

Estimating Source Carbon from Crop Residues, Roots and Rhizodeposits Using the National Grain-Yield Database

J. M.-F. Johnson,* R. R. Allmaras, and D. C. Reicosky

ABSTRACT

Crop residue management received little attention until about 1970. Records of crop residue production are limited, but crop yield databases have been available since 1865. Carbon sequestration and other conservation benefits require a detailed knowledge of crop residue production and management. Our objectives are to: (i) review grain and biomass yield, harvest index (HI), and root C/shoot C ratios (k) of major grain crops in the USA; (ii) discuss historical agricultural-practice impacts on soil organic C (SOC); and (iii) compare estimates of total (above- and belowground) source C production (ESC) relative to minimum source C inputs required to maintain SOC (MSC). Aboveground MSC input averaged $2.5 \pm 1.0 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ($n = 13$) based on moldboard plow sites and $1.8 \pm 0.44 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ($n = 5$) based on no-till and chisel plow sites. These MSC values included only aboveground source C, thus underestimate the total MSC. When ESC is estimated from k , including rhizodeposition (k_{rec}), the true magnitude of the C cycle is at least twice that when ESC is estimated using k excluding rhizodeposition (k_{his}). Neglecting rhizodeposition C underestimates the net production of C in cropland. Current yields and measured MSC predict continued SOC loss associated with soybean [*Glycine max* (L.) Merr.] and some wheat (*Triticum aestivum* L.) production management unless conservation tillage is used and ESC is increased. The adequacies of ESC to maintain SOC has direct implications for estimating the amount of crop residue that can be harvested and yet maintain SOC.

SOIL organic C is the net result of simultaneous processes, the addition of floral and faunal biomass and the C losses due to biological respiration and physical losses related to tillage, erosion, and leaching and runoff of dissolved organic C as part of the C cycle. Terrestrial C stocks are sensitive to changes in land management (e.g., conversion to cropland, or changes in crop rotation or tillage system), climate, and soil. Inventories of soil C stocks are necessary for the development of strategic policies regarding U.S. agriculture and its associated environment (Eve et al., 2001). Inventories (e.g., Eve et al., 2001, 2002) are helpful; however, an improved inventory of current and potential source C inputs is needed. *Source C*, as used in this review, refers

to the organic C inputs derived from plant biomass (Allmaras et al., 2004).

A net loss of SOC (20–60%) was measured in most agricultural land in the first 50 yr after conversion from its native prairie or forest state (Huggins et al., 1998a; Janzen et al., 1998; Lal et al., 1998; Follett et al., 1997). In prairie soils, C losses were 17% in the upper landscape position and >70% in the footslope position (Slobodian et al., 2002). Greater biomass production and greater retention of crop residues through adoption of a diverse crop rotation and conservation tillage (especially no tillage) that retains crop residue on or near the soil surface can often reverse this loss and increase SOC (Lal et al., 1998; Allmaras et al., 2000; Reicosky and Allmaras, 2003). An increase in organic C inputs relative to the CO₂ efflux or other losses (e.g., tillage, erosion, or leaching) is necessary to increase SOC.

Before we continue our discussion of the C cycle, we would like to define related terms. We use the term *soil organic matter* (SOM) as defined by Stevenson (1994) to include the whole of organic matter in soils including litter, light fraction, microbial biomass, water-soluble organics, and stabilized organic matter. *Soil organic C* is the C fraction of these pools. Carbon from all these various pools is included when SOC is determined by combustion methods, except surface litter, if the samples are sieved to remove surface litter. According to the Stevenson (1994) definition, most SOM is comprised of stable organic matter, which are protected pools having a mean residence time of >5 yr, to the very recalcitrant C, which may have mean residence times on the order of centuries or longer. Stable organic matter or *humus* corresponds to the Soil Science Society of America (1998) definition of SOM. Generally, SOM is calculated by assuming SOM is 40% C by mass, therefore values reported in the literature usually fit the Stevenson (1994) definition of SOC and SOM. Therefore, in this review, SOM reflects the broader definition as defined by Stevenson (1994).

The simple C cycle showing the flow of C from photosynthesis to the roots, through the soil, and back to the atmosphere is presented in Fig. 1 to exemplify complexities of understanding the rapid C cycling within an agricultural system. In this schematic, the C found in various pools (stable SOM, decomposing tissue, soil organisms, free organic C, exudates, etc.) all contribute to SOC. Photosynthate provides the energy for plant

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Abbreviations: ESC, estimate of source C production; HI, harvest index; k_{his} , root biomass C/grain C plus vegetative C ratio; k_{rec} , root biomass plus rhizodeposition C/grain C plus vegetative C ratio; MSC, minimum amount of source C inputs to maintain SOC; RLD, root length density; SOC, soil organic carbon; SOC_i, initial soil organic carbon; SOM, soil organic matter; TRL, total root length.

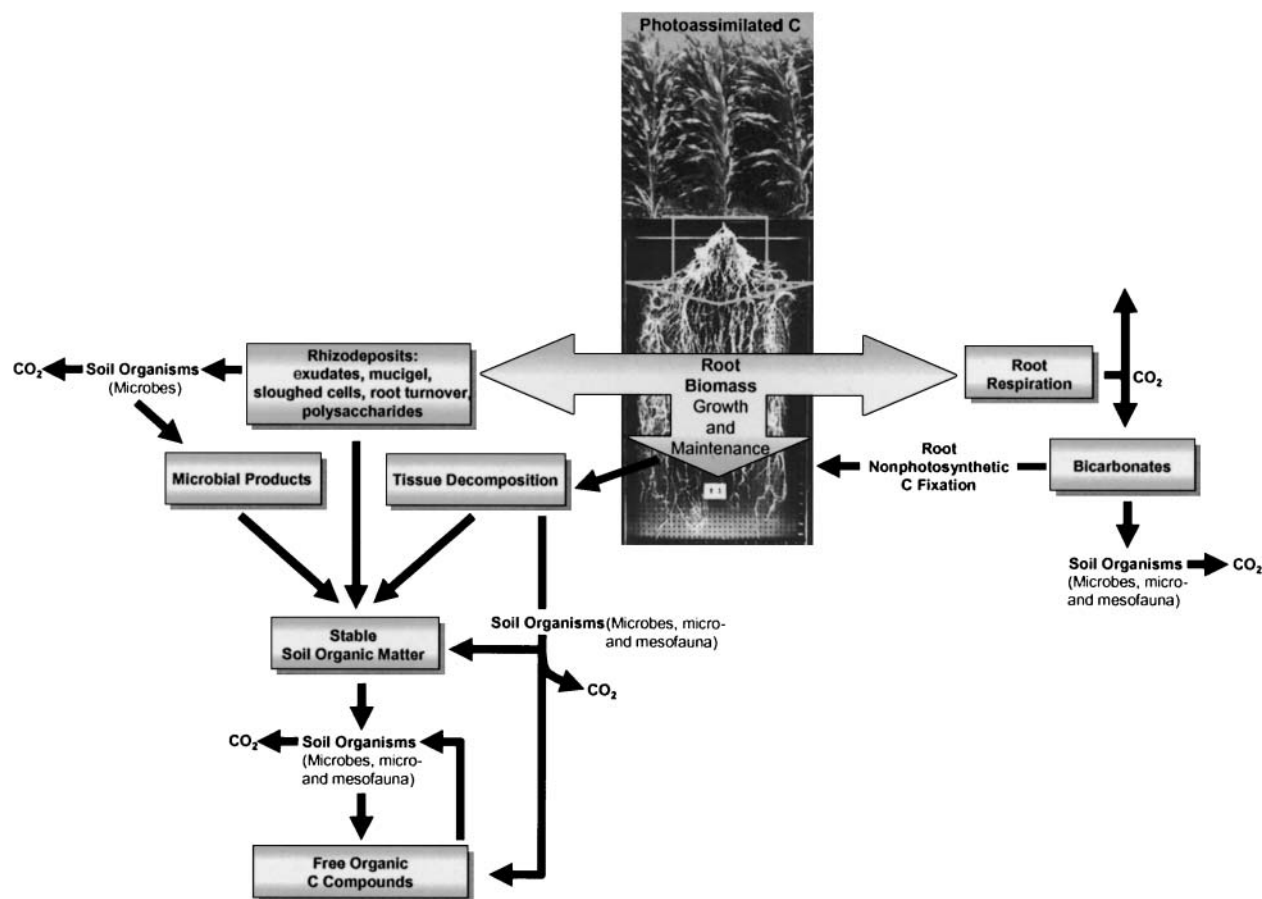


Fig. 1. Schematic of photosynthate fate (modified from Smucker, 1984). The C in the various pools (stable SOM [soil organic matter], decomposing tissue, soil organisms, soluble C pools, exudates, etc.) contributes to soil organic C. The rate and amount of translocation depends on age, nutritional status, and genetics of the plant. Labeling studies indicate about 50 to 70% of photosynthetic C remains above ground and 20 to 30% is translocated below ground. Of the translocated C, about 50% is used for root growth, and about 30% moves into the rhizosphere or is released during root respiration (Johnen and Sauerbeck, 1977; Kuzyakov and Cheng, 2001; Kuzyakov 2002a, 2002b). Molina et al. (2001) predicted that 24% of the net C fixed by photosynthesis became rhizodeposition, which is C found in the rhizosphere derived from root exudates, mucigel, and sloughed cells. Rhizodeposition is a critical component for driving the belowground food web. Respirated CO₂ can be recycled into roots via nonphotosynthetic carboxylation of phosphoenol pyruvate using HCO₃⁻ to form oxaloacetate by the ubiquitous plant enzyme phosphoenol pyruvate carboxylase (Latzko and Kelly, 1983). Nonphotosynthetic C fixation may be important for balancing C in roots (Vuorinen et al., 1992). The decomposition and humification of plant and faunal material forms stable SOM. Further decomposition of SOM releases free C compounds and, ultimately, organic C is converted into inorganic CO₂.

(above- and belowground) growth and maintenance, but a significant fraction, as much 40% (Johnen and Sauerbeck, 1977) provides food for the belowground food web. A unit of C captured, reduced, and moved through the plant and soil organisms may traverse several trophic levels before returning to the atmosphere as CO₂ and only a small fraction becomes stabilized SOM. Stabilized SOM is not immune to decomposition, but decomposes at a slower rate. Soil respiration combines live root respiration and respiration of other soil organisms. Some fungi and bacteria are primary feeders on sloughed root cells, root exudates, or other rhizodeposits, which links their respiration directly to root-derived C. Moving up the food web, heterotrophs feed on primary consumers, other micro- and mesofauna, detritus, and SOM; their respiration then is linked indirectly to root-derived C. The decomposition and humification of plant and faunal material form stable SOM. Further decomposition of SOM releases free organic C compounds and ultimately organic C is converted into inorganic CO₂.

Nonphotosynthetic C fixation via phosphoenolpyruvate carboxylase, which catalyses the carboxylation of phosphoenol pyruvate using HCO₃⁻ to form oxaloacetate and inorganic P (Latzko and Kelly, 1983), may be important for C balance in roots (Poel, 1955; Maxwell et al., 1984; Vuorinen et al., 1992), especially during N assimilation (Vance et al., 1983; Maxwell et al., 1984) and organic acid exudation from P-starved lupin (*Lupinus albus* L.; Johnson et al., 1996). A detailed discussion of direct C fixation by roots is beyond the scope of this review, but is presented as an example of other complexities of the C cycle that are not well understood.

The study of root systems and belowground processes has not received as much attention as their aboveground counterpart (Norby, 1994). An understanding of belowground processes requires measurement of root biomass and rhizodeposition including mucilage, sloughed cells, and root exudates (Johnen and Sauerbeck, 1977). Root biomass values from periodic sampling of roots can differ greatly from gross root production (including rhizo-

deposition) associated with root turnover (Goss and Watson, 2003). The amount of photosynthate translocated belowground during the entire growing season has been estimated based on assumptions derived from laboratory and controlled studies (Johnen and Sauerbeck, 1977; Kuzyakov, 2002a, 2002b), but results extrapolated from laboratory studies to field conditions can be hampered by temporal and spatial variation in the field.

Growing concerns about agriculture's potential negative or positive impacts on climate change call for more knowledge about all aspects of C cycling (Lal et al., 2003). More detailed evaluation of the processes controlling soil C dynamics in agricultural systems is required to improve the management of soil C stocks such that more C is sequestered to reduce the rate of increase in atmospheric C levels. The growing interest in using crop residues as renewable energy (Biomass Technical Advisory Committee, 2002; Wilhelm et al., 2004) demands that we have accurate estimates of MSC to sustain long-term soil productivity, including biomass cover for erosion control. Our objectives are to: (i) review grain yield, HI, biomass yields, and root C/shoot C ratios (k_{his} and k_{rec}) of seven major grain crops in the USA; (ii) discuss historical practices in agriculture, which have earlier accelerated the decline of SOC and then improved the potential to sequester C; and (iii) compare ESC relative to MSC. This review focuses on the input component rather than a detailed discussion of the SOC loss mechanisms, such as erosion or leaching. A conceptual pathway is presented using published data to estimate MSC and using yield databases, HI, k_{his} , and k_{rec} from the literature to calculate source C available for SOC and simple extrapolation techniques to discuss the potential for current and future source C inputs to maintain or increase SOC.

GRAIN YIELD: PAST AND PRESENT

Grain yields were relatively low and constant until after the 1930s (Fig. 2) while U.S. farmers focused on food production and their own solvency (Cochrane, 1993). Depending on the crop, historical records show grain yields increased 92 to 344% from 1940 to 2000 (Table 1). Many mechanical, genetic, and chemical (pesticide and fertilizer) technological innovations contributed to the increased production (Ruttan, 1982). Stewart et al. (2005) estimated that commercial fertilizer (especially N and P) accounts for 30 to 50% of the yield increase since 1940. The use of P and K commercial fertilizers began in the 1940s, with most N fertilizer chemically associated with phosphates; the large increases in N fertilizer use began around 1960 with the production of anhydrous NH_3 by the Bosch Háber process (Allmaras et al., 1998; Keeney and Hatfield, 2001). Genetic improvements account for 28 to 39% of the sorghum [*Sorghum bicolor* (L.) Moench] yield increase (Miller and Kebede, 1984; Unger and Baumhardt, 1999), about 60% for soybean (Voldeng et al., 1997; Kumudini, 2002), about 60% for corn (*Zea mays* L.; Duvick, 1992; Tollenaar and Lee, 2002), 30 to 60% for wheat (Brancourt-Hulmel et al., 2003), and 30 to 50%

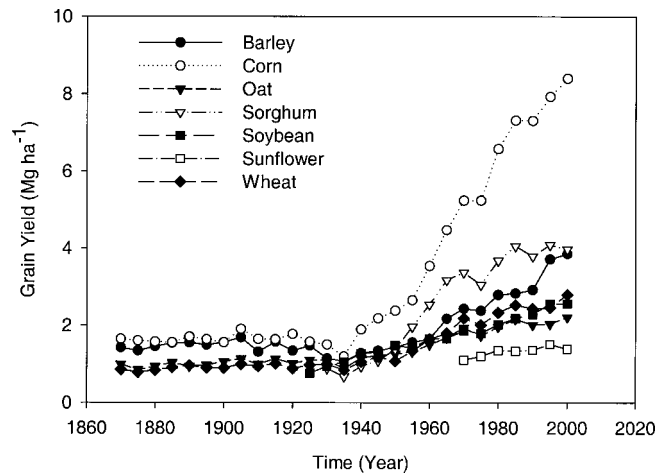


Fig. 2. Historic grain yields of major crops in the USA from 1865 to 2000. Each point is the 3-yr average centered on the year indicated (USDA–National Agricultural Statistics Service, 2004).

for barley (*Hordeum vulgare* L.; Ortiz et al., 2002; Abeledo et al., 2003). Genetics and improved management interact closely in influencing final yield; thus, it is the interaction of these factors that is responsible for increases in yield with time (Evans and Fischer, 1999; Duvick, 2005). Evans and Fischer (1999) indicated that the maximum yield potential of certain crops (e.g., corn) has not yet been realized; therefore, the potential for increased biomass production continues. Corn has an estimated genetic yield potential of 25 Mg ha^{-1} (Tollenaar, 1983; Tollenaar and Lee, 2002). Much of the observed yield increase in corn is attributed to improved tolerance of high plant populations as well improved tolerance of biotic and abiotic stress, rather than to improved yield per plant at low population density (Tokatlidis and Koutroubas, 2004). Transgenic crops are now providing herbicide tolerance and insect resistance, which may also increase yield potential (Duvick, 2005).

Table 1. Average grain yield, harvest index, and crop residue production for seven selected crops from 1940 to 2000 in the USA.

Crop	Grain yield†		Harvest index		Crop residue	
	1940‡	2000§	1940¶	2000#	1940	2000
	— kg ha^{-1} —				— kg ha^{-1} —	
Barley (<i>Hordeum vulgare</i> L.)	1280	3860	0.27	0.50	3460	3860
Corn (<i>Zea mays</i> L.)	1890	8400	0.35	0.53	3510	7450
Oat (<i>Avena sativa</i> L.)	1150	2210	0.33	0.44	2340	2810
Sorghum [<i>Sorghum bicolor</i> (L.) Moench]	930	3980	0.34	0.47	1800	4490
Soybean [<i>Glycine max</i> (L.) Merr.]	1260	2560	0.30	0.46	2940	3000
Sunflower (<i>Helianthus annuus</i> L.)	NR††	1390	NR	0.40	NR	2080
Wheat (<i>Triticum</i> ssp.)	1050	2800	0.28	0.45	2700	3420

† Three-year average centered on the shown year.

‡ Cochrane, 1993; USDA–National Agricultural Statistics Service, 2004.

§ USDA–National Agricultural Statistics Service, 2004.

¶ Allmaras et al., 1998.

From Lynch and Frey, 1993; Prince et al., 2001; Halvorson et al., 2002; Pedersen et al., 2004; Vetsch and Randall, 2004; Yang et al., 2004.

†† NR = not reported.

HARVEST INDEX FOR ESTIMATING CROP RESIDUE

Grain yields of major U.S. crops are available in the national crop yield databank (USDA-National Agricultural Statistic Service, 2004), but neither their vegetative shoot nor root biomass are available. These ancillary data are needed to estimate historic, current, and potential source C inputs. Before 1970, HI was not measured or reported in the literature (Donald and Hamblin, 1976; Hay, 1995); however, since its introduction for comparing cereal cultivar improvements due to plant breeding, HI has been estimated frequently for a wide array of species, cultivars, and growing conditions. Harvest index is calculated (Donald and Hamblin, 1976) as:

$$HI = Y_{gr}/Y_{biol} \quad [1]$$

where Y_{gr} is harvested grain and Y_{biol} is the total above-ground biomass including the harvested grain (above-ground net primary production) at maturity. Harvest index has increased about 45% during the 1940 to 2000 period for most crops (Table 1). Generally, this increase has been attributed to genetic improvement (Miller and Kebede, 1984; Simmons, 1987; Cox et al., 1988; Voldeng et al., 1997; Kumudini, 2002).

Harvest index reaches a maximum when there is little or no nutrient or water stress (Prihar and Stewart, 1991). Adverse field conditions may distort estimates of HI when foliage is damaged from hail (Halvorson et al., 2002), foliar disease (Peltonen-Sainio and Karjalainen, 1990), and insect damage (Riedell and Evenson, 1993). Nutrient stress (Linden et al., 2000; Vetsch and Randall, 2004; Wilts et al., 2004) and water stress (Robinson, 1978; Eck and Musick, 1979; Jones and Popham, 1997; Lyon, 1998; Linden et al., 2000; Prince et al., 2001) usually reduce HI. The timing of final biomass determination also plays a significant role in HI estimates, especially in species that abscise leaves before grain harvest, such as soybean. These species can have a 20 to 30% positive bias because of leaf loss before harvest (Schaupaugh and Wilcox, 1980; Morrison et al., 1999). There are limitations due to other unknown stresses; however, HI of an unstressed crop, as noted for 2000 in Table 1, offers a conservative estimate of vegetative aboveground biomass production in the absence of measured HI.

Rearranging Eq. [1] allows calculation of vegetative aboveground biomass (Y_r ; Table 1) from harvested grain biomass and reported HI as follows:

$$Y_r = Y_{gr}[(1/HI) - 1] \quad [2]$$

We use HI and reported yield to estimate Y_r for C inputs to form SOC, recognizing that HI is influenced by cultivar and the environment as discussed above.

RESIDUE PRODUCTION, MANAGEMENT, AND SOIL ORGANIC CARBON: PAST AND PRESENT

Especially before 1940, many agronomic practices reduced soil C and were not conducive to sustained

biomass production (Allmaras et al., 1998). Crop residues were often mistakenly considered problematic, and efforts to accommodate crop residue was referred to as "trash management" (Larson, 1979; Power and Follett, 1987). Typically, farmers moved the crop and associated residues to a central point for threshing so the residue (vs. the grain) could be used for feed and livestock bedding. Frequently, straw stacks and corn stover, especially the cobs, were burned. During this period, very little commercial fertilizer, especially N, was used to replace nutrients removed with the harvested grain and biomass. Other management practices that accelerated SOC loss included fallow and tillage, such as moldboard plowing or other soil-inverting tillage practices. Consequently, SOC levels decreased as much as 60% below the original value in tallgrass prairie soils before 1870 (Paustian et al., 1997; Huggins et al., 1998a; Lal et al., 1998). Decreases of SOC in semiarid lands ranged between 20 and 40% after cultivation began (Follett et al., 1997; Janzen et al., 1998; Peterson et al., 1998). It was not until about 1980 that sequestering C as SOC was recognized as a means to remove atmospheric CO₂, thus reducing potential global climate change (Council for Agricultural Sciences and Technology, 1992).

Crop residue was calculated using Eq. [2], biomass yield, and HI (Table 1). Crops now produce more biomass than at any time in the past. Crop residue biomass increased 12% (barley), 112% (corn), 20% (oat [*Avena sativum* L.]), 150% (sorghum), 2% (soybean), and 26% (wheat) between 1940 and 2000. Now, more of the biomass also remains at the site of production because of current livestock management (e.g., fewer crop residues removed for bedding) and improved harvest technology. For example, without modern wheat harvest technology, only ~20% (~680 kg ha⁻¹) of the 3420 kg ha⁻¹ vegetative biomass produced by a crop of semidwarf wheat in 2000 would be returned to the field (Douglas et al., 1989). Harvesting with corn pickers in 2000 instead of combines would reduce the corn residue returned to the field from 7450 to 4990 kg ha⁻¹ due to the removal of the corn cob after shelling off site (Ritchie and Hanway, 1982). Increased biomass production, improved crop residue management (e.g., leaving residue in the field and on the soil surface) associated with conservation tillage management, and increased fertilizer inputs have all contributed to decreased rates of soil erosion and associated loss of soil C (Allmaras et al., 1998; Lal et al., 1998; Sperow et al., 2003).

TOTAL ROOT CARBON (ROOT BIOMASS CARBON PLUS RHIZODEPOSITION CARBON)

In a cropping system, the vegetative aboveground biomass and the root system represent the available organic source C inputs into the soil, unless manure or another organic amendment was applied, which adds additional inputs. Understanding the role of C translocated belowground is critical to understanding the soil C cycle. It is the reduced C (photosynthate) translocated

belowground that supports root growth and maintenance; root biomass plus root rhizodeposition provides the energy inputs into the soil food web (Fig. 1). Balesdent and Balabane (1996), Allmaras et al. (2004), and Wilts et al. (2004) noted the relative importance of root biomass C plus rhizodeposition (total root C) compared with shoot C. An accurate accounting of total root C sources is critical for assessing the overall plant-derived C inputs into the soil.

Root Measurements and Interpretation

There are many challenges for estimating the amount and forms of C allocated belowground (Smucker, 1984). Root plasticity and variability (spatial and temporal) together with sampling challenges make it very difficult to accurately measure root biomass. As noted by Taylor (1986), all root biomass sampling techniques (e.g., soil cores, monoliths, minirhizotron, etc.) are hampered by high variability, loss of fine root biomass, and high labor requirements. Moreover, overall gross root production including rhizodeposition is not adequately represented by periodic root biomass sampling (Goss and Watson, 2003). Hence, root biomass sampling alone is inadequate for estimating belowground source C inputs. Direct measurements of rhizodeposition are hampered by their inherent labile nature, even in controlled environments (e.g., Hoffland et al., 1990; Hutsch et al., 2002). Moreover, the amount and form of rhizodeposition are influenced genetically and environmentally (Marschner, 1995).

Roots and rhizodeposition are mechanisms for moving C below the zone of tillage. Vertical root growth distributes the root biomass C and rhizodeposition throughout the soil profile. The quantity and location of this C requires knowledge of the depth and amount of root C throughout the entire rooting depth. Rooting depths of annual crops range from ~0.5 to ~3.0 m (Borg and Grimes, 1986; Dardanelli et al., 1997; Merrill et al., 2002; Stone et al., 2002) in contrast to perennial root crops such as alfalfa (*Medicago sativa* L.), which can reach depths of 6 m after several growing seasons (Borg and Grimes, 1986).

Root biomass in grams measured by root extraction, root length density (RLD in meters per cubic meter) or total root length (TRL in kilometers per square meter) measured by minirhizotron or root extraction are common determinants of rooting characteristics. Root length density is an excellent measure of comparative rooting depth (Merrill et al., 2002). When combined with specific root length (in kilometers per kilogram), RLD allows an estimation of both root biomass (in the absence of direct biomass measurement) and root/shoot ratio (belowground biomass divided by aboveground biomass, in kilograms per kilogram).

Reported TRL for soybean varied from 2.5 km m⁻² in a 0.75-m profile (Barber, 1978), 5.5 km m⁻² in a 1.8-m profile (Sivakumar et al., 1977), and 7.7 km m⁻² in a 1.4-m profile (Merrill et al., 2002). A TRL of 9.9 km m⁻² in a 1.8-m profile was reported for sunflower (*Helianthus annuus* L.) by Merrill et al. (2002). Spring wheat was

reported to have 15.5 km m⁻² in a 1.4-m profile (Merrill et al., 2002), similar to the values for spring wheat and spring barley reviewed by Barraclough et al. (1991), who found winter cultivars to have TRL from 20 to 36 km m⁻² in 0.2 m. Reports of corn TRL values vary from 5.0 km m⁻² in a 1.2-m profile (Newell and Wilhelm, 1987) to 15.8 km m⁻² in a 0.9-m profile (Dowdy et al., 1991) and a very high value of 45 km m⁻² in a 1.0-m profile (Hilfiker and Lowery, 1988). Connor and Hall (1997) found sunflower and annual legumes to have similar RLDs, which are typically shorter than in roots of cereals and other monocots. Van Noordwijk and Brouwer (1991) summarized that cereals including corn have ~200 km kg⁻¹ specific root length and dicotyledonous crops range from 100 to 400 km kg⁻¹. The wide-ranging TRL and RLD values for different species reflect large variation in potential root biomass C inputs, both amounts and placement.

It has long been recognized that soil environment (e.g., local available water, nutrient placement and local availability, microbial activity, soil structural variations related to root impedance, and thermal variations) modifies root growth and development (e.g., Drew, 1975; Drew and Saker, 1975; Russell, 1977; O'Toole and Bland, 1987; Rendig and Taylor, 1989). Plant growth, including root–shoot relationships, has a thermal and developmental component. Klepper et al. (1984) described the relationship between shoot (stem and leaf) and root development on a thermal-time basis in winter wheat. Porter et al. (1986) then used field-measured relations to simulate the development of TRL (37.5 km m⁻²) in the top 100 cm, the bulk of which was associated with first-order laterals (29.8 km m⁻²). The roots of most species may proliferate in parts of the root zone differentially, depending on the soil environment (e.g., nutrient availability, bulk density, and water or air status). Cultivars in some species may respond differently to these root zone variations of soil environment (O'Toole and Bland, 1987; Klepper, 1991). In general, environments such as low N, impeded gas flux, deficient or excessive water supply, high bulk density, or non-optimal temperatures in the root zone increase root/shoot ratios in the very early vegetative stages of growth (Klepper, 1991). Brouwer (1983) developed the concept of a functional equilibrium between roots and shoots of young developing plants. Klepper (1991) used Brouwer's concept to explain the interdependence of roots and shoots, in which each is considered a compartment or "sink" of biomass C supply that is essential to the other.

Beyond early vegetative stages, the root/shoot ratio decreases as a result of N fertilization because shoots tend to be more responsive than roots, although the biomass of both roots and shoots increase in response to N application (Russell, 1977; Jenkinson, 1981; Anderson, 1988; Huggins and Fuchs, 1997; Sattelmacher et al., 1990). The increased shoot biomass produced by greater N fertilizer rates to cereal crops was facilitated by reduced lodging associated with an increased HI, especially in semidwarf wheat (Simmons, 1987), stiff structural barley stems (Anderson and Reinbergs, 1985), and less stalk

with less lodging in corn (Duvick, 1992). Anderson (1988) found that N fertilization of corn increased shoot growth, TRL, specific root length, and total shoot N, but did not change root weight. Huggins and Fuchs (1997) found an increased grain yield and stover biomass based on measured HI, but a smaller increase in root biomass due to N fertilization. Jenkinson (1981) cited a number of long-term Rothamsted studies where N-fertilized wheat showed a greater increase in shoot biomass than root biomass. Both Jenkinson (1981) and Huggins and Fuchs (1997) commented that the total effect of N fertilization on belowground plant parts requires a measure of rhizodeposition response. Sattelmacher et al. (1990) found a similar decreased root/shoot ratio in potato (*Solanum tuberosum* L.) with increased N availability. Barraclough et al. (1991) showed that N fertilization increased wheat rooting depth to as deep as 1.2 m under both irrigation and dryland management. Rooting depth was 20 cm deeper under a dryland than an irrigated environment, and rooting was 20 to 30 cm deeper when soil was not compacted in the 20- to 40-cm layer.

As one would expect, roots display genotypic and phenotypic variation. Mitchell and Russell (1971) observed genotypic variation in soybean biomass and rooting depth, but the seasonal rooting response to a 16°C soil isotherm controlled the depth of rooting (Mason et al., 1982); this result was supported by Kaspar and Bland (1992), who also reported a strong dependence of rooting depth on seasonal isotherms. Hurd (1974) demonstrated a genotypic drought tolerance of wheat, such that the response remained consistent when compared under different initial profiles of soil water content to 120 cm. Sorghum has phenotypic plasticity, in that some cultivars produce deeper roots and greater RLD below 100 cm when the water supply above the 100-cm depth is limited by deficient rainfall (Jordan and Miller, 1980; Jordan and Monk, 1980). These deeper rooting cultivars also had a larger shoot biomass corresponding to an increased root/shoot ratio when there was a rainfall deficiency. Riedell and Evenson (1993) found that single-cross corn hybrids of the 1970 and 1980 eras produced larger root systems than those of the 1960 era as determined by a standard root-pull technique to characterize resistance to corn rootworm damage. These 1970- and 1980-era hybrids also lodged less and produced more grain even though no change in HI was observed. Riedell and Evenson (1993) supported the earlier conclusion of Duvick (1992) that newer hybrids tolerate N and water stress in a high population density and produce more shoot growth and larger root systems. Siddique et al. (1990) measured a lower specific root length in a new dwarf wheat cultivar in the upper 15 cm compared with an older cultivar; comparative values were 50 vs. 100 km kg⁻¹, respectively. At depths below 15 cm, the newer (dwarf) cultivar had a greater specific root length than the older cultivar. Clarkson (1985) concluded that 20% of the total photosynthate exudes from root tips; thus, more exudation is expected with more root tips per unit of RLD, as shown by Siddique et al. (1990).

Estimating Total Root-derived Carbon (Root Biomass Carbon plus Rhizodeposition Carbon)

Even if all root biomass at physiological maturity were measured accurately, biomass alone would still underestimate the total amount of root-derived C because rhizodeposition was not measured. Estimates are that 2.5 to 6 times the amount of C incorporated into root biomass may be represented as rhizodeposition (Johnen and Sauerbeck, 1977; Molina et al., 2001). Molina et al. (2001) predicted that 24% of the net photosynthetic C in corn became rhizodeposition; root biomass retained less photosynthate C than was released from roots to rhizodeposition, but actual root biomass contributed more C to SOM. Much of the rhizodeposition is highly labile and therefore cycled through the soil food web during the growing season, with the respired portion of the C returned to the atmosphere as CO₂ (Fig. 1). Carbon cycle models based on recoverable root biomass alone underestimate C movement from the shoot to the root and the root to the soil pools (Edwards et al., 2004). Labile rhizodeposits represent a large amount of C not included in root biomass (Hütsch et al., 2002); however, they have a critically important role in soil C sequestration and biological activity (Balesdent and Balabane, 1996; Allmaras et al., 2004; Wilts et al., 2004; Hooker et al., 2005) and soil aggregation (Tisdall and Oades, 1982; Hütsch et al., 2002). Unless there is a large increase in SOC due to rhizodeposition, the SOC turnover rate is overestimated. Jenkinson (1981) defined the soil turnover rate as the SOC sequestration rate divided by annual source C inputs, which is essentially the same as the C sequestration efficiency defined by Follett et al. (2005). For example, Follett et al. (2005) reported C sequestration efficiency of 24% when only aboveground C was included in the annual source C, but a C sequestration efficiency of 11% when residue C plus belowground C plus weed-residue C were included, emphasizing the need of improved estimates of total C inputs.

Historically, the root C/shoot C ratio (k_{his}) was defined as

$$k_{\text{his}} = \frac{\text{Root biomass C}}{\text{Harvested grain C} + \text{Vegetative aboveground C}} \quad [3]$$

where k_{his} is dimensionless and C is expressed as a mass. This ratio is calculated from C recovered in the root biomass at physiological maturity, which excludes C from rhizodeposits. We used Eq. [3] to calculate k_{his} values of 0.50, 0.33, and 0.37 for wheat, corn, and soybean, respectively, using the extracted root biomass C (1.54, 3.14, 1.25 g, respectively) at physiological maturity divided by total aboveground C (3.1, 9.56, 3.37 g, respectively) reported by Buyanovsky and Wagner (1997). These k_{his} values are higher than those computed by Huggins and Fuchs (1997) and from data presented by Wilhelm et al. (1982) and Klepper (1991) for wheat and corn, which probably reflects variation resulting from different root-washing procedures.

More recent work has attempted to include rhizodeposits in a variable similar to k_{his} . Total root C is root biomass C plus rhizodeposition C (Balesdent and

Balabane, 1996; Allmaras et al., 2004; Wilts et al., 2004) defined as

$$k_{\text{rec}} = \frac{\text{Root biomass C} + \text{Rhizodeposition C}}{\text{Harvested grain C} + \text{Vegetative aboveground C}} \quad [4]$$

Buyanovsky and Wagner (1997) used soil-applied ^{14}C -labeled crop residue to estimate that rhizodeposition C represented 40% of root biomass C plus rhizodeposition C. Their total root C corresponds to 2.57, 5.24, and 2.09 g C for wheat, corn, and soybean, respectively. The corresponding k_{rec} values using Eq. [4] are 0.82, 0.55, and 0.62 for wheat, corn, and soybean, respectively.

Methods that account for rhizodeposition and seasonal contribution provide an improved estimate of the total root-derived C in the belowground C cycle. Follett et al. (1997) used a k_{rec} value of 0.53 to calculate total wheat-root C inputs. An estimate of $k_{\text{his}} = 0.15$ for sunflower included only the C in the recovered root biomass (Robinson, 1978); if we assume 60% of root C is from biomass (Buyanovsky and Wagner, 1997), then k_{rec} is 0.25. Pulse labeling with $^{14}\text{CO}_2$ indicates that the k_{rec} for wheat may be at least 0.60 (Swinnen et al., 1994; Kuzyakov, 2002a; Kuzyakov, 2002b). Critics of controlled studies argue that the period for $^{14}\text{CO}_2$ exposure is less than in a field season of plant growth. Therefore, the rhizodeposition, root/shoot ratio, and k_{his} values are all underestimated because not all the C contributed during the season is labeled. Wilts et al. (2004) reported k_{rec} values of 1.14 to 1.17 for corn in a field study. Measurements of seasonal soil CO_2 efflux during corn production (Rochette and Flanagan, 1997; Rochette et al., 1999a; Brye et al., 2002) suggest a k_{rec} much closer to 1.14 (Wilts et al., 2004). A seasonal soil CO_2 efflux during barley production after corn (Rochette et al., 1999b) suggests that the k_{rec} values of barley must also be larger than the $k_{\text{his}} = 0.48$ for wheat calculated from Buyanovsky and Wagner (1997).

Estimates of Total Root Carbon: Past and Present

Grain yield, HI (Table 1), an assumed average C concentration of 0.4 kg kg^{-1} for both above- and belowground biomass, and conservative k_{rec} values (Table 2) were used to estimate past and present total root C. We can calculate changes in the amount of root C between 1940 and 2000, similar to what was done above for grain and residue yields. For example, calculation of barley root C in 1940 (Table 1) is total root C = $0.6\{[1280 \text{ kg ha}^{-1} (\text{grain yield})0.4] + [3460 \text{ kg ha}^{-1} (\text{residue yield})0.4]\} = 1140 \text{ kg C ha}^{-1}$ after rounding (Table 2). The same type of calculation can then be made for 2000 yield ($1850 \text{ kg total root C ha}^{-1}$, Table 2) and the increase calculated as

$$\% \text{ Increase} = \left(\frac{\text{Root C}_{2000} - \text{Root C}_{1940}}{\text{Root C}_{1940}} \right) \times 100 \quad [5]$$

Thus, total root C increases were: barley (63%), corn (190%), oat (44%), sorghum (210%), soybean (32%), and wheat (66%). Total root plus vegetative shoot C (Table 2) during this 60-yr period increased 35% for barley, 150% for corn, 31% for oat, 180% for sorghum,

Table 2. Estimated changes (1940–2000) of source C contained in the vegetative shoot and the root system including rhizodeposition.

Crop	Vegetative shoot C [†]		Root plus shoot C [‡]		Root C	
	1940	2000	1940	2000	1940	2000
	kg ha ⁻¹					
Barley	1380	1540	2520	3390	1140	1850
Corn	1400	2980	2700	6780	1300	3800
Oat	940	1120	1780	2330	840	1210
Sorghum	720	1800	1380	3830	660	2030
Soybean	1180	1200	2190	2530	1010	1330
Sunflower	NR [§]	830	NR	1180	NR	350
Wheat	1080	1370	1980	2860	900	1490

[†] Crop residue from Table 1 $\times 0.4 \text{ kg C kg}^{-1}$ estimated mean C content in shoot and root.

[‡] Estimated root biomass plus rhizodeposition C/grain C plus vegetative C ratio (k_{rec}) = 0.60 for barley, corn, oat, sorghum, soybean, and wheat (Swinnen et al., 1994; Buyanovsky and Wagner, 1997; Kuzyakov, 2002a); $k_{\text{rec}} = 0.25$ for sunflower (Robinson, 1978).

[§] NR = not reported.

16% for soybean, and 44% for wheat. These increases in total root C assume a constant k_{rec} value with time, which requires verification. There is some evidence to suggest k_{rec} may have changed. Allmaras et al. (2004) observed that rhizodeposition from corn increased by 100% with N fertilizer compared with no N fertilizer, which suggests a significant increase in k_{rec} after 1960, due to N application increases not taken into account in Table 2. Wilts et al. (2004) observed similar N effects on rhizodeposition. These observations suggest caution in evaluating this approach, but provide a conservative estimate, which is probably more accurate than when rhizodeposition is ignored.

Long-term studies generally show that SOC is greater in systems receiving N fertilizer than those with zero or low N inputs (Paustian et al., 1997). Diekow et al. (2005) reported increases in SOC and soil N with N fertilizer and legumes, which they attributed to a larger crop residue input; however, Clapp et al. (2000) found that the soil continued to lose SOC although their moldboard-plowed treatment with fertilizer had returned the greatest amount of residue. They observed an increase in SOC only when stover was returned and fertilizer was applied in the conservation (chisel plow) or no-tillage treatments. Reicosky et al. (2002) reported similar results; they found an SOC loss regardless of fertility or other residue management treatments when soil was moldboard plowed for 29 yr. Follett et al. (2005) observed that no-till with N fertilizer in an irrigated wheat-corn (double crop) rotation had the potential to sequester C in central Mexico.

Impact of Rhizodeposition on Soil Organic Matter

The impact of rhizodeposition on SOM turnover appears to be dependent on the source or form of the rhizodeposits. Total root-derived C contributes 1.5 times to >3 times more C to SOC than shoot-derived C (Balesdent and Balabane, 1996; Allmaras et al., 2004; Wilts et al., 2004; Hooker et al., 2005). Hooker et al. (2005) attributed the difference to different cycling rates of shoot and root material. When preferentially consumed by microbes, rhizodeposition may retard decom-

position of more recalcitrant plant biomass and native SOM (Goudrain and De Ruyter, 1983; Lekkerkerk et al., 1990; Torbert et al., 2000). This is contrary to the soybean rhizosphere effect, which was first identified in a controlled environment study comparing four plant species (Fu and Cheng, 2002). Cheng et al. (2003) studied the rhizosphere priming effects from soybean and spring wheat on SOM decomposition and concluded that soybean can prime decomposition in the rhizosphere sufficiently to intensify crop residue and SOM decomposition, but spring wheat did not prime SOM decomposition to the same extent. The residue priming effect was responsible for a major portion of the total soil CO₂ efflux from the soybean system. Soybean, induced decomposition of relict SOC has been found in a field study (D. Huggins, personal communication, 2005). Sisti et al. (2004) found that the quality of the crop residue had little impact on the decomposition of native SOM in a no-till system. In the same study, incorporation of residues by tillage with an average C/N ratio of 24 to 30 stimulated faster decomposition of native SOM than incorporation of residue with an average C/N ratio of 36. Clapp et al. (2000) noted that N application reduced the decomposition loss of relict SOC; similar results were noted by Green et al. (1995) in a laboratory study. Clearly, there are many questions yet to be answered on the interaction of management on belowground C dynamics.

Both root biomass C and rhizodeposition C are influenced by genetic and environmental factors, which add to the complexity of accurately estimating k_{res} . Early in the growing season, relatively profuse root exudation provides source C for an active microbial community. Carbon contribution to the rhizosphere as a proportion of photosynthate decreases as the plant approaches physiological maturity. Source C in the root zone early in the growing season is derived mainly from three sources: senescing roots, shoots incorporated from the previous season, and photosynthate translocated from the shoot during the current season (Kuzyakov and Cheng, 2001). Nutrient availability also influences root exudation composition and rates. Frequently, low-molecular-weight root exudates (such as carbohydrates and organic acids) increase in response to nutrient-limited environments, although the composition of root exudates is species, age, and nutrient dependent (Marschner, 1995). Barley root exudation per unit root biomass increased with decreasing N status (Darwent et al., 2003). Several species have been shown to increase exudation of organic acids (e.g., malic and citric acids) in response to Al stress (Ojima et al., 1984) and P and Fe deficiency (Gardner et al., 1982; Gardner and Boundy, 1983; Ric de Vos et al., 1986; Lipton et al., 1987). These complicating factors contribute to a limited understanding of the real cause-and-effect parameters on root biomass decomposition, rhizodeposition, and SOC turnover.

MINIMUM CARBON INPUTS REQUIRED TO MAINTAIN SOIL ORGANIC CARBON

Increasing source C inputs coupled with static or reduced losses of C produces a net increase in SOC. The

level of SOC changes until a new dynamic equilibrium level is reached, after which little additional net increase in SOC occurs (Jenkinson, 1981; Lal et al., 1998) without an additional shift in the equilibrium; however, much more research is needed to estimate this equilibrium accurately under different soil, climatic, and management systems. Cropping systems with ample C inputs will increase sequestered C; enhance microbial activity; improve soil physical properties related to soil structure, soil resilience, and aggregate stability, as well as water flux and water-holding characteristics; and nutrient cycling (Kay, 1998; Collins et al., 2000), especially if associated with more rhizodeposition.

The MSC depends on precipitation and temperature, as well as crop, crop rotation, and tillage. The MSC has been estimated by a simple linear relationship (e.g., Larson et al., 1972; Paustian et al., 1997; Follett et al., 2005):

$$y = a + bx \quad [6]$$

where y is SOC and x is source C. When we determine the amount of x required to hold $y = 0$, the values of a and b can be determined by various levels of measured x and y . Thus, solving for x when $y = 0$, theoretically $a \leq 0$.

Once MSC is known for a given system, the amount of source C needed to increase SOC can be inferred. It is possible that global warming could increase SOM decomposition and thus increase MSC values. Using stable isotope techniques in mesocosms, Heath et al. (2005) reported a decline in root-derived C sequestered due to increased soil microbial respiration, even though short-term growth stimulation occurred due to the ambient CO₂ environment. Moreover, Bellamy et al. (2005) reported a loss of SOC from all soils across England and Wales irrespective of land use; they suggested the loss was linked to climate change. This region has had a mean temperature increase of 0.5°C and changes in rainfall distribution between 1978 and 2003 (Bellamy et al., 2005).

Several studies attempted to estimate MSC (Table 3). Most of these studies address only the input of aboveground residues; therefore, these values underestimate the total MSC. Averaging across crops with a positive change in SOC, an annual aboveground source C of 2.5 ± 1.0 Mg C ha⁻¹ ($n = 13$) was needed with moldboard-plow systems, while 1.8 ± 0.4 Mg C ha⁻¹ ($n = 5$) was needed in no-tillage and chisel-plow tillage systems. A smaller C input to maintain SOC with no-till compared with a moldboard system is due to less erosion of SOC-rich soil (Lal et al., 1998) and less tillage-induced C loss (Reicosky and Lindstrom, 1993; Reicosky and Allmaras, 2003). Tillage-induced SOC losses are caused by greater convective aeration and accelerated microbial activity. In a long-term (28-yr) tillage and silage removal study, there was no difference in SOC between silage harvested and stover returned with no-tillage (Hooker et al., 2005); however, dramatic SOC losses occurred if silage was harvested and the soil was moldboard plowed (Wilts et al., 2004; Hooker et al., 2005). Corn-based rotations with moldboard plowing tended to have a higher source C requirement (3.0 ± 1.0

Table 3. Reported estimates on the minimum amount of annual source C inputs needed to maintain soil organic C (MSC), aboveground vegetative C (V) and aboveground vegetation plus roots (V+R), and the corresponding annual change in soil organic C (SOC) from sites with different initial SOC (SOC_i) concentrations, texture, and cropping practices.

MSC† V	MSC V+R	Annual ΔSOC‡	Duration	SOC _i	Texture§	State	Crop¶	Tillage#	Citation††
Mg C ha ⁻¹ yr ⁻¹			yr	g kg ⁻¹					
2.2	9.4	0.72	13	55.5	sil	MN	C	CP	o, r
2.1	6.96	0.15	13	55.5	sil	MN	C	NT	o, r
2.0	NA	NA	NA	18.7	sil	WI	C	NT	p
2.4	NA	0.043	12	18	cl	IA	C	MBP	c
>4.0	NA	0.12	11	19	sil	IN	C	MBP	e
2.9	5.83	NA‡‡	10	26–35	cl	MN	C	MBP	g, n
2.3	NA	0.045	25	18.8	sil	WI	C	MBP	l
4.5	NA	0.063	20	9.5	sal	MI	C	MBP	m
2.1	6.6	0.27	13	55.5	sil	MN	C	MBP	o, r
3.3	6.0	-0.41 to -0.56	30	24.4–28.2	cl, si, sil	MN	C	MBP	q, s
3.0	5.45	NA	10	26–35	cl	MN	Sy	MBP	g, n
1.7	NA	0.076	11	25	sil	KS	Sy, Sr	CP	j
1.2	NA	0.36	11	25	sil	KS	Sy, Sr	NT	j
2.0	NA	NA	30	17	sil	WA	W	MBP	a, k
2.0	NA	NA	42	10–16	sil	KS	W	MBP	b, f
0.3	NA	0.145	6	11–18	sal	MO	W	V	d
1.5	NA	0.36	31	15	sac	Sweden	W–B	HT	h
1.45	NA	0.4	5	14–15	c	Mexico	W–C	MBP	t
1.45§§	NA	1.45	5	14–15	c	Mexico	W–C	NT	t
1.2	NA	NA	23	8.7	sil	WA	W–F	MBP	a, f
2.1	NA	0.1	45	12.5	sil	OR	W–F	MBP	a, f
4.0	NA	NA	30	17	sil	WA	W–F	MBP	a, k
0.9	2.02	-0.42	22	17.2	l	NE	W–F	MBP	i
1.1	1.8	-0.18	84	12.4	l	CO	W–F	MBP	i

† Assuming 0.4 kg C kg⁻¹ residue (except Vanotti et al. 1997, who reported C concentration as 0.45 kg C kg⁻¹).

‡ ΔSOC = change in SOC between final and initial values, divided by years; negative values indicate a loss of SOC.

§ si = silt, sa = sandy, l = loam, c = clay.

¶ B = barley, C = corn, F = fallow, Sr = sorghum, Sy = soybean, W = wheat.

CP = chisel plow, HT = hand tillage, MBP = moldboard plow, NR = not reported, NT = no-till, V = V-blade 9–12 cm.

†† a = Horner et al. (1960), b = Hobbs and Brown (1965), c = Larson et al. (1972), d = Black (1973), e = Barber (1979), f = Rasmussen et al. (1980), g = Crookston et al. (1991), h = Paustian et al. (1992), i = Follett et al. (1997), j = Havlin and Kissel (1997), k = Paustian et al. (1997), l = Vanotti et al. (1997), m = Vitosh et al. (1997), n = Huggins et al. (1998b), o = Clapp et al. (2000), p = Kucharik et al. (2001), q = Reicosky et al. (2002), r = Allmaras et al. (2004), s = Wilts et al. (2004), t = Follett et al. (2005).

‡‡ NA, not available.

§§ Estimated critical C inputs were calculated using both NT and MBP data and from wheat–corn and wheat–soybean rotations (Follett et al., 2005).

Mg C ha⁻¹, $n = 6$) than moldboard plowed, wheat-based rotations (2.2 ± 1.1 Mg C ha⁻¹, $n = 5$), which may be related to the climatic conditions of the production regions. Typically, wheat is grown in regions with less rainfall and lower temperatures than required for corn, thus C turnover in the soil may be slower.

CURRENT AND PROJECTED SOURCE C INPUTS

The yield data (Fig. 2) for the seven crops shows a reasonably linear trend from 1940 to 2000, each with a different slope, largely as a result of a range of technological advances, discussed above. The yield projections (Tables 4 to 7) assume that harvestable yield will continue to follow a linear trend, as they have since 1940. It is reasonable to assume that technological advances will continue and grain yields will continue to increase at least for some time. The highest corn yield projected (Table 4) is consistent with the high yields observed by Yang et al. (2004) and genetic yield potentials suggested by Tollenaar and Lee (2002). It must be noted that yield maximums may occur due to physiological limitation or adverse climatic changes, in which case our projections would overestimate future yield.

Corn

Current available source C inputs from aboveground corn vegetation (ESC) were estimated using state-

average grain yields in 2003 and HI (Table 1) to estimate if they would provide MSC, recognizing that there is substantial yield variation within and among states. For example, county yield averages for corn across the country ranged from 1.1 to 14.7 Mg ha⁻¹, with the highest yields from irrigated regions (11.3 ± 2.1 Mg ha⁻¹, 41 counties) and from the Corn Belt (9.4 ± 1.6 Mg ha⁻¹, 507 counties) (USDA–National Agricultural Statistics Service, 2003). Irrigated corn (Table 4) is estimated to provide an average 4.0 ± 0.8 Mg C ha⁻¹ of ESC, while the U.S. national average ESC was 2.8 ± 0.8 Mg C ha⁻¹ (2371 counties in 41 states). In the five Corn Belt states with predominately rain-fed agriculture, the ESC from vegetative corn biomass provided 3.3 ± 0.6 Mg C ha⁻¹ (507 counties). A measured average of aboveground MSC of 3.0 ± 1.0 Mg C ha⁻¹ ($n = 6$) for corn when moldboard plowed (Table 3) suggests that many fields within these regions have sufficient C inputs to store C; however, an aboveground ESC of 3.3 Mg C ha⁻¹ in a 29-yr field study receiving annual moldboard plowing in western Minnesota did not prevent continued SOC loss (Table 3; Reicosky et al., 2002). In a similar study, located in southeastern Minnesota, plots receiving high N fertilizer with an annual aboveground ESC of 2.3 Mg C ha⁻¹ increased SOC as much as 0.27 ± 0.14 Mg C ha⁻¹ yr⁻¹ (Table 3; Allmaras et al., 2004). A significant difference between these two studies was the presence of secondary tillage in the Reicosky et al. (2002) study and its absence in the Allmaras et al. (2004) study.

Table 4. Corn grain yield, residue C (ESC), and residue plus root C (total ESC) for selected states based on 2003 averages (USDA–National Agricultural Statistics Service, 2003) and projected U.S. national average values for 2030 and 2100.

Comment	State	Grain yield	ESC†	Total ESC‡
		Mg ha ⁻¹	Mg C ha ⁻¹	
Irrigated	USA§	8.92	3.12	7.13
	AZ	11.92	4.17	9.53
	NM	11.29	3.95	9.03
	OR	10.66	3.73	8.52
	WA	12.23	4.28	9.78
Corn Belt states	IA	9.85	3.45	7.88
	IL	10.29	3.60	8.23
	IN	9.16	3.21	7.33
	MN	9.16	3.21	7.33
	OH	9.78	3.42	7.81
Projected 2030¶	USA	12.0	4.26	9.69
Projected 2100	USA	20.4	7.24	16.5

† Estimated assuming harvest index = 0.53 and mean C content = 0.40 kg C kg⁻¹ in shoot and root.

‡ Estimated root biomass plus rhizodeposition C/grain C plus vegetative C ratio (k_{rec}) = 0.60 (Swinnen et al., 1994; Buyanovsky and Wagner, 1997; Kuzyakov, 2002a).

§ U.S. average.

¶ Projection based on current linear trend of data from 1940 to 2000 [Mg C ha⁻¹ = 0.12(years) - 230; r^2 = 0.99] in Fig. 2.

There are few MSC measurements for no-till or other conservation tillage methods (Table 3). Based on the very limited dataset, the required vegetative above-ground corn residue inputs may be reduced to 2.1 ± 0.1 Mg C ha⁻¹ yr⁻¹, $n = 3$. The total above- and below-ground required input is two- to threefold greater than the shoot inputs, which reflects the importance of root C to SOC formation as discussed above. Follett et al. (1997) suggested that aboveground input requirements are multiplied by a factor of 2.2 to estimate both aboveground, root, and weed contributions in a winter wheat system, which supports our calculated values.

The MSC has direct implications for determining how much corn stover can be removed without decreasing SOC; as MSC increases, the amount of biomass harvestable for bioenergy decreases. Using a conservative average for MSC of 3.0 ± 1.0 Mg C ha⁻¹ ($n = 6$) based on

Table 5. Soybean grain yield, residue C (ESC), and residue plus root C (total ESC) for selected states based on 2003 averages (USDA–National Agricultural Statistics Service, 2003) and projected U.S. national average values for 2030 and 2100.

Comment	State	Grain yield	ESC†	Total ESC‡
		Mg ha ⁻¹	Mg C ha ⁻¹	
Corn Belt states	USA§	2.28	1.07	2.26
	MN	2.15	1.01	2.13
	IL	2.49	1.17	2.47
	NE	2.72	1.28	2.70
	WI	1.88	0.88	1.86
	MO	1.98	0.93	1.96
	KS	1.55	0.73	1.54
Southern states	KY	2.92	1.37	2.89
	MS	2.62	1.23	2.60
	USA	3.36	1.57	3.33
Projected 2030¶	USA	5.13	2.41	5.09

† Estimated assuming harvest index = 0.46 and mean C content = 0.40 kg C kg⁻¹ in shoot and root.

‡ Estimated root biomass plus rhizodeposition C/grain C plus vegetative C ratio (k_{rec}) = 0.6 (Buyanovsky and Wagner, 1997).

§ U.S. average.

¶ Projection based on current linear trend of data from 1940 to 2000 [Mg C ha⁻¹ = 0.023(years) - 42; r^2 = 0.96] in Fig. 2.

Table 6. Wheat grain yield, residue C (ESC), and residue C plus root C (total ESC) for selected states based on 2003 averages (USDA–National Agricultural Statistics Service, 2003) and projected U.S. national average values for 2030 and 2100.

Comment	State	Grain yield	ESC†	Total ESC‡	
		Mg ha ⁻¹	Mg C ha ⁻¹		
Irrigated	USA§	2.97	1.46	3.06	
	AZ	6.73	3.30	6.89	
	Great Plains states	KS	3.23	1.58	3.30
	MT	1.84	0.90	1.68	
	ND	2.51	1.23	2.57	
Corn Belt states	NE	3.09	1.51	3.16	
	MI	4.60	2.25	4.70	
	MN	3.88	1.90	3.97	
Pacific NW states	OR	3.33	1.63	3.41	
	WA	3.99	1.96	4.10	
Projected 2030¶	USA	3.57	1.74	3.65	
Projected 2100	USA	5.36	2.62	5.48	

† Estimated assuming harvest index = 0.46 and mean C content of 0.40 kg C kg⁻¹ in shoot and root.

‡ Estimated root biomass plus rhizodeposition C/grain C plus vegetative C ratio (k_{rec}) = 0.60 (Swinnen et al., 1994; Buyanovsky and Wagner, 1997; Kuzyakov, 2002a).

§ U.S. average.

¶ Projection based on current linear trend of data from 1940 to 2000 [Mg C ha⁻¹ = 0.030(years) - 58; r^2 = 0.94] in Fig. 2.

moldboard-plowed corn systems (Table 3), we can estimate potential biomass availability. For example, using Eq. [1], a grain yield of 10 Mg ha⁻¹ with an HI of 0.53 would produce 8.9 Mg ha⁻¹ stover, which contains 3.56 Mg C ha⁻¹. Carbon in crop residues in excess of MSC is what would be available to harvest for bioenergy. In this example, there would be 0.56 Mg C ha⁻¹ yr⁻¹ or 1.4 Mg residue ha⁻¹ yr⁻¹ of corn stover available to harvest for bioenergy. If a less conservative MSC estimate of 2.1 ± 0.1 Mg C ha⁻¹ yr⁻¹ ($n = 3$) is used, the amount of available corn stover increases to 3.7 Mg residue ha⁻¹ yr⁻¹, which leaves 50% of the biomass on the field for erosion control. In the Corn Belt states (Table 4), assuming a no-till system, state-average available stover ranges from 2.8 to 3.8 Mg ha⁻¹ yr⁻¹. Assuming corn yields continue to increase and MSC remains constant, it is reasonable to assume that the amount of stover for bioenergy harvest should increase. For example, a grain yield of 20 Mg ha⁻¹ is expected to

Table 7. Sorghum grain yield, residue C (ESC), residue plus root C (total ESC) for selected states based on 2003 averages (USDA–National Agricultural Statistics Service, 2003) and projected U.S. national average values for 2030 and 2100.

Comment	State	Grain yield	ESC†	Total ESC‡
		Mg ha ⁻¹	Mg C ha ⁻¹	
Great Plains states	USA§	3.31	1.49	3.18
	TX	3.39	1.53	3.26
	OK	2.32	1.04	2.22
	KS	2.80	1.26	2.69
	CO	1.69	1.53	2.86
	NE	3.89	1.75	3.74
	AZ	5.64	2.54	5.42
Other	MS	5.27	2.37	5.06
	KY	5.96	2.68	5.72
	USA	6.15	2.77	5.91
Projected 2030¶	USA	8.60	3.88	8.27

† Estimated mean C content = 0.40 in shoot and root.

‡ Estimated root biomass plus rhizodeposition C/grain C plus vegetative C ratio (k_{rec}) = 0.60 (Swinnen et al., 1994; Buyanovsky and Wagner, 1997; Kuzyakov, 2002a).

§ U.S. average.

¶ Projection based on current linear trend of data from 1940 to 2000 [Mg C ha⁻¹ = 0.057(years) - 1098; r^2 = 0.90] in Fig. 2.

produce about 12.5 Mg ha⁻¹ of harvestable stover, compared with an MSC of 2.1 ± 0.1 Mg C ha⁻¹ yr⁻¹.

The amount of available stover for bioenergy is dependent on MSC; inherent is the assumption that if we manage for SOC, sufficient cover will be available to prevent erosion. This is only a reasonable assumption if conservation or no-till practices are followed. Larson's (1979) statement that "the need to maintain soil productivity should be our first consideration and only, once this criterion has been met, should crop biomass be removed for alternative purposes" is still relevant. Recently, Lal (2004) concluded that crop residue as a biofuel could not produce sufficient energy to make a major difference in reducing fossil fuel consumption; however, its removal may seriously jeopardize soil and environmental quality.

Soybean, Wheat, and Sorghum

There is very limited MSC data specific to soybean and sorghum available to determine the amount of C inputs required to maintain SOC. Using an overall average of 2.2 ± 1.0 Mg C ha⁻¹ ($n = 21$) from soybean (Table 3) as critical residue C, there is not sufficient ESC produced, except perhaps in Kentucky and Missouri, where the yield is 2.22 Mg C ha⁻¹ (Table 5). Even if the current trend for yield increases continues during the next century, the ESC produced from soybean in many states will not be sufficient to maintain SOC (Table 5). Our projected yield estimates are even more conservative than the 3.2 to 4.0 Mg ha⁻¹ by 2030 predicted by Specht et al. (1999). Controlled environment studies indicate that soybean causes a positive rhizosphere priming effect (Fu and Cheng, 2002) that increases relict SOM decomposition. The soybean priming effect was responsible for a major portion of the total soil C efflux from that system (Cheng et al., 2003). Thus, while soybean has many desirable attributes as a food crop, it presents unique challenges for designing management strategies that minimize its potential to accelerate SOC decline.

For wheat in the Pacific Northwest (Washington and Oregon), the critical source C input ranged from 1.2 to 4.0 Mg C ha⁻¹ (Table 3), depending on cropping system and moisture regime. This limited dataset for Washington suggests that critical source C for wheat fallow maybe twice that for continuous wheat. The ESC in Washington (Table 6) suggests that current inputs are nearly adequate for sustaining SOC, provided wheat is grown continuously without fallow and assuming an MSC of 1.8 ± 1.0 Mg C ha⁻¹ yr⁻¹ ($n = 9$) based on all wheat studies in Table 3. For the Great Plains, estimates of above-ground MSC range from 0.3 Mg C ha⁻¹ in Montana using mulch tillage (Black, 1973) to 2.1 Mg C ha⁻¹ in Kansas using moldboard-plow tillage (Hobbs and Brown, 1965; Rasmussen et al., 1980; Table 3). It should be noted that the 0.3 Mg C ha⁻¹ of input C to maintain SOC estimated by Black (1973) is at least threefold lower than any other estimates reported in Table 3. This vast difference may be caused by the use of a sweep with no other tillage in a cool, dry Montana environment. Using an MSC of 1.8 Mg C ha⁻¹ yr⁻¹ and 2003 state-average yields suggests

that current wheat ESC inputs in many states are insufficient to maintain SOC. If the current yield trend continues nationally, it is projected that it would take about 30 yr for biomass yield to consistently provide sufficient ESC to maintain SOC.

Potter et al. (1997) observed an annual average source C input in wheat-fallow (0.74 Mg C ha⁻¹) and continuous sorghum (1.72 Mg C ha⁻¹) in a 10-yr experiment in Texas; no-till and stubble mulch produced the same amount of source C. In the same experiment, residue source C inputs for continuous wheat were 1.12 Mg C ha⁻¹ if not tilled and 0.88 with stubble mulch tillage. Corresponding annualized increases in SOC in a 20-cm profile between no-till and stubble mulch was 0.24, 0.55, and 0.30 Mg C ha⁻¹ in wheat-fallow, continuous wheat, and continuous sorghum, respectively. These increases suggest that a lower N concentration in wheat than sorghum residue was responsible for the larger SOC accumulation under wheat than under sorghum.

In Kansas, MSC values were 1.2 Mg C ha⁻¹ with no-till and 1.7 Mg C ha⁻¹ if conventionally tilled when comparing residue inputs among continuous soybean, soybean-sorghum rotation, and continuous sorghum (Havlin and Kissel, 1997). The 2003 sorghum grain yields and their corresponding ESC in the Great Plains (Table 7) exceed the suggested MSC for a no-till system, but not for a conventionally tilled system. Therefore, only those areas that are no-tilled are expected to be gaining SOC. If sorghum yield and corresponding source C continue the current yield trends, there is potential to sequester additional SOC (Table 7).

Total Estimated Source Carbon Production

The total ESC values based on a conservative estimate of rhizodeposition and harvested yields of corn, soybean, wheat, and sorghum are reported in Tables 4, 5, 6, and 7, respectively. These total ESC values provide a more realistic estimate of the net primary production (including C in the grain) and the size of the C cycle. In some cases, these ESC values can be compared with the total MSC values in Table 3, but these comparisons are less precise than the comparison between vegetative ESC and vegetative MSC. The projected ESC values indicate the potential to sequester SOC for many crops, assuming constant C sequestration efficiency. Improvements in soil management (e.g., reducing tillage) may increase C sequestration efficiency. Thus one can expect more rhizodeposition and sequestered SOC for improved soil physical properties due to more biological activity.

CONCLUSIONS

Changes in available crop residue, soil management, and technological inputs enable agriculture to reduce SOC losses and to begin restoring SOC. Reviewing the role of total root-derived C to SOC from field studies suggests that previous estimates of root-derived C have been low. The underestimate of total root C may also imply that previous estimates of primary production were also low. This review identifies the role of total root C (root biomass C plus rhizodeposition C) and discusses

the importance of defining MSC under different management systems (tillage, fertility, and crop rotation) for a given climate and soil. Similarly, accurate HI, k_{rec} values, and MSC are a valuable step toward an indirect but easy method of predicting C storage and associated production and environmental benefits. The amount of total source C inputs estimated only from aboveground contributions, including those made in this review, underestimate the total C required to achieve dynamic equilibrium among C inputs and output, thus maintaining SOC. The growing interest in using crop residues as renewable energy demands that we have accurate estimates of MSC for long-term soil sustainability in addition to biomass cover for erosion control. The results also highlight the synergic benefits from simultaneously reducing tillage intensity and increasing biomass yield and therefore increasing source C needed to improve soil quality. Including rhizodeposition C in the calculation of k_{rec} improves our estimates of total root C and total plant C inputs. We illustrated only a few of the many situations where this assumption of k_{rec} and HI may be used to estimate total source C. This approach can be expanded to more crops and their impacts in crop rotations. These estimates, along with new information about rhizodeposition and seasonal CO₂ efflux, can evaluate photosynthetic potential. Knowledge of how soil and crop management influences stored C will allow agriculture to reduce its negative impacts on global climate change and lead to improved soil and environmental quality.

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REFERENCES

- Abeledo, L.G., D.F. Calderini, and G.A. Slafer. 2003. Genetic improvement of barley yield potential and its physiological determinants in Argentina (1944–1998). *Euphytica* 130:325–334.
- Allmaras, R.R., D.R. Linden, and C.E. Clapp. 2004. Corn-residue transformations into root and soil carbon as related to nitrogen, tillage and stover management. *Soil Sci. Soc. Am. J.* 68:1366–1375.
- Allmaras, R.R., H.H. Schomberg, C.L. Douglas, Jr., and T.H. Dao. 2000. Soil organic carbon sequestration potential of adopting conservation tillage in US croplands. *J. Soil Water Conserv.* 55:365–373.
- Allmaras, R.R., D.E. Wilkins, O.C. Burnside, and D.J. Mulla. 1998. Agricultural technology and adoption of conservation practices. p. 99–157. *In* F.J. Pierce and W.W. Frye (ed.) *Advances in soil and water conservation*. Sleeping Bear Press, Chelsea, MI.
- Anderson, E.L. 1988. Tillage and N fertilization effects on maize root growth and root:shoot ratio. *Plant Soil* 108:245–251.
- Anderson, M.K., and E. Reinbergs. 1985. Barley breeding. p. 231–268. *In* D.C. Rasmussen (ed.) *Barley*. Agron. Monogr. 26. ASA, CSSA, and SSSA, Madison, WI.
- Balesdent, J., and M. Balabane. 1996. Major contribution of roots to soil carbon storage inferred from maize cultivated soils. *Soil Biol. Biochem.* 28:1261–1263.
- Barber, S.A. 1978. Growth and nutrient uptake of soybean roots under field conditions. *Agron. J.* 70:457–461.
- Barber, S.A. 1979. Corn residue management and soil organic matter. *Agron. J.* 71:625–627.
- Barraclough, P.B., A.H. Weir, and H. Kuhlman. 1991. Factors affecting the growth and distribution of winter wheat roots under U.K. conditions. p. 410–417. *In* B.L. McMichael and H. Person (ed.) *Plant roots and their environment*. Elsevier Sci. Publ., Amsterdam.
- Bellamy, P.H., P.J. Loveland, R.I. Bradley, R.M. Lark, and G.J.D. Kirk. 2005. Carbon losses from all soils across England and Wales 1978–2003. *Nature* 437:245–248.
- Biomass Technical Advisory Committee. 2002. Vision for bioenergy and biobased products in the United States. Available at www.bioproducts-bioenergy.gov/pdfs/BioVision_03_Web.pdf (accessed 20 Sept. 2005; verified 4 Jan. 2006). U.S. Dep. of Energy, Washington, DC.
- Black, A.L. 1973. Soil property changes associated with crop residue management in a wheat–fallow rotation. *Soil Sci. Soc. Am. J.* 37: 943–946.
- Borg, H., and D.W. Grimes. 1986. Depth development of roots with time: An empirical description. *Trans. ASAE* 29:194–197.
- Brancourt-Hulmel, M., G. Doussinault, C. Lecomte, P. Berard, B. Le Buanec, and M. Trotter. 2003. Genetic improvement of agronomic traits of winter wheat cultivars released in France from 1946 to 1992. *Crop Sci.* 43:37–45.
- Brouwer, R. 1983. Functional equilibrium: Sense or nonsense? *Neth. J. Agric. Sci.* 31:335–348.
- Brye, K.R., S.T. Gower, J.M. Norman, and L.G. Bundy. 2002. Carbon budgets for a prairie and agroecosystems: Effects of land use and interannual variability. *Ecol. Appl.* 12:962–979.
- Buyanovsky, G.A., and G.H. Wagner. 1997. Crop residue input to soil organic matter on Sanborn Field. p. 73–83. *In* E.A. Paul et al. (ed.) *Soil organic matter in temperate agroecosystems: Long-term experiments in North America*. CRC Press, Boca Raton, FL.
- Cheng, W., D.M. Johnson, and S. Fu. 2003. Rhizosphere effects on decomposition: Controls of plant species, phenology, and fertilization. *Soil Sci. Soc. Am. J.* 67:1418–1427.
- Clapp, C.E., R.R. Allmaras, M.F. Layese, D.R. Linden, and R.H. Dowdy. 2000. Soil organic carbon and 13-C abundance as related to tillage, crop residue and nitrogen fertilizer under continuous corn management in Minnesota. *Soil Tillage Res.* 55:127–142.
- Clarkson, D.T. 1985. Factors affecting mineral nutrient acquisition by plants. *Annu. Rev. Plant Physiol.* 36:77–115.
- Cochrane, W. 1993. The development of American agriculture: A historical analysis. 2nd ed. Univ. of Minnesota Press, Minneapolis.
- Collins, H.P., E.T. Elliott, K. Paustian, L.E. Bundy, W.A. Dick, D.R. Huggins, A.J.M. Smucker, and E.A. Paul. 2000. Soil carbon pools and fluxes in long-term Corn Belt agroecosystems. *Soil Biol. Biochem.* 32:157–168.
- Connor, D.J., and A.J. Hall. 1997. Sunflower physiology. p. 113–182. *In* A.A. Schneiter (ed.) *Sunflower production and technology*. Agron. Monogr. 35. ASA, CSSA, and SSSA, Madison, WI.
- Council for Agricultural Sciences and Technology. 1992. Preparing U.S. agriculture for global climate change. Task Force Rep. 119. CAST, Ames, IA.
- Cox, T.S., J.P. Shroyer, B.-H. Liu, R.G. Sears, and T.J. Martin. 1988. Genetic improvement in agronomic traits of hard red winter wheat cultivars from 1919 to 1987. *Crop Sci.* 28:756–760.
- Crookston, R.K., J.E. Kurle, P.J. Copeland, J.H. Ford, and W.E. Leuschen. 1991. Rotational cropping sequence affects yield of corn and soybeans. *Agron. J.* 83:108–113.
- Dardanelli, J.L., O.A. Bachmeier, R. Sereno, and R. Gil. 1997. Rooting depth and soil water extraction patterns of different crops in a silty loam Haplustoll. *Field Crops Res.* 54:29–38.
- Darwent, M.J., E. Paterson, A.J.S. McDonald, and A.D. Tomos. 2003. Biosensor reporting of root exudation from *Hordeum vulgare* in relation to shoot nitrate concentration. *J. Exp. Bot.* 54:325–334.
- Diekow, J., J. Mielniczuk, H. Knicker, C. Bayer, D.P. Dick, and I. Kogel-Knabner. 2005. Soil C and N stocks as affected by cropping systems and nitrogen fertilisation in a southern Brazil Acrisol managed under no-tillage for 17 years. *Soil Tillage Res.* 81:87–95.
- Donald, C.M., and J. Hamblin. 1976. The biological yield and harvest index of cereals as an agronomic and plant breeding criteria. *Adv. Agron.* 28:361–405.
- Douglas, C.L., Jr., P.E. Rasmussen, and R.R. Allmaras. 1989. Cutting height, yield level, and equipment modification effects on residue distribution by combines. *Trans. ASAE* 32:1258–1262.
- Dowdy, R.H., D.R. Linden, M.S. Dolan, and R.R. Allmaras. 1991. Impact of tillage on maize rooting patterns. p. 401–404. *In* L. Kutschera et al. (ed.) *Root ecology and its practical applications*. Proc. ISRR Symp., 3rd, Vienna, Austria. 2–6 Sept. 1991. Verein für Wurzelforschung, Klagenfurt, Austria.
- Drew, M.C. 1975. Comparison of the effects of a localized supply of

- phosphate, nitrate, ammonium and potassium on the growth of the seminal root, and the shoot, in barley. *New Phytol.* 75:479–490.
- Drew, M.C., and L.R. Saker. 1975. Nutrient supply and the growth of the seminal root system in barley: II. Localized compensatory increase in lateral root growth and rates of nitrite uptake when nitrate supply is restricted to only part of the root system. *J. Exp. Bot.* 29:435–451.
- Duvick, D.N. 1992. Genetic contributions to advances in yield of U.S. maize. *Maydica* 37:69–79.
- Duvick, D.N. 2005. The contribution of breeding to yield advances in maize (*Zea mays* L.). *Adv. Agron.* 86:83–145.
- Eck, H.V., and J.T. Musick. 1979. Plant stress effects on irrigated grain sorghum: I. Effects on yield. *Crop Sci.* 19:589–592.
- Edwards, E.J., D.G. Benham, L.A. Marland, and A.H. Fitter. 2004. Root production is determined by radiation flux in a temperate grassland community. *Global Change Biol.* 10:209–227.
- Evans, L.T., and R.A. Fischer. 1999. Yield potential: Its definition, measurement, and significance. *Crop Sci.* 39:1544–1551.
- Eve, M.D., K. Paustian, R. Follett, and E.T. Elliot. 2001. A national inventory of changes in soil carbon from national resources inventory data. p. 593–610. *In* R. Lal et al. (ed.) Assessment methods for soil carbon. Lewis Publ., Boca Raton, FL.
- Eve, M.D., M. Sperow, K. Paustian, and R.F. Follett. 2002. National-scale estimation of changes in soil carbon stocks on agricultural lands. *Environ. Pollut.* 116:431–438.
- Follett, R., J.Z. Castellanos, and E.D. Buenger. 2005. Carbon dynamics and sequestration in an irrigated Vertisol in central Mexico. *Soil Tillage Res.* 83:148–158.
- Follett, R., E.A. Paul, S.W. Leavitt, A.D. Halvorson, D. Lyon, and G.A. Peterson. 1997. Carbon isotope ratios of Great Plains soils in wheat–fallow systems. *Soil Sci. Soc. Am. J.* 61:1068–1077.
- Fu, S., and W. Cheng. 2002. Rhizosphere priming effects on the decomposition of soil organic matter in C4 and C3 grassland soils. *Plant Soil* 238:289–294.
- Gardner, W.K., and K.A. Boundy. 1983. The acquisition of phosphorus by *Lupinus albus* L.: IV. The effect of interplanting wheat and white lupins on the growth and mineral composition of the two species. *Plant Soil* 70:391–402.
- Gardner, W.K., D.G. Parbery, and D.A. Barber. 1982. The acquisition of phosphorus by *Lupinus albus* L.: II. The effects of varying phosphorus supply and soil type on some characteristics of the soil/root interface. *Plant Soil* 68:33–41.
- Goss, M.J., and C.A. Watson. 2003. The importance of root dynamics in cropping systems research. *J. Crop Prod.* 8:127–155.
- Goudrain, J., and H.E. De Ruiter. 1983. Plant growth in response to CO₂ enrichment at two levels of nitrogen and phosphorus supply: I. Dry matter, leaf area and development. *Neth. J. Agric. Sci.* 31: 157–169.
- Green, C.J., A.M. Blackmer, and R. Horton. 1995. Nitrogen effects on conservation of carbon during corn residue decomposition in soil. *Soil Sci. Soc. Am. J.* 59:453–459.
- Halvorson, A.D., G.A. Peterson, and C.A. Reule. 2002. Tillage system and crop rotation effects on dryland crop yields and soil carbon in the central Great Plains. *Agron. J.* 94:1429–1436.
- Havlin, J.L., and D.E. Kissel. 1997. Management effects on soil organic carbon and nitrogen in the east-central Great Plains of Kansas. p. 381–386. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems: Long-term experiments in North America. CRC Press, Boca Raton, FL.
- Hay, R.K.M. 1995. Harvest index: A review of its use in plant breeding and crop physiology. *Ann. Appl. Biol.* 126:197–216.
- Heath, J., E. Ayres, M. Possell, R.D. Bardgett, H.I.J. Black, H. Grant, P. Ineson, and G. Kerstiens. 2005. Rising atmospheric CO₂ reduces sequestration of root-derived soil carbon. *Science* 309:1711–1713.
- Hilfiker, R.E., and B. Lowery. 1988. Effect of conservation tillage systems on corn root growth. *Soil Tillage Res.* 12:269–283.
- Hobbs, J.A., and P.I. Brown. 1965. Effects of cropping and management on nitrogen and organic carbon contents of a western Kansas soil. *Tech. Bull.* 144. Kansas Agric. Exp. Stn., Manhattan.
- Hoffland, E., J.A. Nelemans, and G.R. Findenegg. 1990. Origin of organic acids exuded by roots of P stressed rape plants. p. 179–184. *In* M.L. Van Beusichem (ed.) Plant nutrition—physiology and applications. Kluwer Acad. Publ., Dordrecht, the Netherlands.
- Hooker, B.A., T.F. Morris, R. Peters, and Z.G. Cardon. 2005. Long-term effects of tillage and corn stalk return on soil carbon dynamics. *Soil Sci. Soc. Am. J.* 69:188–196.
- Horner, G.M., M.M. Overson, G.O. Baker, and W.W. Pawson. 1960. Effect of cropping practices on yield, soil organic matter, and erosion in the Pacific Northwest wheat region. *Coop. Bull.* 1. Washington Agric. Exp. Stn., Pullman; Idaho Agric. Exp. Stn., Moscow; Oregon Agric. Exp. Stn., Corvallis; USDA-ARS, Washington, DC.
- Huggins, D.R., G.A. Buyanovsky, G.H. Wagner, J.R. Brown, R.G. Darmody, T.R. Peck, G.W. Lesoing, M.B. Vanotti, and L.G. Bundy. 1998a. Soil organic C in the tallgrass prairie-derived region of the Corn Belt: Effects of long-term crop management. *Soil Tillage Res.* 47:219–234.
- Huggins, D.R., C.E. Clapp, R.R. Allmaras, J.A. Lamb, and M.F. Layese. 1998b. Carbon dynamics in corn–soybean sequences as estimated from natural carbon-13 abundance. *Soil Sci. Soc. Am. J.* 62:195–203.
- Huggins, D.R., and D.J. Fuchs. 1997. Long-term N management effects on corn yield and soil C of an Aquic Haplustoll in Minnesota. p. 121–128. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate ecosystems: Long-term experiments in North America. CRC Press, Boca Raton, FL.
- Hurd, E.A. 1974. Phenotype and drought tolerance in wheat. *Agric. For. Meteorol.* 14:39–55.
- Hütsch, B.W., J. Augustin, and W. Merbach. 2002. Plant rhizodeposition—an important source for carbon turnover in soils. *Z. Pflanzenernaehr. Bodenkd.* 165:397–407.
- Janzen, H.H., C.A. Campbell, R.C. Izaurralde, B.H. Ellert, N.G. Juma, W.B. McGill, and R.P. Zentner. 1998. Management effects on soil C storage on the Canadian prairies. *Soil Tillage Res.* 47: 181–195.
- Jenkinson, D.S. 1981. The fate of plant and animal residues in soil. p. 505–561. *In* D.J. Greenland and M.H.B. Hayes (ed.) The chemistry of soil processes. John Wiley & Sons, Chichester, UK.
- Johnen, G., and D. Sauerbeck. 1977. A tracer technique for measuring growth, mass and microbial breakdown of plant roots during vegetation. p. 366–373. *In* V. Lohm and T. Persson (ed.) Soil organisms as components of ecosystems. *Proc. Int. Soil Zoological Colloquium*, 6th. Ecol. Bull., Stockholm, Sweden.
- Johnson, J.F., D.L. Allan, C.P. Vance, and G. Weiblen. 1996. Root carbon dioxide fixation by phosphorus-deficient *Lupinus albus*. Contribution to organic acid exudation by proteoid roots. *Plant Physiol.* 112:19–30.
- Jones, O.R., and T.W. Popham. 1997. Cropping and tillage systems for dryland grain production in the southern High Plains. *Agron. J.* 89:222–232.
- Jordan, W.R., and F.R. Miller. 1980. Differences in adaptation to water stress within crop species. p. 383–399. *In* P.J. Kramer and N.C. Turner (ed.) Adaptations of plants to water and high temperature stresses. John Wiley & Sons, New York.
- Jordan, W.R., and R.L. Monk. 1980. Enhancement of drought resistance of sorghum: Progress and limitations. *Corn Sorgh. Res. Conf. Rep.* 35:185–204.
- Kaspar, T.E., and W.L. Bland. 1992. Soil temperature and root growth. *Soil Sci.* 154:290–298.
- Kay, B.D. 1998. Soil structure and organic carbon: A review. p. 169–197. *In* R. Lal et al. (ed.) Soil processes and the carbon cycle. CRC Press, Boca Raton, FL.
- Keeney, D.R., and J.L. Hatfield. 2001. The nitrogen cycle: Historical perspective, and current and potential future concerns. p. 3–16. *In* R. Follett and J.L. Hatfield (ed.) Nitrogen in the environment: Sources, problems, and solutions. Elsevier, Amsterdam.
- Klepper, B. 1991. Root–shoot relationships. p. 265–286. *In* Y. Waisel et al. (ed.) Plant roots: The hidden half. Marcel Dekker, New York.
- Klepper, B., R.K. Belford, and R.W. Rickman. 1984. Root and shoot development in winter wheat. *Agron. J.* 76:117–122.
- Kucharik, C.J., K.R. Brye, J.M. Norman, J.A. Foley, S.T. Gower, and L.G. Bundy. 2001. Measurements and modeling of carbon and nitrogen cycling in agroecosystems of southern Wisconsin: Potential for SOC sequestration during the next 50 years. *Ecosystems* 4: 237–258.
- Kumudini, S. 2002. Trials and tribulations: A review of the role of assimilate supply in soybean genetic improvement. *Field Crops Res.* 75:211–222.

- Kuzyakov, Y. 2002a. Review: Factors affecting rhizosphere priming effects. *Z. Pflanzenernaehr. Bodenkd.* 165:382–396.
- Kuzyakov, Y. 2002b. Separating microbial respiration of exudates from root respiration in non-sterile soils: A comparison of four methods. *Soil Biol. Biochem.* 34:1621–1631.
- Kuzyakov, Y., and W. Cheng. 2001. Photosynthesis controls of rhizosphere respiration and organic matter decomposition. *Soil Biol. Biochem.* 33:1915–1925.
- Lal, R. 2004. Is crop residue a waste? *J. Soil Water Conserv.* 59: 136–139.
- Lal, R., R.F. Follett, and J.M. Kimble. 2003. Achieving soil carbon sequestration in the United States: A challenge to the policy makers. *Soil Sci.* 168:827–845.
- Lal, R., J.M. Kimble, R.F. Follett, and C.V. Cole. 1998. Potential of US cropland to sequester carbon and mitigate the greenhouse effect. Sleeping Bear Press, Chelsea, MI.
- Larson, W.E. 1979. Crop residues: Energy production or erosion control? *J. Soil Water Conserv.* 34:74–76.
- Larson, W.E., C.E. Clapp, W.H. Pierre, and Y.B. Morachan. 1972. Effects of increasing amounts of organic residues on continuous corn: II. Organic carbon, nitrogen, phosphorus and sulfur. *Agron. J.* 64:204–208.
- Latzko, E., and G.J. Kelly. 1983. The many-faceted function of phosphoenolpyruvate carboxylase in C3 plants. *Physiol. Veg.* 21: 805–815.
- Lekkerkerk, L.J.A., S.C. Van De Geijn, and J.A. Van Veen. 1990. Effects of elevated atmospheric CO₂ levels on the carbon economy of a soil planted with wheat. p. 423–429. *In* A.F. Bouwman (ed.) *Soils and the greenhouse effect.* John Wiley & Sons, New York.
- Linden, D.R., C.E. Clapp, and R.H. Dowdy. 2000. Long-term corn grain and stover yields as a function of tillage and residue removed in east central Minnesota. *Soil Tillage Res.* 56:167–174.
- Lipton, D.S., R.W. Blanchard, and D.G. Blevins. 1987. Citrate, malate, and succinate concentration in exudates from P-sufficient and P-stressed *Medicago sativa* L. seedlings. *Plant Physiol.* 85:315–317.
- Lynch, P.J., and K.J. Frey. 1993. Genetic improvement in agronomic and physiological traits of oat since 1914. *Crop Sci.* 33: 984–988.
- Lyon, D.J. 1998. Sunflower residue weight and ground cover loss during summer fallow. *J. Soil Water Conserv.* 53:71–73.
- Marschner, H. 1995. *Mineral nutrition of higher plants.* 2nd ed. Academic Press, Boston.
- Mason, W.K., H.R. Rowse, A.T.P. Bennie, T.C. Kaspar, and H.M. Taylor. 1982. Responses of soybeans to two row spacings and two water levels: II. Water use, root growth, and plant water status. *Field Crops Res.* 5:15–29.
- Maxwell, C.A., C.P. Vance, G.H. Heichel, and S. Stade. 1984. CO₂ fixation in alfalfa and birdsfoot trefoil root nodules and partitioning of ¹⁴C to the plant. *Crop Sci.* 24:257–264.
- Merrill, S.D., D.L. Tanaka, and J.D. Hanson. 2002. Root length growth of eight crop species in Haplustoll soils. *Soil Sci. Soc. Am. J.* 66: 913–923.
- Miller, F.R., and Y. Kebede. 1984. Genetic contributions to yield gains in sorghum, 1950 to 1980. p. 1–14. *In* W.R. Fehr (ed.) *Genetic contributions to yield gains of five major crop plants.* CSSA Spec. Publ. 7. CSSA, Madison, WI.
- Mitchell, R.L., and W.J. Russell. 1971. Root development and rooting patterns of soybean (*Glycine max* L. Merrill) evaluated under field conditions. *Agron. J.* 63:313–316.
- Molina, J.A.E., C.E. Clapp, D.R. Linden, R.R. Allmaras, M.F. Layese, R.H. Dowdy, and H.H. Cheng. 2001. Modeling incorporation of corn (*Zea mays* L.) carbon from roots and rhizodeposition into soil organic matter. *Soil Biol. Biochem.* 33:83–92.
- Morrison, M.J., H.D. Voldeng, and E.R. Cober. 1999. Physiological changes from fifty-eight years of genetic improvement of short-season soybean cultivars in Canada. *Agron. J.* 91:685–689.
- Newell, R.L., and W.W. Wilhelm. 1987. Conservation tillage and irrigation effects on corn root development. *Agron. J.* 79:160–165.
- Norby, R.J. 1994. Issues and perspectives for investigating root responses to elevated atmospheric carbon dioxide. *Plant Soil* 165: 9–20.
- Ojima, K., H. Abe, and K. Ohira. 1984. Release of citric acid into the medium by aluminum-tolerant carrot cells. *Plant Cell Physiol.* 25:855–858.
- Ortiz, R., M. Nurminiemi, S. Madsen, O.A. Rognli, and A. Bjornstad. 2002. Genetic gains in Nordic spring barley breeding over sixty years. *Euphytica* 126:283–289.
- O'Toole, J.C., and W.L. Bland. 1987. Genotypic variation in crop root systems. *Adv. Agron.* 41:91–145.
- Paustian, K., H.P. Collins, and E.A. Paul. 1997. Management controls on soil carbon. p. 15–49. *In* E.A. Paul et al. (ed.) *Soil organic matter in temperate agroecosystems: Long-term experiments in North America.* CRC Press, Boca Raton, FL.
- Paustian, K., W.J. Parton, and J. Persson. 1992. Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. *Soil Sci. Soc. Am. J.* 56:476–488.
- Pedersen, P., K.J. Boote, J.W. Jones, and J.G. Lauer. 2004. Modifying the CROPGRO-soybean model to improve predictions for the Upper Midwest. *Agron. J.* 96:556–564.
- Peltonen-Sainio, P., and R. Karjalainen. 1990. Yield reduction of oat cultivars in relation to disease development caused by barley yellow dwarf virus. *J. Agric. Sci. (Helsinki)* 62:265–273.
- Peterson, G.A., A.D. Halvorson, J.L. Havlin, O.R. Jones, D.J. Lyon, and D.L. Tanaka. 1998. Reduced tillage and increased cropping intensity in the Great Plains conserves soil C. *Soil Tillage Res.* 47:207–218.
- Poel, L.W. 1955. Carbon dioxide fixation by barley roots. *J. Exp. Bot.* 4:157–163.
- Porter, J.R., B. Klepper, and R.K. Belford. 1986. A model (WHTROOT) which synchronizes root growth and development with shoot development for winter wheat. *Plant Soil* 92:133–145.
- Potter, K.N., O.R. Jones, H.A. Torbert, and P.W. Unger. 1997. Crop rotation and tillage effects on organic carbon sequestration in the semi-arid southern Great Plains. *Soil Sci.* 162:140–147.
- Power, J.F., and R.F. Follett. 1987. Monoculture. *Sci. Am.* 255:78–86.
- Prihar, S.S., and B.A. Stewart. 1991. Sorghum harvest index in relation to plant size, environment and cultivar. *Agron. J.* 83:603–608.
- Prince, S.D., J. Haskett, M. Steininger, H. Strand, and R. Wright. 2001. Net primary production of U.S. Midwest croplands from agricultural harvest yield data. *Ecol. Appl.* 11:1194–1205.
- Rasmussen, P.E., R.R. Allmaras, C.R. Rohde, and N.C. Roager, Jr. 1980. Crop residue influences on soil carbon and nitrogen in a wheat-fallow system. *Soil Sci. Soc. Am. J.* 44:596–600.
- Reicosky, D.C., and R.R. Allmaras. 2003. Advances in tillage research in North American cropping systems. *J. Crop Prod.* 8(1–2):75–125.
- Reicosky, D.C., S.D. Evans, C.A. Cambardella, R.R. Allmaras, A.R. Wilts, and D.R. Huggins. 2002. Continuous corn with moldboard tillage: Residue and fertility effects on soil carbon. *J. Soil Water Conserv.* 57:277–284.
- Reicosky, D.C., and M.J. Lindstrom. 1993. Fall tillage method: Effect on short-term carbon dioxide flux from soil. *Agron. J.* 85:1237–1243.
- Rendig, V.V., and H.M. Taylor. 1989. *Principles of soil-plant interrelationships.* McGraw-Hill, New York.
- Ric de Vos, C., H.J. Lubberding, and H.F. Bienfait. 1986. Rhizosphere acidification as a response to iron deficiency in bean plants. *Plant Physiol.* 81:842–846.
- Riedell, W.E., and P.D. Evenson. 1993. Rootworm feeding tolerance in single-cross maize hybrids from different eras. *Crop Sci.* 33: 951–955.
- Ritchie, S.W., and J.J. Hanway. 1982. How a corn plant develops. Spec. Rep. 48. Iowa State Univ., Ames, IA.
- Robinson, R.G. 1978. Production and culture. p. 89–143. *In* J.F. Carter (ed.) *Sunflower science and technology.* Agron. Monogr. 19. ASA, CSSA, and SSSA, Madison, WI.
- Rochette, P., D.A. Angers, and L.B. Flanagan. 1999a. Maize residue decomposition measurement using soil surface carbon dioxide fluxes and natural abundance of carbon¹³. *Soil Sci. Soc. Am. J.* 63:1385–1396.
- Rochette, P., and L.B. Flanagan. 1997. Quantifying rhizosphere respiration in a corn crop under field conditions. *Soil Sci. Soc. Am. J.* 61:466–474.
- Rochette, P., L.B. Flanagan, and E.G. Gregorich. 1999b. Separating soil respiration into plant and soil components using analyses of the natural abundance of carbon¹³. *Soil Sci. Soc. Am. J.* 63:1207–1213.
- Russell, R.S. 1977. *Plant root systems: Their function and interaction with the soil.* McGraw-Hill, London.
- Ruttan, V.W. 1982. *Agricultural research policy.* Univ. of Minnesota Press, Minneapolis.

- Sattelmacher, B., F. Klotz, and H. Marschner. 1990. Influence of the nitrogen level on root growth and morphology of two potato varieties differing in nitrogen acquisition. *Plant Soil* 123:131–137.
- Schaupaugh, W.T., Jr., and J.R. Wilcox. 1980. Relationships between harvest indices and other plant characteristics in soybean. *Crop Sci.* 20:529–533.
- Siddique, K.H.M., R.K. Belford, and D. Tennant. 1990. Root:shoot ratios of old and modern, tall and semi-dwarf wheats in a Mediterranean environment. *Plant Soil* 121:89–98.
- Simmons, S.R. 1987. Growth, development and physiology. p. 77–113. In E.G. Heyne (ed.) *Wheat and wheat improvement*. Agron. Monogr. 13. ASA, CSSA, and SSSA, Madison, WI.
- Sisti, C.P.J., H.P. dos Santos, R. Kohmann, B.J.R. Alves, S. Urquiaga, and R.M. Boddey. 2004. Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. *Soil Tillage Res.* 76:39–58.
- Sivakumar, M.V.K., H.M. Taylor, and R.H. Shaw. 1977. Top and root relations of field-grown soybeans. *Agron. J.* 69:470–475.
- Slobodian, N., K. Van Rees, and D. Pennock. 2002. Cultivation-induced effects on belowground biomass and organic carbon. *Soil Sci. Soc. Am. J.* 66:924–930.
- Smucker, A.J.M. 1984. Carbon utilization and losses by plant root systems. p. 27–46. In S.A. Barber et al. (ed.) *Plants, nutrient and water influx, and plant growth*. ASA Spec. Publ. 49. ASA, CSSA, and SSSA, Madison, WI.
- Soil Science Society of America. 1998. Internet glossary of soil science terms [Online]. Available at www.soils.org/sssagloss/search.html (accessed 9 Sept. 2005; verified 4 Jan. 2006). SSSA, Madison, WI.
- Specht, J.E., D.D. Hume, and S.V. Kumundi. 1999. Soybean yield potential: A genetic and physiological perspective. *Crop Sci.* 39:1560–1570.
- Sperow, M., M. Eve, and K. Paustian. 2003. Potential soil C sequestration on US agricultural soils. *Clim. Change* 57:319–339.
- Stevenson, F.J. 1994. *Humic chemistry: Genesis, composition, reactions*. 2nd ed. John Wiley & Sons, New York.
- Stewart, W.M., D.W. Dibb, A.E. Johnston, and T.J. Smyth. 2005. The contribution of commercial fertilizer nutrients to food production. *Agron. J.* 97:1–6.
- Stone, L.R., D.E. Goodrum, A.J. Schlegel, M.N. Jaafar, and A.H. Khan. 2002. Water depletion depth of grain sorghum and sunflower in the central High Plains. *Agron. J.* 94:936–943.
- Swinnen, J., J.A. van Veen, and R. Merckx. 1994. Rhizosphere carbon fluxes in field-grown spring wheat: Model calculations based on ¹⁴C partitioning after pulse-labeling. *Soil Biol. Biochem.* 26:171–182.
- Taylor, H.M. 1986. Methods of studying root systems in the field. *HortScience* 21:952–956.
- Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water-stable aggregates in soils. *J. Soil Sci.* 33:141–163.
- Tokatlidis, I.S., and S.D. Koutroubas. 2004. A review of maize hybrids: Dependence on high plant populations and its implications for crop yield stability. *Field Crops Res.* 88:103–114.
- Tollenaar, M. 1983. Potential vegetative productivity in Canada. *Can. J. Plant Sci.* 63:1–10.
- Tollenaar, M., and A.F. Lee. 2002. Yield potential, yield stability and stress tolerance in maize. *Field Crops Res.* 75:161–169.
- Torbert, H.A., S.A. Prior, H.H. Rogers, and C.W. Wood. 2000. Review of elevated atmospheric CO₂ effects on agro-ecosystems: Residue decomposition processes and soil C storage. *Plant Soil* 224:59–73.
- Unger, P.W., and R.L. Baumhardt. 1999. Factors related to dryland grain sorghum yield increases: 1939 through 1997. *Agron. J.* 91:870–875.
- USDA–National Agricultural Statistics Service. 2003. Crops county data files. Available at www.usda.gov/nass/graphics/county03/indexdata.htm (accessed 1 Sept. 2005; verified 4 Jan. 2006). USDA–NASS, Washington, DC.
- USDA–National Agricultural Statistic Service. 2004. USDA historical track records. Available at www.usda.gov/nass/pubs/trackrec/croptr04.pdf (accessed 10 May 2005; verified 4 Jan. 2006). USDA–NASS, Washington, DC.
- Vance, C.P., S. Stade, and C.A. Maxwell. 1983. Alfalfa root nodule carbon dioxide fixation: I. Association with nitrogen fixation and incorporation into amino acids. *Plant Physiol.* 72:469–473.
- van Noordwijk, M., and G. Brouwer. 1991. Review of quantitative root length data in agriculture. p. 515–524. In B.L. McMichael and H. Person (ed.) *Plant roots and their environment*. Elsevier, Amsterdam.
- Vanotti, M.B., L.G. Bundy, and A.E. Peterson. 1997. Nitrogen fertilizer and legume–cereal rotation effects on soil productivity and organic matter dynamics in Wisconsin. p. 105–119. In E.A. Paul et al. (ed.) *Soil organic matter in temperate agroecosystems: Long-term experiments in North America*. CRC Press, Boca Raton, FL.
- Vetsch, J.A., and G.W. Randall. 2004. Corn production as affected by nitrogen application timing and tillage. *Agron. J.* 96:502–509.
- Vitosh, M.L., R.E. Lucas, and G.H. Silva. 1997. Long-term effects of fertilizer and manure on corn yield, soil carbon, and other soil chemical properties in Michigan. p. 129–139. In E.A. Paul et al. (ed.) *Soil organic matter in temperate agroecosystems: Long-term experiments in North America*. CRC Press, Boca Raton, FL.
- Voldeng, H.D., E.R. Cober, D.J. Hume, C. Gillards, and M.J. Morrison. 1997. Fifty-eight years of genetic improvement of short season cultivars in Canada. *Crop Sci.* 37:428–431.
- Vuorinen, A.H., E.M. Vapaavuori, O. Raatikainen, and S.P. Lapinjok. 1992. Metabolism of inorganic carbon taken up by roots in *Salix* plants. *J. Exp. Bot.* 43:789–795.
- Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, W.B. Voorhees, and D.R. Linden. 2004. Crop and soil productivity response to corn residue removal: A literature review. *Agron. J.* 96:1–17.
- Wilhelm, W.W., L.N. Mielke, and C.R. Fenster. 1982. Root development of winter wheat as related to tillage practices in western Nebraska. *Agron. J.* 74:85–88.
- Wilts, A.R., D.C. Reicosky, R.R. Allmaras, and C.E. Clapp. 2004. Long-term corn residue effects: Harvest alternatives, soil carbon turnover, and root-derived carbon. *Soil Sci. Soc. Am. J.* 68:1342–1351.
- Yang, H.S., A. Dobermann, J.L. Lindquist, D.T. Walters, T.J. Arkebauer, and K.G. Cassman. 2004. HYBRID-MAIZE: A maize accumulation model that combines two crop modeling approaches. *Field Crops Res.* 87:131–154.