers. Agriculture started in these alluvial plains in an arid climate where farmers began to grow food crops by irrigation in quantities greater than their own needs and released their fellow humans for a division of labor that gave rise to the so-called civilization. Importance of agriculture and the need to maintain and enhance soil fertility were written by Spanish Moores during the 12th century (Aboul-Khayr et al., 1946). Lowdermilk (1953) presented a story of precarious agriculture by people who lived and grew up under the threat of raids and invasions from marauders of the grasslands in the desert. In Mesopotamia, agriculture was practiced in the very dry climate with canal irrigation using muddy water.

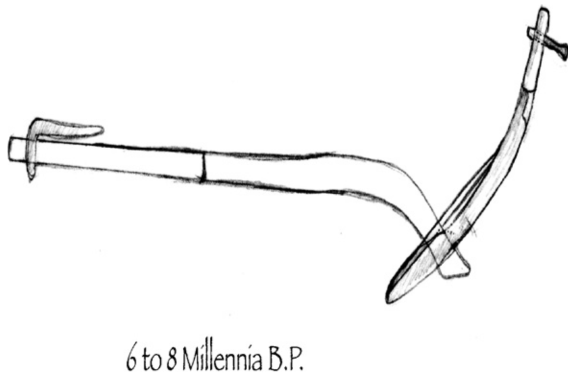

Fig. 1. One of the earliest tillage tools that evolved from "digging sticks" to be pulled by animals or humans, sometimes referred to as the "ard". (Redrawn from Glob, 1951, and others).

A wide variety of tillage tools were originally designed, ranging from a simple digging stick to a paddle-shaped spade or hoe that could be pulled by humans or animals (Fig. 1). A wooden plow, called an "ard," was probably developed in Mesopotamia about 4000 to 6000 BC. The "Triptolemos ard" was named after the Greek God and hero about 4000 BC (Glob, 1951). Historical documents and archaeological evidence illustrate the "mystique" of tillage implements that were thought to "nourish the earth" and to "break the drought." Over time, the ard evolved into the well-known "Roman plow" described by Virgil by around 1 AD (White, 1967; Fowler, 2002). The plow with iron share was widely used in Europe about fifth century AD, and the Roman plow evolved into a soil-inverting plow during 8th to 10th century AD (Lerche, 1994). The major advance before 1000 AD was the development of the heavy plow, which was more than the simple plows farmers used earlier. It had a coulter designed to cut a thin strip in the turf (Fig. 2). The coulter was followed by a share that would slice into the soil and then the soil would ride up the moldboard and subsequently be turned over. Later, wheels were attached to this type of plow and eventually a seat was added. By turning over the soil, crop residues were incorporated and organic matter mineralized, weeds were limited and overall it helped the growing process. A parallel evolution of plow tillage through the centuries in Ethiopia was reviewed by Gebregziabher et al. (2006). While there may be a few specific cultural differences, the similarity to other parts of the world is remarkable.

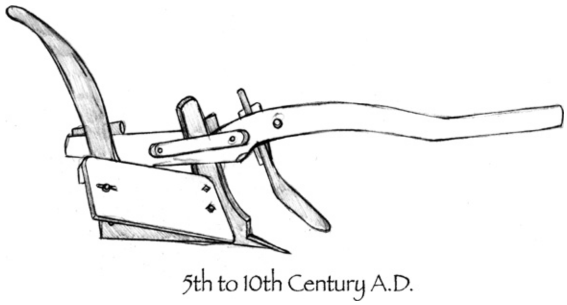

Fig. 2. Early model of the ‘‘iron share’’ plows with coulter designed to cut a thin strip in the sod share that would slice into the soil and ride up the moldboard and subsequently be inverted. (Redrawn from White, 1967; Fowler, 2002; Lerche, 1994; and others)

A moldboard plow used in the U.S. was designed by Thomas Jefferson in 1784, patented by Charles Newfold in 1796, and marketed in the 1830s as a cast iron plow by a blacksmith named John Deere. The use of plows expanded rapidly with the introduction of the steam horse in 1910 (Olmstead and Rhode, 2001). By 1940, there were 2 million tractors in the U.S. (Danbom, 1995). Introduction of tractors enhanced farm income, which rose as much as 156% between 1939 and 1944 (Danbom, 1995). As new technology evolved, farmers in the U.S. got equipped with some of the largest equipment in the world (Fig. 3). Use of powerful tractors and large machinery along with fertilizers and improved varieties enhanced crop yields by a factor of 3–5. The ratio of civilian to agriculturally employed population increased from 10.5 in 1940 to 63.0 in 2000, and the number of farms decreased from 5.65 million in 1950 to 2.17 million in 2000 (Table 1). The number of people fed by one U.S. farmer increased exponentially during the 20th century (Fig. 4).

3. Environmental implications of plow tillage

Intensive tillage and use of heavy machinery brought mixed blessings. Accelerated soil erosion has plagued the earth since the dawn of settled agriculture, and has been a major issue in the rise and fall of early civilization (Diamond, 2004). With increasing demand on the limited prime soil resources and shrinking per capita arable land area in densely populated regions of the world, soil erosion has became a global issue with regard to its on-site impact on productivity and agricultural sustainability. Both water and wind erosion are exacerbated by plow tillage. It loosens the soil, buries crop residues and exposes the soil to high-intensity rainfall and high wind speeds that lead to severe erosion. Intensive tillage systems leave the soil bare allowing rain to pulverize it excessively, creating conditions where soil and nutrients are carried away by heavy rains. Later, the surface sealing

Fig. 3. A large modern moldboard plow used in the north-central U.S. agricultural production areas.

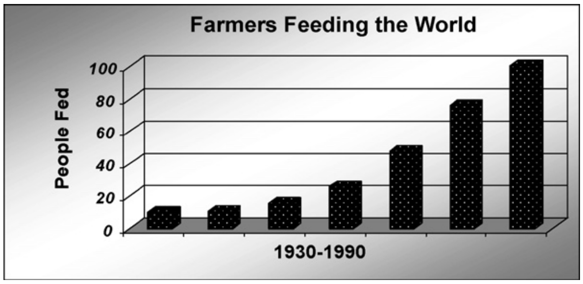

Fig. 4. The increasing number of people fed by one U.S. farmer in the 20th century (adapted from Brown, 1999; Seitz, 1985).

Table 1
Trends in U.S. agriculture during the second half of the 20th century (FAO, 2006; CIA, 2006)

Year	Total civilian population (millions)	Agricultural employment (millions)	Ratio of civilian: agricultural population	Farm number (millions)
1940	100	9.5	10.5	–
1950	105	7.2	14.6	5.65
1960	117	5.5	21.3	3.96
1970	137	3.5	39.1	2.95
1980	168	3.4	49.4	2.44
1990	189	3.2	59.1	2.15
2000	208	3.3	63.0	2.17

dries, resulting in crusting that may hinder or impede the germination and emergence of crop seeds. This accelerated soil erosion and other degradation processes influence agronomic productivity and environment through their impact on the physical, chemical and biological factors related to soil quality.

Accelerated erosion is one of the causes of soil degradation, others being soil C loss and nutrient depletion, soil compaction, acidification, pollution, and salinization. Currently, the average rate of soil erosion on U.S. cropland is 15.7 Mg ha^{-1} $year^{-1}$(Sullivan, 2004). The most ubiquitous form of erosion is that caused by water and leads to increased runoff and off-site degradation. When uncontrolled, agricultural runoff removes topsoil, nutrients, pesticides, and organic materials and carries them to water bodies where they become pollutants.

Sediment fills streams, rivers, reservoirs, lakes and roadside ditches, reducing their useful life. The once-productive soil then becomes a costly maintenance problem since the sediment must be removed to provide adequate water-carrying capacity and to prevent flood damage. In addition to loss of storage capacity, the sediment fills water bodies and impairs water quality. When runoff enters a water course, the lighter soil particles remain in suspension and block sunlight vital to the growth of desirable, oxygen-producing plants living in the water. Sediment-darkened water also absorbs more heat from sunlight than clearer water, thus causing warming. The combination of warm and muddy water leads to ecological shifts by replacing desirable fish species with less desirable types more tolerant to these conditions.

Nutrients and pesticides that may be present in agricultural runoff also cause serious economic and environmental problems. The direct effect on the producer is the economic losses connected with removing these materials from the field. In addition, nutrients derived from soil, commercial fertilizers or animal manure may cause excessive algal growths in ponds and lakes. These growths filter out and absorb sunlight, and release offensive odors and toxicants. Pesticides are as toxic in the water as they are on the field and may affect a wide variety of aquatic organisms. If contacted or ingested in sufficient quantity, pesticides pose a health hazard to all forms of life. Water supplies can be jeopardized by the presence of pesticide or algal growths, and purification expenses must be endured by the producer as well as other users.

Erosion is also caused directly by the action of tillage implements. Tillage erosion, the progressive downslope movement of soil through the action of tillage implements, is also a serious problem that needs to be considered during the development of conservation management plans (Lindstrom et al., 2001). Landscapes subject to tillage erosion are topographically complex or have a high number of field boundaries. Tillage erosion increases landscape heterogeneity through creation of distinct landforms and relatively rapid redistribution of soils from upland positions to depressions. Severe adverse impacts of tillage erosion, now widely recognized, are directly proportional to degree and scale of topographic complexity (Lindstrom et al., 2001; Lobb et al., 2004). The magnitude of soil translocation from upslope positions, either convex slopes or upper field boundaries, can result in soil loss that greatly exceeds what would be considered sustainable. Interactions between tillage and water erosion requires that both processes be considered when developing conservation plans. The net effect of soil erosion, either tillage or water erosion, is an increase in field variability and a reduction in crop production potential (Lobb et al., 2004). Conservation planners and practitioners can use the information to develop more effective conservation plans insuring the long-term sustainability of agricultural production.

4. Plow tillage and the dust bowl

Historically, the moldboard plow was an essential tool for the early pioneers in settling the prairies of central and western U.S. and Canada. The moldboard plow has been a symbol of U.S. agriculture since about 1850. It allowed the farmer to create a soil environment in which grain crops could thrive and meet the needs of the increasing population. At the same time, it degraded soil from increased water, wind and tillage erosion. Plowing also decreased the soil organic matter (SOM) concentration because of increase in rate of mineralization with an attendant release of plant-available nutrients (e.g., N, P, S). While plowing improved soil fertility and agronomic productivity, it set in motion a long-term trend of decline in soil structure and increase in susceptibility to crusting, compaction and erosion. In drier areas, other types of chisel plows and large sweeps developed as primary tillage tools with similar impact on the crops and available water (Reeder, 2000; Owens, 2001).

The ‘‘Dust Bowl’’ was as much about tillage as it was about drought. The combination of intensive tillage and drought resulted in the catastrophe. Poor agricultural practices and years of sustained drought caused the Dust Bowl which lasted for about a decade. The rainfall received in 1934 and 1936 was less than half of the normal. Although droughts and dust were recorded during the 1850s and 1860s, the scale and frequency of storms during the 1930 s was alarming. A dust storm in May 1935 carried an estimated 350 million tons of soil into the air, of which 12 million tons were dropped on Chicago, and also as far east as Buffalo and New York (Danbom, 1995) (Fig. 5). A documentary film by Lorenz, ''The Plow that Broke the Plains'' blamed the Dust Bowl on excessive plowing (Danbom, 1995). The book, ''Grapes of Wrath'' narrated the plight of migrants from Oklahoma called ''Okies'' (Steinbeck, 1939). Therefore, people developed a keen interest in farming methods that would reduce water erosion and, even more important to the U.S. Southern Great Plains, wind erosion.

The soil erosion crisis of America, highlighted by the Dust Bowl storms, prompted the U.S. Congress to take action. Hugh Hammond Bennett led the soil conservation movement in the U.S. in the 1920s and 1930s, and urged the nation to address the ''national menace'' of soil erosion. Bennett's crusading zeal for conservation was born of his experiences studying soils and agriculture nationally and internationally. The gullied land as well as the less visible evidences of what he called sheet erosion convinced him of the need for conservation. Bennett's actions led to congressional establishment of the Soil Conservation Act in 1935, a new federal agency, the Soil Conservation Service (SCS), now the Natural Resources Conservation Service (NRCS) in the U.S. Department of Agriculture (USDA). Bennett's flair for showmanship and his evangelistic commitment to soil conservation, convinced national leaders and farmers alike for the need to conserve soil and water resources (Bennett, 1939). As early as 1937, President Franklin D. Roosevelt stated in a letter to the state governors that ''A nation that destroys its soils destroys itself.'' President Franklin D. Roosevelt sent to the governors of all states legislation that would allow the formation of soil conservation districts to extend the battle against soil erosion (Roosevelt and Franklin, 1937). Prior to the U.S., a Soil Conservation Service was initiated in Iceland in 1907. The Icelandic SCS is probably the oldest among such institutions in the world (Arnaulds et al., 2001). Many countries of the world developed soil conservation departments during the second half of the 20th century.

Fig. 5. Typical scenes from the mid-1930 ''dust bowl'' days in the Great Plains of the U.S.: (a) intense dust storms in Texas; (b) deposition of windblown soils on a farm site.

5. Transition from moldboard plow to less intensive tillage

The Dust Bowl created a controversy about the usefulness of ''moldboard plow'' as a tool for seedbed preparation. There were two strong but opposing schools of thought: no-till and plow tillage. The no-till movement was spearheaded by Edward Faulkner, who wrote the book ''Plowman's Folly'' published in 1942 (Faulkner, 1942b). Faulkner, an extension worker in Ohio thus opined: ''Briefly, this book sets out to show that the moldboard plow which is in use on farms throughout the civilized world is the least satisfactory implement for the preparation of land for the production of crops. This sounds like a paradox, perhaps, in view of the fact that for nearly a century there has been a science of agriculture, and that agricultural scientist almost to a man approved use of the moldboard plow. . . The truth is that no one has ever advanced a scientific reason for plowing.'' (Quoted from page 3, paragraph 1.) While some refer to plowing as ''recreational tillage,'' plowing enhances soil fertility and increases agronomic yield when fertilizers are not used. Certainly, the bountiful harvest from many soils depended largely on the fact that these soils were tilled to mineralize SOM to make nutrients available.

Faulkner (1942a) continued the discussion on the traditional aspects of the plow: ''The answer to the question, Why do farmers plow? Should not make it difficult to arrive at. Plowing is almost universal. Farmers like to plow. If they did not get pleasure from seeing the soil turned turtle, knowing the while that by plowing, they dispose of trash that would later interfere with planting and cultivation, less plowing might be done. Yet farmers are encouraged to plow. The plowing is approved; or, you knew of the plowing, farmers are advised to cut deep into the subsoil in every furrow. Such advice comes from farm papers, bulletins, county agents, and a long list of other sources from which farmers commonly welcome suggestions and information. There should be clear-cut scientific reasons to justify a practice so unanimously approved and recommended.'' (Quoted from page 43, paragraph 1.) The irony demonstrated in Faulkner's comments is summarized in the following statement ''The entire body of'' reasoning ''about the management of soil has been based on the axiomatic assumption of the correctness of plowing. But plowing is not correct.'' (Quoted from page three, paragraph 2.)

The opposite view, strongly in favor of using moldboard plow, was spearheaded by Walter Thomas Jack in the book, ''Furrow and Us'' published in 1946. Views by Jack were based on the common observations of increase in soil fertility through mineralization of SOM by plowing. Jack thus opined, ''The method of stirring the soil without turning under the top with its crop residues was practiced by primitive people of every land since the beginning of time. The principle was outmoded with the advent of the woodboard type that turned only a portion of the surface under, since the wood surface could not be induced to scour. . .. Only after it was discovered that soil building agencies were living organisms supplying fertility and tilth to the soil, was the present moldboard plow designed'' (Jack, 1946, p. 19). In the same writing, Jack presented his views on science of agronomy by stating, ''Those hostile to present tillage practice (plowing) point out that, since most of the N requirement of the plant comes from the air, there is no need to encourage soil bacteria to supply the major portion, therefore the organic matter in the form of trash and manure has just as well remain on the surface as a guard against erosion. This argument seems to be a radical departure from the true principle of agronomy'' (Jack, 1946, p. 20).

This controversy between ''no-till'' and ''plow tillage'' was dubbed by Time Magazine as the ''hottest farming argument since the tractor first challenged the horse''. The plow tillage argument won, especially in the South, where the clay ridden thin soils and perennial poverty made N dependent no-till methods impractical during the 1950s and 1960s.

Since the 1950s, there's been a gradual transition from the moldboard plow to various forms of conservation tillage to no-till with minimum soil disturbance throughout the world (Hood et al., 1963, 1964; Jeater and Mcilvenny, 1965; Triplett and Van Doren, 1969; Kuipers, 1970; Blevins et al., 1971; Reeves and Ellington, 1974; Lal, 1974, 1976a,b; Phillips et al., 1980; Cannell et al., 1980; Carter and Rennie, 1982; Vaidyanathan and Davies, 1980; Derpsch et al., 1986; Owens, 2001). Conservation tillage is a term used to describe a number of technologies that are utilized in agriculture to conserve water and soil. Emphasis is placed on decreasing the amount of soil disturbance and managing crop residues to protect the soil surface. Conservation tillage practices include, amongst others, strip tillage, cover cropping, contour farming, zero or chemical tillage, mulch tillage, and reduced tillage, with the ultimate being low disturbance no-till or direct seeding (Unger, 1984).

Since the 1970s, new technology has been redefining these operations where tillage and planting are combined in conservation tillage and where mechanical cultivation has been replaced by herbicides. Modern, large farm equipment can perform these operations easily and quickly with one pass. New tillage systems with emphasis on crop residue management and soil conservation will encompass new technology and continue to evolve around the best systems within a given geographic location as driven by economic and environmental considerations (Reeder, 2000; Coughenour and Chamala, 2000; Owens, 2001). As new agricultural tillage and planting practices are developed across the world, their impacts on the environment and energy use will need to be evaluated critically to ensure their compatibility and sustainability with societal needs.

Peak plow production in the U.S. occurred in the 1950s and 1960s when 75,000 to 140,000 units were shipped annually (USDA, 1965, 1977; Reicosky and Allmaras, 2003). In the late 1980s to 1990, fewer than 3000 moldboard plows were shipped annually in the U.S., and the number of moldboard plows shipped by manufacturers dropped from 46,300 in 1977 to 1400 in 1991 (USDC, 1992). Some of the impetus for change came from the new farm bills and stewardship incentives that encouraged conservation farming. The primary reasons given by farmers for this transition away from the plow were efficiency, equipment width, and speed which the multiple combination tillage tools can be pulled through the soil. Other reasons for going away from the moldboard plow range from no more ''dead furrows,'' no headlands, higher skilled operators, leaving residue on the surface for decreased erosion and to overall economics. The moldboard plow may have special uses depending on soil type and wetness, but combination tillage tools recently have become more prevalent over much of the U.S.

The no-till movement began with the invention of 2,4-D after World War II, and development of paraquat by ICI in U.K. (Hood et al., 1963, 1964). In the early 1960s, no-till agriculture was not widely supported among farmers and agriculture specialists in the U.S. It was intended to be a way of farming without losing a great deal of soil, but few thought that no-till would make a difference in farming. A few no-till pioneers were instrumental in exposing agriculture to these new techniques. At The Ohio State University, David Van Doren and Glover Triplett initiated long-term no-till plots in 1962 at Wooster, South Charleston and Hoytville. These are the longest running no-till experiments in the world. At the University of Kentucky, Shirley Phillips, extension specialist and farmer, Harry Young enthusiastically promoted no-till agriculture (Phillips and Young, 1973; Phillips and Phillips, 1984). George Elvert McKibben, an agronomist with the University of Illinois, helped make no-till the accepted farming technique that it is today. Believing in his cause, McKibbben said, ‘‘I was convinced from the start that it would succeed.’’ The basic principles of no-till agriculture include the following:

- Growing crops without using traditional tillage.
- Using special planting equipment that cuts through the residue mulch.
- Using seeders that require four-wheel tractors, although the seed can be dibbled in by hand (often using sticks to make the opening), or some small equipment suitable for animals or hand tractors.
- Retaining surface residue that reduces erosion, evaporation and limits weed growth.
- Sowing directly into the soil covered by residue mulch.
- Improving water infiltration capacity by ameliorating effects of residue mulch which provides bioturbation and enhances macro-porosity despite some increase in bulk density.

No-till implements are specifically designed for the management of crop residue left on the soil surface (Fig. 6). Most tillage practices bury or remove large amounts of crop residue. For example, the moldboard plow retains less than 10% of the residue, the chisel plow and disking retain between 25 and 75% of the residue, disking 25–75%, and ridge-planting and till planting retain about 40–60% of residue (CTIC, 2006). No-till agriculture on the other hand retains more than 90% of the crop residue, and the seeder is specifically designed to cut through the residue and sow seed in a small furrow (Fig. 7). Residue mulch is essential to reducing losses by erosion (Table 2), even on steep slopes (Harrold and Edwards, 1972). It is a conservation-effective measure. Currently, no-till farming is practiced globally on about 95 Mha of cropland worldwide (Derpsch, 2005), and is likely to expand especially in Asia.

No-till agriculture has gained acceptance in South America at a faster rate than in the U.S. The rate of conversion from plow tillage to no-till has been high in Brazil, Argentina and Chile. In addition to high rate of adoption, no-till system observed in South America has been on a continuous basis. In contrast, no-till practiced in the U.S. Corn Belt has been rotational: 1 year no-till and the second year chisel till. Another variance of rotational no-till is observed in the rice-wheat system in

Fig. 6. No-till soybean seeded through the crop residue.

Fig. 7. A no-till seeder fitted with a fluted disk which can cut through the crop residue mulch and place seed in a narrow slot. The seed is covered by a press wheel that follows the slot opener.

Table 2
Effect of mulch rate on runoff and soil loss in 1974 from Alfisols in western Nigeria (adapted from Lal, 1976a,b)

Slope (%)	Mulch rate (Mg ha^{-1} season^{-1})					
	0	2	4	6	No-till	Mean
(A) Water runoff (mm year^{-1})						
1	411.7	36.2	6.7	0.0	11.5	93.2
5	483.0	126.1	28.3	10.7	14.8	132.6
10	302.9	73.8	34.7	21.1	24.0	91.3
15	374.7	86.8	50.6	19.9	22.6	105.0
Mean	393.1	80.7	30.1	12.9	18.3	
(B) Soil erosion (Mg ha^{-1} year^{-1})						
1	9.3	0.9	0.3	0.0	0.0	2.1
5	134.3	6.3	1.5	0.2	0.7	26.8
10	137.0	5.5	1.0	0.2	0.1	28.8
15	95.5	16.8	2.7	0.7	0.1	23.2
Mean	94.0	7.4	1.4	0.3	0.2	

Total rainfall = 769.2 mm.

the Indo-Gangetic plains of South Asia (Lal et al., 2004). While rice is grown in an intensively puddled field to deliberately destroy soil structure and reduce seepage losses, the following wheat crop is grown by a no-still system with or without burning the rice straw. The system is gaining popularity not so much for soil or water conservation but for saving time needed in the conventional plow-based method of seedbed preparation. Late planting of wheat results in yield reduction and poor quality of grains due to onset of hot weather at the grain ripening stage of wheat (Lal et al., 2004). No-till sowing of wheat was practiced on almost 2 Mha in the Indo-Gangetic plains in 2005. Despite the progress, there is a strong need to develop systems of direct seeding of rice in an unpuddled soil followed by no-till sowing of wheat through the stubble mulch of rice straw. This technology remains to be a high research and development priority.

In addition to erosion control, no-till also saves energy (Lal, 2004a). It utilizes less fossil fuel energy than plow tillage. With diverse crop rotations including legumes, fertilizer use efficiency is also enhanced which further reduces the energy input (West and Marland, 2002). In view of rising energy costs, the five typical operations in traditional agricultural production (including tillage, planting, cultivating, harvesting, and processing, transporting, and storage) must be re-examined in light of the need for energy conservation. During the 20th century, agriculture has undergone vast transformations in the U.S. The number of farmers has decreased, more farmers are relying on off-farm income, agriculture's contribution to the U.S. gross domestic product has declined, and a minority of non-metro counties in the U.S. are farming dependent. Productivity per unit input of energy is the principal criteria of success.

The transition to no-till has implications to environmental quality for its effectiveness in controlling soil erosion and runoff, increasing water infiltration, enhancing SOM concentration, increasing soil biological activity, and saving energy. The transition to no-till also has technical implications for farmers in determining crop rotations, using cover crops, selecting suitable soil type, managing residues, selecting crop varieties and seeding rate, controlling pests, managing soil fertility and pH, and choosing the right equipment. This complex and integrated technology must be understood and implemented to protect soils for sustainable productivity. No-till farming can provide all of the above with nonfood producing functions that also create environmental and ecological benefits. No-till farming also increases farm wildlife for pest and disease control, creates biodiversity, cleans water and air, increases aesthetic value, provides recreation and other amenities, increases water accumulation, storage and management, provides storm protection and flood control, strengthens nutrient cycling and fixation of C and N, increases C sequestration in soils and trees, provides jobs and contributes to the local economy. Proper use of the full no-till system approach improves food production efficiency, profitability, and environmental stewardship important to all society.

6. No-till and carbon sequestration

The most important factor in determining soil quality is the SOM. Decline in SOM concentration under conventional plow tillage occurs independent of soil erosion. In the U.S. Corn Belt, intensive tillage has caused a soil C loss between 30 and 50% (Schlesinger, 1985), leading to emission of greenhouse gases (GHGs), and the attendant global warming. The "bigger the better" approach to plowing has exacerbated the problem of soil erosion and non-point source pollution on undulating terrains. Increase in SOM mineralization also accentuates CO_2 emission following plowing.

The short-term impact of moldboard plow and various tillage methods on CO_2 emission from the soil can be evaluated using a portable dynamic chamber mounted on a high clearance forklift implement. Using this technique, it has been documented that there occurs a rapid and severe loss of C immediately following intensive tillage (Reicosky and Lindstrom, 1993). Experiments conducted in Minnesota have indicated that the moldboard plow produces the roughest soil surface, the highest initial CO_2 flux and maintains the highest flux for two to three weeks following the tillage event. High initial CO_2 fluxes are related to the depth of soil disturbance that results in a rougher surface and larger voids than to residue incorporation. Lower CO_2 fluxes result from tillage systems associated with low soil disturbance and small soil pores. No-till causes the least amount of CO_2 loss during the 2–3-week period following tillage. Reicosky and Lindstrom (1993) and Reicosky (1997, 1998, 2002) concluded that intensive tillage methods, especially moldboard plowing to 0.25 m depth, affects this initial soil flux differently and suggested improved soil management techniques such as strip tillage or forms of conservation tillage to minimize agricultural impact on global CO_2 increase.

Concern for environmental quality and GHG emissions (carbon dioxide, methane, nitrous oxide) require knowledge of tillage effects on C emission. The link between global warming and atmospheric CO_2 abundance has heightened interest in soil C storage in agricultural production systems. Agricultural soils play an important role in C sequestration or storage and thus can help mitigate global warming (Lal et al., 1998). Tillage processes and mechanisms, (e.g., tillage-induced CO_2 efflux), lead to C loss and are directly linked to soil productivity, soil properties and environmental issues (Paustian et al., 1997). Soil C dynamics indirectly affect climate change through net absorption or release of CO_2 from soil to the atmosphere in the natural C cycle. Carbon comes into the system through photosynthesis and is returned to the atmosphere as CO_2 through microbial respiration accentuated by anthropogenic intervention. A judicious management of SOM is vital because of its role in maintaining soil fertility, physical properties and biological activity required for food production and environmental quality. Soil C sequestration is also needed to partially offset GHG emissions from manufacture and use of fertilizers, liming and use of fossil fuels as well as to minimize the release of more potent nitrous oxide and methane. However, nitrous oxide emission may be greater under no-till than plow tillage on many soils (Baggs et al., 2003; MacKenzie et al., 1997; Linn and Doran, 1984; Palma et al., 1997). Researchers in Michigan (Robertson et al., 2000) have suggested that nitrous oxide—with nearly 310 times the global warming potential of carbon dioxide needs to be factored into GHG calculations. Nitrous oxides are associated with fertilizer nitrogen use and, like carbon levels, can be influenced by tillage regimes (Parkin and Kasper, 2006; Steinbach and Alvarez, 2006; Liu et al., 2005; Dale et al., 2005). Venterea et al. (2005) have shown that over a 2-year period, the combination of anhydrous ammonia fertilizer use and no-till can lead to nitrous oxide emissions. The global potential of C sequestration if all croplands were converted to no-till farming is 1 Pg C $year^{-1}$ (Pacala and Socola, 2004). The rate of SOC sequestration upon conversion from plow tillage to no-till farming is 0.1–1.0 Mg C ha^{-1} $year^{-1}$ (Lal, 2004b). Whereas plowing increases the rate of mineralization and makes nutrients available for plant growth, putting crop residue back into the soil will cause nutrient immobilization. Conversion of crop residue into humus would need additional nutrients for humification. Thus, rate of nutrient application for sustainable soil use must consider replacement of those removed by crops, leached, lost in runoff, and for humification of biomass C.

7. Challenges and opportunities in agricultural research during the 21st century

The world population of a few million at the dawn of agriculture has increased several fold to reach 6.5 billion in 2006. The population is likely to stabilize around 10 billion towards the end of the 21st century. Yet, the future increase in population will likely happen in the developing countries of Africa and Asia, where soil resources are already under great stress (Lal, 1989; Smil, 1987; Oldeman et al., 1991). Future food demand of these countries is expected to more than double over the next few decades because of both the increase in population and also change in diet from mostly vegetarian to increasingly meat-based food. Yet, there are almost one billion food insecure people in the world and there is a growing consensus that the U.N. Millennium Development Goals will not be realized. Thus, there is a strong need to bring about a drastic increase in food production in developing countries of Asia, Africa, Latin America and the Caribbean.

The data in Table 3 outlines the chronological development of yield-enhancing innovations. Past developments in agriculture, with a notable impact on productivity and population carrying capacity, included evolution of a plow, use of supplemental irrigation, and development of fertilizers. Future innovative technologies will include developments with regards to supply of water and nutrients directly to plant roots to minimize losses and enhance use efficiency, precision farming, conservation tillage, C sequestration and land-saving technologies.

Table 3
Evolution of agricultural technologies with strong impact on agronomic productivity and population carrying capacity

Era	Locale	Technology
Past achievements		
11000–9000 BC	Mesopotamia	Beginning of settled agriculture
9500–8800 BC	Sumerians	Use of supplemental irrigation
5000–4000 BC	Mesopotamia	Use of simple tools such as an "ard" or plow
3000–2000 BC	Indus Valley	Use of animal-driven plow
2500–2000 BC	Mesopotamia	The concept of fertility of cropland soils
900–700 BC	Greece	Use of animal manure
370–280 BC	Rome	Use of green manures
1 AD	Rome	Use of lime and saltpeter (KNO_3)
1604–1668 AD	Germany	Impact of saltpeter on plant growth
1100–1200 AD	Moorish Spain	Soil quality
1803–1873 AD	Germany	Use of chemical fertilizers
1950–1970 AD	U.S. Corn Belt	Conservation tillage, no-till farming.
1960s AD	Israel	Drip irrigation, fertigation
1980s AD		Biotechnology and GM crops
2000 AD		Deliver nutrients and water directly to plant roots, biomass-based H_2 fuels, conservation tillage, land-saving technologies, precision farming, soil carbon sequestration

8. Conclusion

Agriculture, as we know it, evolved over 10–13 millennia, and is destined to undergo remarkable change during the 21st century. Eight current trends that will affect future agricultural development include: (1) increased risks of soil degradation; (2) competing soil uses; (3) focus on ecosystem services; (4) increase in farm size; (5) movement toward commercialization; (6) genetic engineering; (7) global markets; (8) changing social structure. Soil management systems will have to be developed to address these emerging issues. While it is certainly not a panacea, conversion of plow tillage to no-till farming can address some of the issues by providing alternatives that are environmentally and economically compatible and sustainable while maintaining a high degree of social acceptability. The agricultural community will face many new and difficult challenges in the years to come, including: (1) competitive pressures; (2) sustainable development; (3) resources conservation; (4) research and development. New agricultural management systems need to be developed that include consideration and inclusion of economics and economic policies, environmental sustainability, social and political concerns, and new and emerging technology. These systems can ultimately assist land managers to develop new and improved sustainable land-use strategies. In some soils and climates, no-till farming can address the emerging issues of the 21st century: global climate change, accelerated soil degradation and desertification, decline in biodiversity, and achieving food security for the expected population of 10 billion in 2050. Replacement of plow tillage by no-till farming, based on crop residue management and use of leguminous cover crops in the rotation cycle, can achieve positive nutrient balance by using manures and other biosolids, and increase C storage in soil and terrestrial ecosystems. The no-till soil and crop residue management system promotes soil carbon storage and long-term sustainable agriculture that provides food, fiber, biofuels, ecosystem services and environmental benefits for all of society.

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