Reply to Comments on "Synthetic Nitrogen Fertilizers Deplete Soil Nitrogen: A Global Dilemma for Sustainable Cereal Production," by R.L. Mulvaney, S.A. Khan, and T.R. Ellsworth in the *Journal of Environmental Quality* 2009 38: 2295–2314

Dear Editor,

We appreciate the opportunity to respond to the comments of Dr. Powlson and his colleagues (Powlson et al., 2010) and to further elaborate a critical but often overlooked aspect of synthetic N fertilizer usage in response to the world's growing demands for food, fiber, and energy. The work reported by Khan et al. (2007a) and Mulvaney et al. (2009) was undertaken to evaluate how synthetic N fertilization has affected soil storage of organic C and N, which is directly related to numerous physical, chemical, and biological processes and ecological functions that ultimately determine agricultural sustainability. Long-term cropping experiments provide the most reliable means for assessing these effects.

To adequately investigate a topic with such important implications, the utmost care must be taken to ensure data integrity. Toward this end, an extensive effort was made in compiling baseline sets of soil C and N data from published cropping experiments. Only data sets involving synthetic N fertilization but not manuring were utilized because of their relevance to modern input-intensive agriculture, and these were documented in all cases with detailed records of crop and soil management. The Morrow Plots qualify in both respects, as the oldest experiment field in the United States. Before the introduction of commercial fertilization, a substantial increase in soil organic C occurred despite moldboard plowing and the removal of aboveground residues, when corn was grown following oats or alfalfa, with a modest application of dairy manure that supplied approximately 20 to 30 kg N and 2 Mg C (roughly equivalent to residue C removal) as an annual average per hectare. As documented by Fig. 2 of Khan et al. (2007a) and in a subsequent letter to the editor (Khan et al., 2008), this buildup reverted to decline following the shift to chemical-based management. Despite increasingly massive fertilizer (116–161 kg N ha^{-1} yr^{-1} on average) and residue (4.3–5.3 Mg C ha^{-1} yr^{-1} on average) inputs, there was very little evidence in 2005 of any soil C or N buildup or sequestration over time, relative to baseline data collected just before the introduction of synthetic N. Rather, the only significant changes were net losses that were almost always more extensive for the subsurface than for the surface soil. These findings are substantiated by baseline data sets from Rothamsted and numerous other cropping experiments with ammoniacal fertilization and are also consistent with the temporal declines in soil C and N noted by Aref and Wander (1998) for the Morrow Plots and by David et al. (2009) for many nonexperimental sites sampled on Illinois Mollisols.

A different interpretation, advocated by Dr. Powlson and his colleagues (Powlson et al., 2010), leads to a different conclusion. Instead of assessing soil C or N changes over time relative to baseline soil profile data that also account for temporal variations in bulk density, their approach invariably involves a comparison of concentration data for surface soils with and without a history of synthetic N fertilization, such that any positive difference for the fertilized versus unfertilized soil is attributed to buildup. As well documented in several review articles (e.g., Glendining and Powlson, 1995; Paustian et al., 1997; Johnston et al., 2009), such differences are a common occurrence and would indeed be expected, for continuous cropping without nutrient inputs necessarily limits biomass production and leads to soil nutrient depletion.

Unfortunately, this sort of finding is immaterial for addressing the research question that was the central focus of our papers: Does synthetic N fertilization increase or decrease soil C or N storage? This question was primarily addressed for the Morrow Plots using a mass-balance approach with a thorough accounting of all inputs and outputs and net profile changes over time, which along with numerous other baseline data sets led to the conclusion that synthetic N fertilization predominately depletes soil C and N.

The main justification for long-term cropping experiments has always been their fundamental value for monitoring temporal changes in yield and soil properties as related to management and sustainability; however, replication is often a limiting factor. In such cases, the baseline approach with sequential sampling over time provides a much more reliable means of assessing treatment effects on soil properties as opposed to a comparative evaluation (e.g., Powlson, 1994; Campbell et al., 2000; VandenBygaart and Angers, 2006; Johnston et al., 2009). Several studies at Rothamsted have utilized baseline data to clearly document trends in yield, pH, P, or K for arable

Published in J. Environ. Qual. 39:753–756 (2010).
doi:10.2134/jeq2010.0002le
© ASA, CSSA, SSSA
677 S. Segoe Rd., Madison, WI 53711 USA

land (e.g., Garner and Dyke, 1969; Johnston and Penny, 1972; Johnston, 1988; Jenkinson, 1991; Powlson, 1994; Blake et al., 1999), which in some cases involved extensive profile sampling. We are thus at a loss as to why Dr. Powlson and his colleagues, sampling only the plow layer, prefer the comparison approach for evaluating soil C and N trends as related to synthetic N fertilization, which invariably redirects the focus away from an understanding of N fertilizers as a causative factor in the gain or loss of soil organic matter. The latter effect is evident from Tables 1 and 2 of Glendining and Powlson (1995), in which case baseline data were often disregarded in favor of a comparative interpretation that transformed soil N depletion into buildup.

The comparison approach provides justification for another misconception advocated by Powlson et al. (2010): Synthetic N fertilization becomes more effective for building soil organic matter when the rate is increased. This view has served a profitable purpose for the fertilizer industry in promoting adoption of yield-based recommendations that not only maximize synthetic N inputs for the most productive soils with the highest indigenous N-supplying power and lowest fertilizer need but are also presumed to contribute toward soil enrichment (Smil, 2001). The usual consequence is fertilization beyond grain N removal, documented for the U.S. Corn Belt by numerous N-response studies (e.g., Lory and Scharf, 2003; Mulvaney et al., 2006) and the budgetary analysis presented in Table 4 of Khan et al. (2007a).

On a global scale, the past five decades have witnessed an eightfold increase in annual fertilizer N consumption, while cereal production has tripled. (Besides fertilization, approximately 50% of this yield increase has been attributed to genetic improvements [Stuber et al., 1999; Duvick, 2005], while the remainder is due to a twofold increase in land area under irrigation and a fourfold increase in pesticide usage [Tilman et al., 2001].) One consequence, addressed by Table 6 of our recent paper (Mulvaney et al., 2009), has been low fertilizer N uptake efficiency that reduces profitability for the producer. Much more attention has been paid to the adverse impact of fertilizer N losses on air and water quality; however, agricultural sustainability should also be a concern because of baseline evidence that synthetic N fertilization does not maintain soil C and N and thereby has negative implications for numerous soil properties and processes that affect food and fiber production. Sustainability is further jeopardized by the high energy demand to manufacture fertilizer N (Smil, 2001), by stagnating or declining grain yields in Southeast Asia (as reported by numerous references cited in Mulvaney et al., 2009, p. 2307), and by a growing reliance on subsidies as a substitute for economic viability (Bansil, 2004; Barah, 2004).

If synthetic N fertilizers are more apt to increase the input than soil storage of C and N, then logic dictates that these fertilizers must be more effective in promoting microbial decomposition as opposed to humification. Years before the modern agricultural era, this effect was linked to soil C and N depletion in long-term fertilizer trials (White, 1927; Albrecht, 1938) and is no less apparent today as evidenced by long-term trials in Iowa demonstrating that synthetic N fertilization is more effective for stimulating C decay than residue C input (Russell et al., 2009). Despite the assertion by Powlson et al. (2010) to the contrary, the same effect is apparent from numerous data sets summarized in Table 3 of Khan et al. (2007a) and Table 2 of Mulvaney et al. (2009) and from more recent studies documenting the loss of organic matter from soils fertilized with synthetic N (Schipper et al., 2007; Fening et al., 2009; Poirier et al., 2009; Senthilkumar et al., 2009). The magnitude of these losses will naturally depend on the initial level of soil C and N and hence will be greater for the Mollisols of the Morrow Plots than for the Broadbalk or Hoosfield Alfisols of Rothamsted. Climatic conditions and other factors will also influence the extent to which synthetic N stimulates microbial decomposition, but the universal nature of this phenomenon is demonstrated even in tundra where low temperatures limit heterotrophic decay (Mack et al., 2004).

By affecting the dynamic balance between immobilization and mineralization, management practices have a major impact on soil C and N levels. As discussed in detail in Mulvaney et al. (2009, p. 2301–2303), the modern trend is an overall decline in response to intensive cash grain cropping that requires tillage and numerous chemical inputs, the most extensive being synthetic ammoniacal fertilizers. These fertilizers have brought about a shift toward microbial decomposition (mineralization), evidenced by declining soil C and N in baseline data sets from cropping experiments throughout the world, including those presented by Dr. Powlson and his colleagues for the Hoosfield barley and the Broadbalk wheat experiments at Rothamsted. The soil N data for Hoosfield reveal a striking contrast between the enriching effect of organic N and the depleting effect of synthetic N (see also Jenkinson and Johnston, 1977; Jenkinson, 1991; Johnston et al., 2009). The same contrast is revealed by Broadbalk data (e.g., see Jenkinson, 1982; Rothamsted Research, 2006), although not by Fig. 2 in Powlson et al. (2010) since the organic N treatment has been omitted. The trend in soil N for Broadbalk was initially upward following management changes in 1968 for plots currently fertilized with 144 or 192 kg N ha^{-1}. For the plot receiving 144 kg N ha^{-1} annually since 1852, this trend is likely related to the introduction of high-yielding varieties that increased the belowground input of residue C, causing a shift toward immobilization of fertilizer N. The resulting accumulation of organic N was, however, a temporary occurrence, as would be expected if ammoniacal N is more effective for stimulating mineralization as compared to immobilization. An obvious soil N decline began in the 1990s, such that concentrations measured for 1992 to 2005 are lower than for 1966 and are also lower than the more erratic levels observed for 192 kg N ha^{-1}.

If synthetic N stimulates microbial decomposition, then net N mineralization should increase with the rate or frequency of N application. This has been demonstrated by Glendining and Powlson (1990) for continuous wheat on the Broadbalk plots at Rothamsted. According to their Tables 1 and 2, total soil N after 130 yr of synthetic N fertilization was very similar with 96 or 144 kg N ha^{-1}, whereas the higher rate increased net mineralization by 17% (see also Jenkinson, 1991). More dramatic evidence of the same effect was noted 20 yr after the N rate was increased from 48 to 192 kg ha^{-1}, in which case the net mineralization rate was 28% higher than with 96 kg N ha^{-1} despite a somewhat lower soil content of total N (Glendining and Powlson, 1990). The implication is that intensive inputs of synthetic N do not contribute to a long-term humus increase but rather stimulate organic matter mineralization (Johnston and Jenkinson, 1989; Shevtsova et al., 2003) that depletes biomass N (Shen et al., 1989; Glendining et al., 1996), thereby exacerbating the long-term loss of N-supplying power and total N from agricultural soils. There is good reason for concern about global food security, considering the extensive evidence from ^{15}N-tracer (e.g., Vos et al., 1993; Schindler and Knighton, 1999; Tran and Tremblay, 2000; Dourado-Neto et al., 2010) and N-response studies (see Table 6 of Mulvaney et al., 2009) that crop N uptake originates largely from the soil rather than fertilizer applied for the current growing season.

The Morrow Plots leave no doubt that cropping and management practices markedly affect corn yields, which have long been lowest for continuous corn and highest for a corn–oats–hay rotation (DeTurk et al., 1927; Welch, 1976; Odell et al., 1982; Aref and Wander, 1998; Khan et al., 2007a,b; Mulvaney et al., 2009). This difference, averaging 33% between 1982 and 2002, is consistent with soil storage of C and N and has persisted despite much more intensive inputs of synthetic N and residue C when corn is grown continuously. Such findings are hardly surprising, in view of other studies that have documented the benefits of legume- over chemical-based cropping systems (Wander et al., 1994; Drinkwater et al., 1998). The only logical conclusion, as stated in our paper (Mulvaney et al., 2009), is that "a transition may be required toward agricultural diversification using legume-based crop rotations, which provide a valuable means to reduce the intensity of ammoniacal fertilization with the input of less reactive organic N." History leaves little doubt about the manifold benefits of forage legumes such as clover, which revolutionized European landscapes and living standards beginning in the 16th century (Kjærgaard, 1995, 2003).

In the modern era of intensified agriculture, soils are generally managed as a commodity to maximize short-term economic gain. Unfortunately, this concept entirely ignores the consequences for a vast array of biotic and abiotic soil processes that affect air and water quality and most important, the soil itself. After five decades of agrocentric management, the world's arable soils have been degraded and cereal production is increasingly exceeded by grain demand for a burgeoning human population. Should not an issue with global economic, political, and environmental ramifications be taken seriously?

References

Albrecht, W.A. 1938. Variable levels of biological activity in Sanborn Field after fifty years of treatment. Soil Sci. Soc. Am. Proc. 3:77–82.

Aref, S., and M.M. Wander. 1998. Long-term trends of corn yield and soil organic matter in different crop sequences and soil fertility treatments on the Morrow Plots. Adv. Agron. 62:153–197.

Bansil, P.C. 2004. Agricultural subsidies. A global view. p. 39–65. *In* B. Dorin and T. Jullien (ed.) Agricultural incentives in India: Past trends and prospective paths towards sustainable development. Manohar Publ., New Delhi, India.

Barah, B.C. 2004. Agricultural production system and environmental sustainability: Lesson from long term manurial experimental trials. p. 281–294. *In* B. Dorin and T. Jullien (ed.) Agricultural incentives in India: Past trends and prospective paths towards sustainable development. Manohar Publ., New Delhi, India.

Blake, L., S. Mercik, M. Koerschens, K.W.T. Goulding, S. Stempen, A. Weigel, P.R. Poulton, and D.S. Powlson. 1999. Potassium content in soil, uptake in plants and the potassium balance in three European long-term field experiments. Plant Soil 216:1–14.

Campbell, C.A., R.P. Zentner, B.-C. Liang, G. Roloff, E.C. Gregorich, and B. Blomert. 2000. Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan: Effect of crop rotations and fertilizers. Can. J. Soil Sci. 80:179–192.

David, M.B., G.F. McIsaac, R.G. Darmody, and R.A. Omonode. 2009. Long-term changes in Mollisol organic carbon and nitrogen. J. Environ. Qual. 38:200–211.

DeTurk, E.E., F.C. Bauer, and L.H. Smith. 1927. Lessons from the Morrow Plots. Bull. 300. Univ. of Illinois, Urbana.

Dourado-Neto, D., D. Powlson, R.A. Bakar, O.O.S. Bacchi, M.V. Basanta, P. thi Cong, G. Keerthisinghe, M. Ismaili, S.M. Rahman, K. Reichardt, M.S.A. Safwat, R. Sangakkara, L.C. Timm, J.Y. Wang, E. Zagal, and C. van Kessel. 2010. Multiseason recoveries of organic and inorganic nitrogen-15 in tropical cropping systems. Soil Sci. Soc. Am. J. 74:139–152.

Drinkwater, L.E., P. Wagoner, and M. Sarrantonio. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396:262–265.

Duvick, D.N. 2005. The contributions of breeding to yield advances in maize. Adv. Agron. 86:83–145.

Fening, J.O., E. Yeboah, T. Adjei-Gyapong, and E. Gaizie. 2009. On farm evaluation of the contribution of three green manures to maize yield in the semi-deciduous forest zone of Ghana. Afr. J. Environ. Sci. Technol. 3:234–238.

Garner, H.V., and G.V. Dyke. 1969. The Broadbalk yields. p. 26–49. *In* Rothamsted Experimental Station Report for 1968. Part 2. Lawes Agric. Trust, Harpenden, Herts, UK.

Glendining, M.J., and D.S. Powlson. 1990. 130 years of inorganic nitrogen fertilizer applications to the Broadbalk wheat experiment: The effect on soil organic nitrogen. p. 9–13. *In* Trans. 14th Int. Congr. Soil Sci. Vol. IV. Int. Soc. Soil Sci., Kyoto, Japan.

Glendining, M.J., and D.S. Powlson. 1995. The effects of long continued applications of inorganic nitrogen fertilizer on soil organic nitrogen: A review. p. 385–446. *In* R. Lal and B. A. Stewart (ed.) Soil management: Experimental basis for sustainability and environmental quality. Lewis, Boca Raton, FL.

Glendining, M.J., D.S. Powlson, P.R. Poulton, N.J. Bradbury, D. Palazzo, and X. Li. 1996. The effects of long-term applications of inorganic nitrogen fertilizer on soil nitrogen in the Broadbalk Wheat Experiment. J. Agric. Sci. 127:347–363.

Jenkinson, D.S. 1982. The nitrogen cycle in long-term field experiments. Phil. Trans. R. Soc. Lond. Ser. B 296:563–571.

Jenkinson, D.S. 1991. The Rothamsted long-term experiments: Are they still of use? Agron. J. 83:2–10.

Jenkinson, D.S., and A.E. Johnston. 1977. Soil organic matter in the Hoosfield continuous barley experiment. p. 87–101. *In* Rothamsted Experimental Station Report for 1976. Part 2. Lawes Agric. Trust, Harpenden, Herts, UK.

Johnston, A.E. 1988. Potassium fertilization to maintain a K-balance under various farming systems. p. 199–226. *In* Nutrient balances and the need for potassium. Proc. 13th IPI-Congress. Int. Potash Inst., Worblaufen-Bern, Switzerland.

Johnston, A.E., and D.S. Jenkinson. 1989. The nitrogen cycle in UK arable agriculture. Proc. Fert. Soc. 286:1–24.

Johnston, A.E., and A. Penny. 1972. The Agdell Experiment, 1848–1970: Estimates of the P and K accumulated from fertiliser dressings given between 1848 and 1951, their recovery by grass between 1958 and 1970, and their effect on the response by grass to new dressings of P and K. p. 38–68. *In* Rothamsted Experimental Station Report for 1971. Part 2. Lawes Agric. Trust, Harpenden, Herts, UK.

Johnston, A.E., P.R. Poulton, and K. Coleman. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Adv. Agron. 101:1–57.

Kjærgaard, T. 1995. Agricultural development and nitrogen supply from an historical point of view. p. 3–14. *In* L. Kristensen (ed.) Nitrogen leaching in ecological agriculture. A. B. Academic Publ., Berkhamstad, UK.

Kjærgaard, T. 2003. A plant that changed the world: The rise and fall of clover 1000–2000. Landscape Res. 28:41–49.

Khan, S.A., R.L. Mulvaney, T.R. Ellsworth, and C.W. Boast. 2007a. The myth of nitrogen fertilization for soil carbon sequestration. J. Environ. Qual. 36:1821–1832.

Khan, S.A., R.L. Mulvaney, T.R. Ellsworth, and C.W. Boast. 2008. Reply to comment on "The myth of nitrogen fertilization for soil carbon sequestration." J. Environ. Qual. 37:739–740.

Khan, S.A., R.L. Mulvaney, T.R. Ellsworth, K. Ferrie, T.J. Smith, J.S. Strock, and R.M. Vanden Heuvel. 2007b. Importance of plant population to soil-based N management with the Illinois soil N test. p. 55–63. *In* Illinois Fert. Conf. 2007 Proc. Univ. of Illinois, Urbana, IL. Available at http://frec.cropsci.illinois.edu/2007/report8/ (verified 25 Jan. 2010).

Lory, J.A., and P.C. Scharf. 2003. Yield goal versus delta yield for predicting fertilizer nitrogen need in corn. Agron. J. 95:994–999.

Mack, M.C., E.A.G. Schuur, M.S. Bret-Harte, G.R. Shaver, and F.S. Chapin, III. 2004. Ecosystem carbon storage in arctic tundra reduced by long-term nutrient fertilization. Nature 431:440–443.

Mulvaney, R.L., S.A. Khan, and T.R. Ellsworth. 2006. Need for a soil-based approach in managing nitrogen fertilizers for profitable corn production. Soil Sci. Soc. Am. J. 70:172–182.

Mulvaney, R.L., S.A. Khan, and T.R. Ellsworth. 2009. Synthetic nitrogen fertilizers deplete soil nitrogen: A global dilemma for sustainable cereal production. J. Environ. Qual. 38:2295–2314.

Odell, R.T., W.M. Walker, L.V. Boone, and M.G. Oldham. 1982. The Morrow Plots: A century of learning. Bull. 775. Univ. of Illinois, Urbana.

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.

Poirier, V., D.A. Angers, P. Rochette, M.H. Chantigny, N. Ziadi, G. Tremblay, and J. Fortin. 2009. Interactive effects of tillage and mineral fertilization on soil carbon profiles. Soil Sci. Soc. Am. J. 73:255–261.

Powlson, D.S. 1994. Quantification of nutrient cycles using long-term experiments. p. 97–115. *In* R.A. Leigh and A.E. Johnston (ed.) Long-term experiments in agricultural and ecological sciences. CAB Int., Wallingford, Oxon, UK.

Powlson, D.S., D.S. Jenkinson, A.E. Johnston, P.R. Poulton, M. J. Glendining, and K.W.T. Goulding. 2010. Comments on “Synthetic nitrogen fertilizers deplete soil nitrogen: A global dilemma for sustainable cereal production,” by R.L. Mulvaney, S.A. Khan, and T.R. Ellsworth in the *Journal of Environmental Quality* 2009 38:2295–2314. J. Environ. Qual. 39:749–752 (this issue).

Rothamsted Research. 2006. Guide to the classical and other long-term experiments, datasets and sample archive. Rothamsted Res., Harpenden, Herts, UK. Available at http://www.rothamsted.bbsrc.ac.uk/resources/LongTermExperiments.pdf (verified 25 Jan. 2010).

Russell, A.E., C.A. Cambardella, D.A. Laird, D.B. Jaynes, and D.W. Meek. 2009. Nitrogen fertilizer effects on soil carbon balances in midwestern U.S. agricultural systems. Ecol. Appl. 19:1102–1113.

Schindler, F.V., and R.E. Knighton. 1999. Fate of fertilizer nitrogen applied to corn as estimated by the isotopic and difference methods. Soil Sci. Soc. Am. J. 63:1734–1740.

Schipper, L.A., W.T. Baisden, R.L. Parfitt, C. Ross, and J.J. Claydon. 2007. Large losses of soil C and N from soil profiles in New Zealand during the past 20 years. Glob. Change Biol. 13:1138–1144.

Senthilkumar, S., B. Basso, A.N. Kravchenko, and G.P. Robertson. 2009. Contemporary evidence of soil carbon loss in the U.S. Corn Belt. Soil Sci. Soc. Am. J. 73:2078–2086.

Shen, S.M., P.B.S. Hart, D.S. Powlson, and D.S. Jenkinson. 1989. The nitrogen cycle in the Broadbalk wheat experiment: ^{15}N-labelled fertilizer residues in the soil and in the soil microbial biomass. Soil Biol. Biochem. 21:529–533.

Shevtsova, L., V. Romanenkov, O. Sirotenko, P. Smith, J.U. Smith, P. Leech, S. Kanzyvaa, and V. Rodionova. 2003. Effect of natural and agricultural factors on long-term soil organic matter dynamics in arable soddy-podzolic soils: Modeling and observation. Geoderma 116:165–189.

Smil, V. 2001. Enriching the earth: Fritz Haber, Carl Bosch, and the transformation of world food production. MIT Press, Cambridge, MA.

Stuber, C.W., M. Polacco, and M.L. Senior. 1999. Synergy of empirical breeding, marker-assisted selection, and genomics to increase crop yield potential. Crop Sci. 39:1571–1583.

Tilman, D., J. Fargione, B. Wolff, C. D’Antonio, A. Dobson, R. Howarth, D. Schindler, W.H. Schlesinger, D. Simberloff, and D. Swackhamer. 2001. Forecasting agriculturally driven global environmental change. Science 292:281–284.

Tran, T.S., and G. Tremblay. 2000. Recovery of ^{15}N-labeled fertilizer by spring bread wheat at different N rates and application times. Can. J. Soil Sci. 80:533–539.

VandenBygaart, A.J., and D.A. Angers. 2006. Towards accurate measurements of soil organic carbon stock change in agroecosystems. Can. J. Soil Sci. 86:465–471.

Vos, G.J.M., B. Duquet, J.C. Vedy, and J.A. Neyroud. 1993. The course of ^{15}N-ammonium nitrate in a spring barley cropping system. Plant Soil 150:167–175.

Wander, M.M., S.J. Traina, B.R. Stinner, and S.E. Peters. 1994. Organic and conventional management effects on biologically active soil organic matter pools. Soil Sci. Soc. Am. J. 58:1130–1139.

Welch, L.F. 1976. The Morrow Plots: Hundred years of research. Ann. Agron. 27:881–890.

White, J.W. 1927. Soil organic matter and manurial treatments. J. Am. Soc. Agron. 19:389–396.

Received 12 Jan. 2010

R. L. Mulvaney, S. A. Khan, and T. R. Ellsworth

Department of Natural Resources and Environmental Sciences
Turner Hall
1102 S. Goodwin Ave.
University of Illinois
Urbana, IL 61801
lesssoiln@gmail.com