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Tillage-induced CO_2 loss across an eroded landscape☆

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Abstract

Soil carbon (C) losses and soil translocation from tillage operations have been identified as causes of soil degradation and soil erosion. The objective of this work was to quantify the variability in tillage-induced carbon dioxide (CO_2) loss by moldboard (MP) and chisel (CP) plowing across an eroded landscape and relate the C loss to soil properties. The study site was a 4 ha wheat (*Triticum aestivum* L. cv. Marshall) field with rolling topography and five soil types in the Svea-Barnes complex in west central Minnesota (N. Latitude = 45°41′W, Longitude = 95°43′). Soil properties were measured at several depths at a 10 m spacing along north–south (N–S) and west–east (W–E) transects through severely eroded, moderately eroded and non-eroded sites. Conventional MP (25 cm deep) and CP (15 cm deep) equipment were used along the pre-marked transects. Gas exchange measurements were obtained with a large, portable chamber within 2 m of each sample site following tillage. The measured CO_2 fluxes were largest with the MP > CP > not tilled (before tillage). The variation in 24 h cumulative CO_2 flux from MP was nearly 3-fold on the N–S transect and 4-fold on the W–E transect. The surface soil organic C on the transects was lowest on the eroded knolls at 5.1 g C kg^{-1} and increased to 19.6 g C kg^{-1} in the depositional areas. The lowest CO_2 fluxes were measured from severely eroded sites which indicated that the variation in CO_2 loss was partially reflected by the degradation of soil properties caused by historic tillage-induced soil translocation with some wind and water erosion.

The spatial variation across the rolling landscape complicates the determination of non-point sources of soil C loss and suggests the need for improved conservation tillage methods to maintain soil and air quality in agricultural production systems.
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Keywords: Tillage; Erosion; Carbon; Soil properties; Moldboard plow; Chisel plow

1. Introduction

Accelerated soil erosion is a global problem of modern times with severe economic (Pimentel et al., 1995) and environmental impacts (Lal, 1995). Economic impacts are caused by decreases in crop yields and environmental impacts are due to deterioration in soil quality from the reduction of the soil's

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ability to regulate water and air qualities. Human-induced soil erosion is a problem because it occurs more rapidly than the process of soil formation. With the loss of fertile topsoil, soil degradation leads to reduced crop production capacity (Larson et al., 1983; Lal, 1987). The loss of organic matter and the accompanying soil biology adversely affects the physical properties for plant growth by decreasing the pore space and the soil root interactions and increasing bulk density. This management-caused degradation can increase the inherent erodibility of the soil and creates a self-perpetuating, downward spiral in soil quality.

Concern for soil erosion and environmental quality has evolved from the link between global warming and atmospheric carbon dioxide (CO_2) which has lead to a focus on soil carbon (C) storage in agricultural production systems. Agricultural soils play an important role in C sequestration or storage; thus, helping mitigate global warming (Lal et al., 1998). Tillage processes and mechanisms leading to C loss are directly linked to soil productivity, soil properties and environmental issues (Paustian et al., 1997). The direct linkage between tillage-induced C loss and tillage-induced soil erosion requires a better understanding to minimize agriculture's impact on the environment.

Soil erosion is a severe global problem, especially in sensitive agricultural eco-regions with high rainfall and sloping lands. Soil erosion will remain a major issue for generations to come as long as intensive tillage is used in agricultural production systems. Successful mitigation of soil erosion requires an objective and reliable assessment of the on-site effects in terms of soil loss and productivity as well as the off-site effects causing environmental damage. Agronomic productivity decline should be evaluated at global scales down through point sources in individual fields and should be used to make global estimates of the long-term effects on society. There is need to develop a quantitative relationship between tillage-induced C loss and tillage-induced soil erosion so that better soil management practices can be developed to minimize the effects of erosion on productivity and the environment before any irreversible damage is done.

Soil translocation from tillage operations has been identified as a source of soil erosion, which at specific landscape positions can be greater than the soil loss tolerance levels (Lindstrom et al., 1992; Govers et al., 1994; Lobb et al., 1995; Poesen et al., 1997). Soil translocation or tillage erosion is the net movement of soil downslope in response to the action of mechanical implements. The soil is not directly lost from the fields by tillage translocation or tillage erosion, rather it is moved away from the convex slopes and deposited in concave slope positions. Schumacher et al. (1999) concluded that tillage erosion resulted in soil loss in the shoulder position, while soil loss from water erosion occurred primarily in the mid to lower back slope position. The decline in soil productivity was greater when both processes were combined compared to either process acting alone. The net effect of soil translation from the combined effects of both tillage and water erosion was an increase in spatial variability of crop yields which led to a decline in overall soil productivity (Schumacher et al., 1999).

The effect of landscape position on soil respiration has been reported by DeJong (1981) who found the highest CO_2 evolution rate for grassland, intermediate for cereals, and lowest under fallow conditions. He also observed a 2-fold increase in soil respiration at the foot of the hill as compared to the top of the hill. Even on uniform, level soils, spatial variability can be large. Dugas (1993) made soil chamber CO_2 measurements sequentially at nine positions in a 5 ha field on a Houston Black clay (fine, montmorillonitic, thermic Udic Pellusterts). The coefficient of variations of chamber CO_2 fluxes across the nine positions averaged 40% throughout the day, indicating the need for a large number of chamber measurements to obtain a representative CO_2 flux measurement. Rochette et al. (1991) found spatial variability, described by the coefficient of variation for each series of measurement, was highest in May at 69% and decreased to 25% toward the end of the season. The number of measurements required to estimate soil respiration within 10% of the mean at a 0.05 probability level was 190 before crop emergence and 30 after 70 days.

Reliable averages of soil and vegetation CO_2 evolution do not reflect spatial variability, but are important measurements related to C cycling. The spatial variability associated with soil CO_2 flux needs to be addressed to obtain reliable averages, but has only received limited attention. Speir et al. (1984) found the spatial variability of soil biochemical properties including soil respiration was significantly greater than that of chemical properties. Robertson et al. (1988) determined that spatial variability of soil respiration was random with no spatial correlation at scales of 1–80 m.

Aiken et al. (1991) reported the variation in the soil CO_2 efflux attributed to positional trends, spatial correlation and random effects in a wheat crop under wet and dry soil conditions. The assumption of spatial homogeneity was not founded for CO_2 efflux in four of the five data sets evaluated. The positional trends accounted for spatial structure in these cases. Residual variability after removing the positional trends was isotropic and randomly distributed. No spatial correlation was observed after removal of the positional trends. However, they did note that there may have been an appearance of spatial correlation if the positional trends had not been removed. The spatial structure was affected by the soil water content under the wheat straw. They further concluded that defining the spatial structure for soil respiration required the determination of a wide-range of environmental conditions that are dynamically changing as a function of time as well as with position in the landscape.

Tillage erosion was considered the main cause of soil translocation from the upper hilly areas down-sloped to lower levels in a watershed. Lobb and Lindstrom (1999) reported that soil loss due to tillage erosion exceeded 15 kg m^{-2} per year in the north central portion of the United States. Lindstrom et al. (1992) estimated an annual soil loss of approximately 30 t ha^{-1} after simulated moldboard plowing for a period of 8 years.

Soils in the western U.S. Corn Belt commonly have different soil properties and yield potentials that are dependent on topographic locations within the landscape (Reicosky, 1995). The awareness of tillage-induced C losses and tillage erosion as a soil degradation process has become increasingly important in intensive agricultural production systems. Prolonged soil movement and cultivated landscapes will likely increase the natural occurring variability of soil properties and yield potentials. Research on tillage erosion by the MP under various cultivation practices is limited. Therefore, the objective of this work was to evaluate the effect of MP and the CP on tillage-induced C loss and relate these losses to soil physical and chemical properties of a landscape in west central Minnesota that had been intensively tilled for 30 years. Specific objectives were to evaluate the variation in tillage-induced CO_2 loss across an eroded landscape, to compare MP and CP effects on CO_2 loss and to relate tillage-induced CO_2 loss to variation in soil physical and chemical properties across the landscape.

2. Materials and methods

The tillage-induced CO_2 loss study was conducted in August 2000 on the Don Skogstad farm located in west central Minnesota, USA (latitude 45°N, 41″ and longitude 95°W, 45″). Previous crops grown on the area were corn, soybean, wheat and alfalfa in various rotations over the previous 30 years. Historical tillage was the MP, disk harrow with an occasional spring CP or field cultivator generally in an east–west direction. Lindstrom et al. (2000b) described the experimental site in detail. The entire 4 ha field was sampled on a 10 m × 10 m grid spacing for various soil physical and chemical parameters. Soil profile descriptions were made across the field where past erosion was evident. The topographic elevation was recorded using global positioning system (GPS) to describe surface topography of the field. Data for the tillage-induced CO_2 loss study was collected at corresponding 10 m intervals along a north–south (N–S) and a west–east (W–E) transect across the eroded landscape. The previous crop grown in the experimental area was spring wheat (*Triticum aestivum* L. cv. Marshall) harvested on 1 August 2000. The area was sprayed with contact herbicide for weed and volunteer wheat control at a rate of 0.8 kg ha^{-1} of active ingredient.

The area was mapped and sampled on 10 m grid spacing according to Lindstrom et al. (2000b). For this analysis, only selected soil profile descriptions identified on the N–S transect (150 m long) and the W–E transect (180 m long) will be described. Surface soil C samples were collected based on defined genetic horizons and ranged from 18–28 cm in thickness for the surface layer along both transects. Total soil C was determined by dry combustion (Nelson and Sommers, 1982). Additional measurements taken from the tilled layer included inorganic C (Wagner et al., 1998), pH using a 1:1 water solution (McLean, 1982) and soil test phosphorous using the Olson method (Olson and Sommers, 1982). Inorganic C is reported as calcium carbonate equivalent, while organic C was determined by the difference between total and inorganic C.

The soil classification for the study site included various amounts of five different soil types (Barnes, Buse, Darnen, Langhei and Svea). The detailed soil taxonomic classification is as follows: Barnes, fine, loamy mixed superactive, frigid Calcic Hapludolls; Buse, fine, loamy mixed superactive, frigid Typic Calciudolls; Darnen, fine, loamy mixed superactive, frigid Cumulic Hapludolls; Langhei, fine, loamy mixed superactive, frigid Typic Eutrutepts; Svea, fine, loamy, mixed, superactive, frigid Pachic Hapludolls. Further soil classification details and the other data can be found in Lindstrom et al. (2000b). The tillage erosion prediction model (TEP) (Lindstrom et al., 2000a) was used to calculate soil translocation rates at each of the sites along both transects. The trends observed from calculated erosion values were then compared to those of soil CO_2 loss as a result of tillage.

Tillage included the conventional CP (15 cm deep) to a 3 m = wide tilled strip. The MP (25 cm deep) treatment was applied to give a total width of 2.74 m (each of six-bottoms were 45 cm wide). Both tillage implements were pulled by a medium-sized farm tractor at ~7 km h^{-1}.

Details of the chamber used to measure the CO_2 flux from the soil surface are described by Reicosky (1990), Reicosky et al. (1990), Reicosky and Lindstrom (1993) with further modification and improvements described by Wagner and Reicosky (1996) and Wagner et al. (1997). Briefly, the chamber (volume of 3.25 m^3 covering a horizontal land area of 2.71 m^2) with mixing fans running, was moved over the tilled surface until the chamber reference points aligned with plot reference stakes, lowered and collected data rapidly at 1 s intervals for a period of 60 s to determine the rate of CO_2 and water vapor increase. The chamber was then raised, calculations completed and the results stored on a computer diskette. Data included, time, plot identification, solar radiation, photosynthetically active radiation, air temperature, wet-bulb temperature, and the output of the infrared gas analyzer measuring CO_2 and water (H_2O) vapor concentration. After the appropriate lag times, data for a 30 s calculation window was selected to convert the volume concentration of H_2O vapor and CO_2 to a mass basis then regressed as a function of time as described by Reicosky et al. (1990) and with refinements of Wagner et al. (1996). The parameters from these regression lines, which reflect the rate of CO_2 and H_2O vapor increase within the chamber, were used to calculate the fluxes expressed on a unit horizontal land area basis. These measurements are presented on a land-area basis and differentiated from an exposed soil surface area basis caused by the difference in surface roughness.

The cumulative amount of CO_2 evolved after the tillage event was calculated using a simple, numerical integration technique (trapezoid rule). This method assumes linear interpolation between the measured fluxes over the time interval of interest. The areas for successive time intervals were summed to give the total amount of CO_2 evolved. The cumulative CO_2 loss following each tillage method was adjusted for a 24 h period based on the last measurement yielding a common time interval for all measurements within each transect. The 24 h values may be subject to error due to the long time between the last two measurements. However, they represent the first approximation for accumulative loss. The cumulative H_2O loss was calculated similarly except that an assumed nighttime flux of 0.05 mm h^{-1} was fixed at sunrise and sunset to more accurately reflect diurnal potential evaporative demand. The relative comparisons should be sufficiently accurate to reflect the general effect of tillage methods on daytime H_2O loss.

Two perpendicular tillage transects were selected to cover the center of the experimental area to represent the largest variation in soil physical properties as a result of tillage erosion. The N–S transect was selected and pre-marked within one meter of the original sampling sites characterized by Lindstrom et al. (2000b). As a result, the chamber measurement area was centered within <2 m of the sample site to correlate with the soil properties. Prior to the initial tillage measurements, a no-till flux was determined with the portable chamber. The no-till measurement sites represent the undisturbed soil with crop residues left on the soil surface that were exactly the same location as those selected for the gas exchange measurements after tillage. The no-till designation was used to describe only ‘‘no recent soil disturbance’’ prior to tillage and does not infer a long-term tillage system. The previous wheat crop was established using conventional tillage and planting equipment.

The N–S transect was CP on 8 August and MP on 9 August. The W–E transect was CP on 14 August and MP on 15 August. Water content measurements were taken just prior to the tillage on the day of CP treatment measurements and were assumed to be similar for MP treatment 1 day later. One pass with CP was applied on the east side while one pass with MP was applied on the west side of the N–S transect. The north end of this transect served as the reference point. A similar transect was set up from W–E with the west end as the reference point and CP passed on the north side and MP on the south side. This enabled the chamber measurements to be directly related to the soil physical and chemical properties that were determined at the point of measurement. All measurement areas were geo-referenced, pre-marked and labeled prior to tillage.

In anticipation of the rapid decline in the initial CO_2 flux as a function of time after tillage, four consecutive measurements were made with the portable chamber starting at 30–40 s after the pre-marked area was tilled on 8 August as follows: the tractor pulled the CP through the designated experimental site to a pre-determined reference point, then stopped and waited while the chamber was quickly moved over the site for four successive measurements which were averaged for one data point at that location. Upon completion of the four measurements, the CP was then pulled through the next experimental site to the next pre-marked location and the chamber moved in over the pre-marked area to repeat another series of four measurements that were averaged for the next data point on the transect. This sequence was repeated along the transect with the CP until all the pre-marked sites had been measured. The measurement cycle at all locations along the transect was repeated with four successive measurements starting on the first site that was measured that day and continued for about 6 h after the initial tillage event yielding four complete measurement cycles after tillage and at 24 h after tillage on the following day. On 9 August, the 24 h values for CP were obtained and the same process was repeated on the west side of the N–S transect with MP with 24–h values determined the following day. The same procedure was used on the W–E transect on 14 and 15 August.

The dynamic nature of tillage-induced gas exchange, with the rapid decline immediately after tillage, measured with only one instrument provides some technical challenges for statistical replication. To give some idea of the experimental error involved in measuring gas exchange with the portable chamber, we selected the average of those four measurements described above and the standard deviation. The magnitude of the standard deviation was related to the magnitude of CO_2 flux that depended on the method of tillage. The standard deviation was generally larger on MP than on CP related to the larger fluxes. The maximum MP standard deviation immediately after tillage on 8 August was 5.35 (mean flux of 22.11 g CO_2 m^{-2} h^{-1}) and the minimum was 1.74 (mean flux of 8.61 g CO_2 m^{-2} h^{-1}) on the N–S transect. The corresponding values 24 h after tillage were 0.614 (mean flux of 5.48 g CO_2 m^{-2} h^{-1}) and 0.073 (mean flux of 2.74 g CO_2 m^{-2} h^{-1}), respectively. The rapid decline in initial flux showed large standard deviations immediately after tillage that decreased as a magnitude of the flux decreased out to 24 h after tillage. The maximum CP standard deviation immediately after tillage was 1.20 (mean flux of 5.47 g CO_2 m^{-2} h^{-1}) and the minimum was 0.623 (mean flux of 8.06 g CO_2 m^{-2} h^{-1}) on the N–S transect. The corresponding values 24 h after tillage were 0.540 (mean flux of 1.71 g CO_2 m^{-2} h^{-1}) and 0.020 (mean flux of 0.74 g CO_2 m^{-2} h^{-1}), respectively. The magnitudes of the standard deviations for the CP reflect shallower tillage and less absolute change 24 h after tillage. These treatment comparisons need to be interpreted with caution due to the spatial variability in soil properties along to transect; however, they do provide some estimate of experimental error with these measurements. Similar standard deviations and trends were noted on the W–E transect for both MP and CP treatments (data not shown).

3. Results and discussion

The weather data for the days of measurement of tillage-induced CO_2 loss are summarized in Table 1. The weather data was collected at a site approximately 4 km from the field site to indicate the general temperature and solar radiation patterns for the area. Weather measurements one day before and one day after the actual field measurements showed that the air temperature was in the normal range for that time of year. The last day of significant rainfall (38 mm) was 14 days before the first set of measurements with no measurable rain between the two sampling periods.

Table 1
Summary of weather data from the USDA-ARS Swan Lake Research Farm weather station 4 km from the experimental site around the two tillage events

Date-2000	DY	Air temperature (°C)		10 cm Bare soil temperature (°C)		Daily radiation (kW m^{-2})	Daily wind (km)
		Min	Max	Min	Max		
7 Aug.	220	14.0	28.9	22.0	30.4	7.075	89.5
8 Aug.	221	16.6	27.6	24.2	28.9	5.532	169.4
9 Aug.	222	14.5	28.5	22.4	29.8	7.409	164.0
10 Aug.	223	14.4	30.0	23.1	30.2	6.799	144.5
13 Aug.	226	14.8	27.4	22.2	29.7	7.065	140.8
14 Aug.	227	17.6	31.9	23.6	29.8	6.135	310.4
15 Aug.	228	11.4	22.8	23.1	28.0	6.969	229.8
16 Aug.	229	9.7	21.0	19.0	25.0	2.508	258.1

Last significant rain before tillage was 38.4 mm on 25 July, 2000 (DY 207).

The daily minimum air temperature was as low as 9.7 °C and daily maximum as high as 31.9 °C, typical for the area. Daily radiation and wind run were also typical. The results suggest normal field conditions with a relatively dry soil based on the last rainfall and warm weather.

The gravimetric water content and elevation (as a function of position) for both days of the measurements are summarized in Fig. 1a and b. With the exception of one unexplained outlier, the gravimetric water content ranged between 10 and 15 g kg^{-1} soil. The elevation difference was as large as 9.5 m on the N–S transect and 4.9 m on the W–E transect. There was substantial variation in water content along both transects. The results showed an expected trend based on the position in the landscape and C content. Two points at 20 and 30 m from the west end of the W–E transect were only slightly lower than the water content at 110 m from the west end of the same transect. These low values reflect the severely eroded knolls where low water content resulted from soil water evaporation due to less residue cover and low C content.

An example of the CO_2 flux as a function of time after tillage is presented in Fig. 2. This example was taken from the N–S transect and represents the highest, median and lowest cumulative CO_2 fluxes. The results show a very low flux prior to tillage (no tillage) for both MP and CP treatments. The maximum CO_2 flux for MP immediately after tillage was 23 g CO_2 m^{-2} h^{-1} and rapidly declined to about 7 g CO_2 m^{-2} h^{-1} 24 h after the tillage event. The largest value for CP was about 7 g CO_2 m^{-2} h^{-1} and rapidly declined to about 2 g CO_2 m^{-2} h^{-1} 24 h after tillage. The data from both CP and MP treatments showed a rapid decline immediately after tillage, but even after 24 h, MP plow had a substantially higher flux than CP. Similar temporal trends and slightly smaller

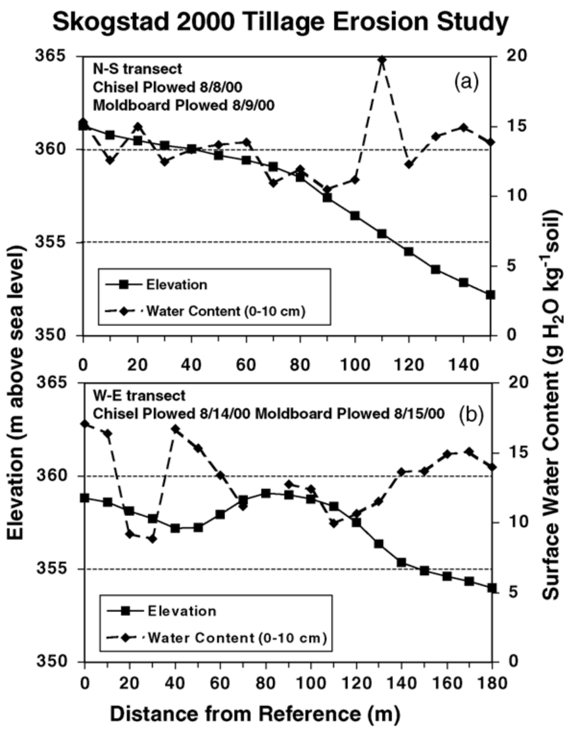

Fig. 1. Gravimetric water content and elevation along the N–S and W–E transects.

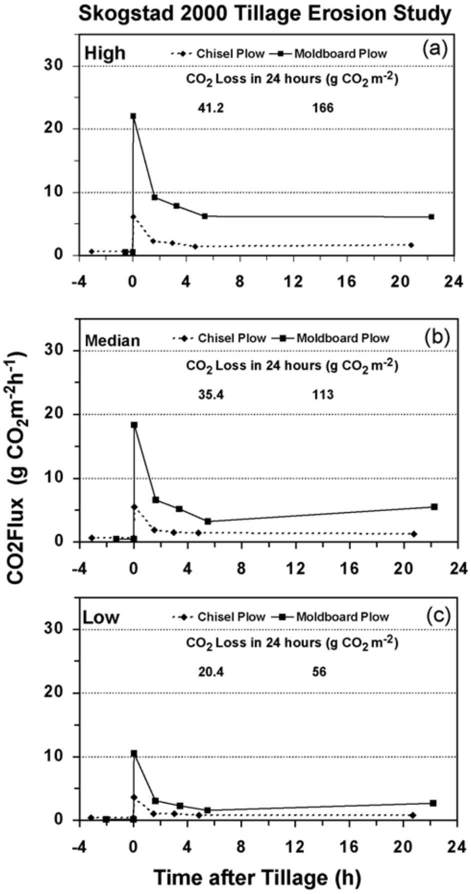

Fig. 2. Soil CO_2 flux as a function of time after MP and CP tillage at the highest, median and lowest cumulative fluxes along the N–S transect.

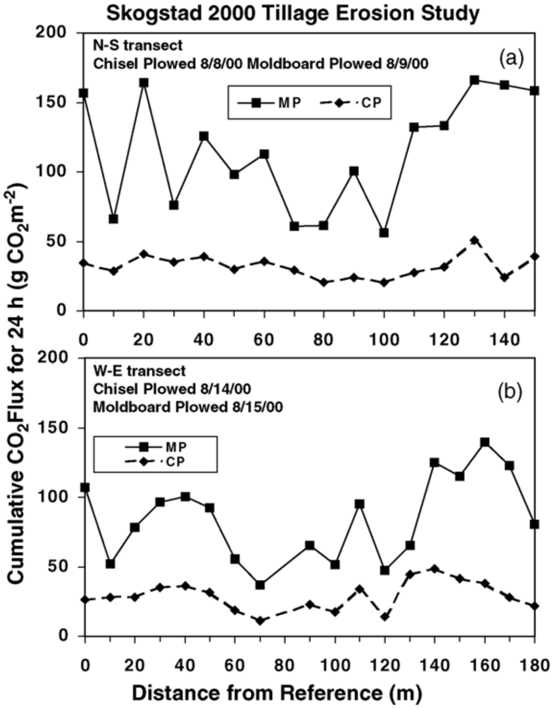

Fig. 3. The cumulative CO_2 flux for 24 h vs. distance along the N–S and W–E transects for both MP and CP.

magnitudes were observed on the W–E transect (data not shown). The spatial variation of MP data agree with earlier results (Reicosky, 1995). The relationship between the MP and the CP was consistent at all locations on both transects.

The cumulative CO_2 loss for a 24–h period after tillage calculated by measuring the area under the corresponding curves in Fig. 2 showed significant variation along both transects. The cumulative CO_2 losses for 24 h for the N–S transect are summarized in Fig. 3a. The variation along the N–S transect in CO_2 loss was large with MP consistently higher than CP. The highest MP loss was 166 g CO_2 m^{-2}, whereas, the lowest MP loss was 56 g CO_2 m^{-2}. The median value at 60 m from the reference end was 113 g CO_2 m^{-2}. For the W–E transect summarized in Fig. 3b, the minimum and maximum cumulative flux for MP was 37 g CO_2 m^{-2} and 140 g CO_2 m^{-2}, respectively. For CP treatment, the maximum CO_2 loss for 24 h was 51 g CO_2 m^{-2} and the minimum loss was 20 g CO_2 m^{-2}. For CP treatment on the W–E transect, the maximum CO_2 loss for 24 h was 48 g CO_2 m^{-2} and the minimum loss was 11 g CO_2 m^{-2}. The results show reasonable agreement with earlier work by Reicosky (1995) and consistent and substantial differences between CP and MP apparently related to the depth of tillage and the degree of soil fracturing and mixing.

The corresponding relationships in the cumulative H_2O loss for 24 h as a function of position in the N–S and W–E transects is summarized in Fig. 4a and b. The H_2O loss results showed variation along both transects with losses consistently higher from MP than CP in H_2O loss. The maximum and minimum 24–h cumulative H_2O loss from MP on the N–S transect were 8.3 mm and 6.1 mm, respectively. Corresponding 24–h maximum and minimum values from CP

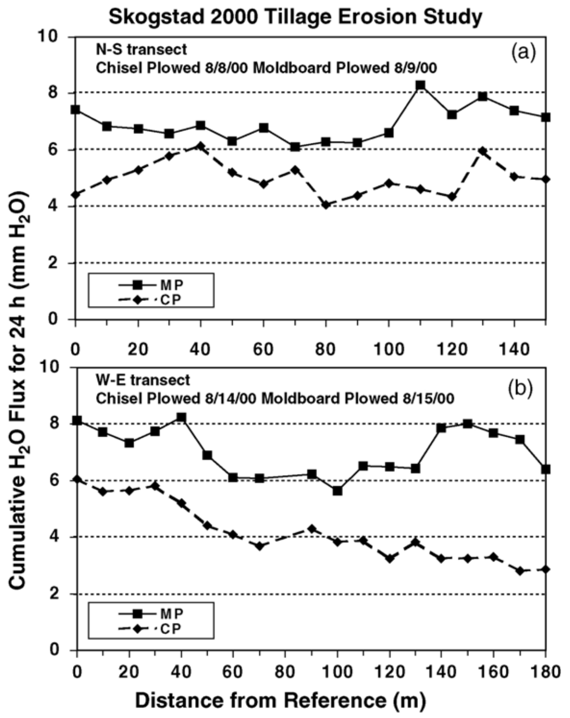

Fig. 4. The cumulative H_2O flux for 24 h vs. distance along the N–S and W–E transects for both MP and CP.

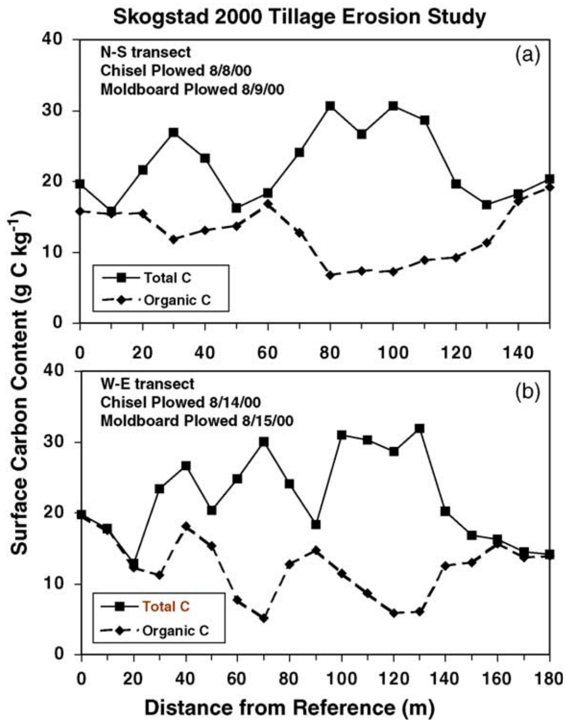

Fig. 5. Surface C contents along the N–S and W–E transects showing the total C and organic C contents.

were 6.1 mm and 4.1 mm, respectively. Similar cumulative minimum and maximum values on the W–E transect were 5.6 mm and 8.2 mm for MP and 2.9 mm and 6.0 mm for CP. There appeared to be a general relationship between MP and CP tillage-induced CO_2 loss across both transects. There were significant differences at places where MP lost more CO_2 than CP, but they were not reflected in the spatial variation of H_2O loss along the transect. The CP was always done one day ahead of MP and should reflect a slightly higher water content than the MP treatment. Tillage method resulted in substantial differences in cumulative H_2O loss, at least for the short-term.

The C content as a function of position along the transects are summarized in Fig. 5a and b. The total C content includes the sum of the organic and inorganic C content as measured from the surface layer. The maximum and minimum total C content on the N–S transect was 30.7 and 15.8 g C kg^{-1} soil, respectively. Both organic and inorganic C varied along the transect which was partly due to tillage translocation. The maximum and minimum organic C content was 19.2 and 6.7 g C kg^{-1} soil. Low organic C values were observed on the eroded knoll and reflect the light soil color as a result of substantial tillage erosion and some water erosion. Lindstrom et al. (2000a) have calculated that as much as 46 cm of soil was moved from this location by tillage.

There was no correlation between the total C and organic C shown in Fig. 5a. The difference between total and organic C reflects the amount of inorganic C. These results need to be interpreted with caution because the depth of the soil sampled in each location may be slightly different and was defined by the depth of the surface horizon at the time of sampling.

The surface C content for the W–E transect summarized in Fig. 5b shows wide variation in the C content in the surface layer. Both the organic and total C showed little relationship to each other as might be expected based on the amount of tillage erosion that had taken place. The maximum total C content at position 130 m from the west reference was 31.9 g C kg^{-1} soil. The minimum total C was 12.9 g C kg^{-1} soil at 20 m from the reference. The organic C content ranged from a maximum of 19.6 g C kg^{-1} soil at the reference point to a minimum of 5.1 g C kg^{-1} soil at 70 m from the reference point. These large variations are reflected in soil color and tillage-induced CO_2 loss. Noteworthy was the lack of correlation between the total C and the organic C where the difference reflects the amount of inorganic C. These glacial till soils typically contain large amounts of free calcium carbonate ($CaCO_3$) in the subsoil that shows up at the surface due to erosion. The tillage mixing and tillage erosion combined with water erosion during the previous 50–100 years suggest dramatic changes taking place resulting in soil degradation that affects soil properties and crop yields.

Relationships between tillage-induced CO_2 loss and forms of surface C measured at each point were investigated. The regression results of tillage-induced CO_2 loss from MP and CP tillage versus soil organic C for both transects are summarized in Fig. 6a and b. It is reasonable to assume that most of CO_2 came from biological oxidation of various sources of organic C.

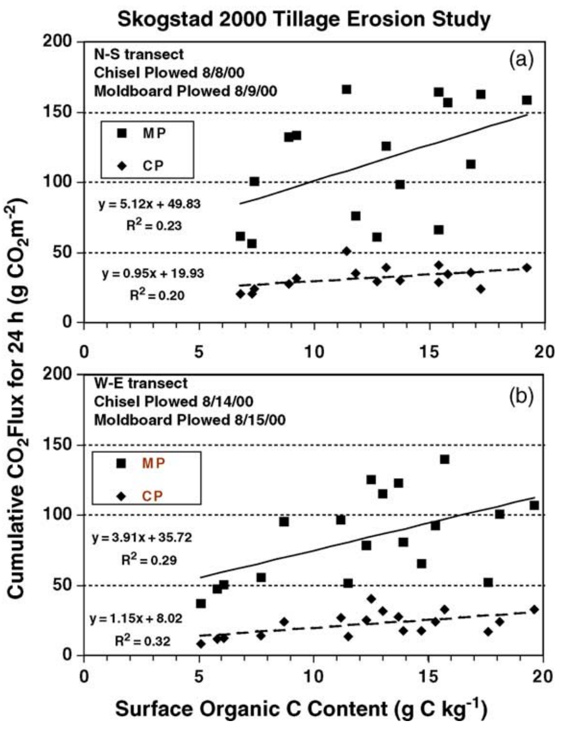

Fig. 6. Regression of 24 h cumulative CO_2 loss from MP and CP vs. organic C content along the N–S and W–E transects.

Regression of cumulative tillage-induced CO_2 loss versus total C showed a negative slope as a result of a larger portion of the total C being inorganic. Fig. 6 shows considerable scatter in the data with low correlation coefficients for both MP and CP tillage on both transects which were not significant at the 95% confidence level. The standard error of regression for the MP treatment was 32.7 on N–S and 26.8 on the W–E transects, respectively. The standard error of regression for the CP treatment was noticeably less at 7.55 on N–S and 7.50 on the W–E transects, respectively. The low correlation coefficients and large standard errors of regression preclude significant conclusions on this limited data set. While there is considerable scatter, the data shows a tendency for tillage-induced CO_2 loss to increase with increasing organic C content.

The tillage erosion prediction (TEP) model was used to calculate 30-year MP soil translocation rates (Lindstrom et al., 2000a,b). Both the N–S and W–E transects showed similar relations between the cumulative CO_2 loss and predicted tillage erosion. Without other justification, a simple linear relationship was envisioned. The linear regression relationships of the cumulative tillage-induced CO_2 loss versus soil translocation rates from MP tillage for both transects are summarized in Fig. 7a and b. The graphs show substantial variation with low correlation coefficients on both transects for the 24 h cumulative loss that were not significant at the 95% level of confidence. The standard error of regression for the MP treatment was 27.4 on N–S and 29.3 on the W–E transects, respectively. The higher slope from regression analysis on the N–S transect may have been related to the historical tillage direction, but remains uncertain in view of the large variation. The predicted tillage erosion (soil loss is negative in t soil ha^{-1} $year^{-1}$) showed areas of soil deposition associated with high CO_2 loss that gradually declined to low CO_2 loss where tillage erosion was the largest (most negative). The largest tillage erosion appeared at the lower CO_2 losses. The smallest tillage erosion (most deposition) was associated with the highest CO_2 loss. The data show an inverse relationship between the CO_2 loss and the predicted tillage erosion. The results suggest that past tillage erosion caused a significant amount of soil translocation and C loss that presently results in relatively small C loss.

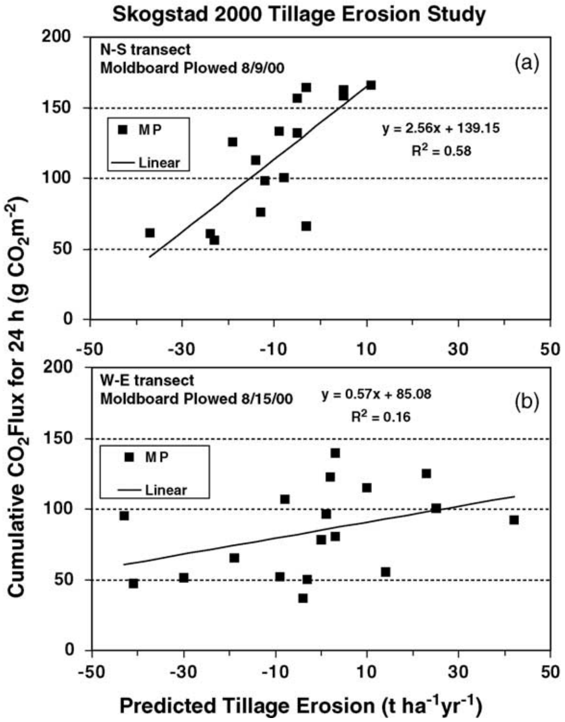

Fig. 7. Regression of 24 h cumulative CO_2 loss from MP vs. predicted tillage erosion along the N–S and W–E transects.

Soil erosion has a major impact on C dynamics that can act to increase or decrease soil organic C loss. A large portion of the soil organic C content is concentrated near the soil surface; therefore, it is highly vulnerable to oxidation processes associated with tillage and sediment transport associative with soil erosion. Carbon loss from the landscape can be in the form of CO_2, as described in this work or as C removed from the landscape in water and soil sediments through water erosion. In the context of C dynamics, it is the amount of soil displaced by erosion and its C contents that are most important. Lal (1995) estimates that of the soil erosion from terrestrial ecosystems, only 10% of the sediments are transported to the oceans each year. He further estimated 20% of the C dislocated by erosion may be released eventually into the atmosphere (1.14×10^{15} g). The sediment load carried in runoff contains detached sediments and C that when re-deposited through siltation on the landscape can serve to deepen the deposit and enhances storage of soil C. The deep placement of the C minimizes impacts of tillage tools. Ecological and environmental effects of erosion cause changes in soil C that warrant serious efforts to reduce soil erosion risks and related soil degradation. While soil erosion may accentuate current C emissions, sedimentation and downslope deposition may lead to burial of C into the developing profile where it may be sequestered over a longer time periods, hi this work, the tillage-induced CO_2 was generally largest where the surface organic C content was the highest and in locations with the most soil deposition. The C emissions reduction potential can be obtained through improved soil and crop management practices that lead to reduced to tillage intensity and subsequently less soil erosion.

The relationship between soil productivity and erosion is complex. Tillage erosion has all the same degrading attributes of water and wind erosion, but few understand the root cause of degraded soil quality and C loss, intensive tillage. While there are other reasons for intensive tillage, tillage sets up the soil to be loose, open and very susceptible to high intensity rainfall and subsequent erosion. Continued intensive tillage only perpetuates the soil degradation processes associated with tillage erosion. Schumacher et al. (1999) used modeling procedures to show that tillage erosion caused soil loss from the shoulder position while soil loss from water erosion occurred primarily in the mid to lower backslope position. The decline in overall soil productivity was greater when both processes were combined compared to either process acting alone. Water erosion contributed to nearly all the decline in soil productivity in the backslope position when both tillage and water erosion processes were combined. The net effect of soil translocation from the combined effects of tillage and water erosion was an increase in spatial variability of crop yield and a likely decline in over all soil productivity (Schumacher et al., 1999).

Tillage erosion and tillage-induced C loss caused by the MP can result in a major degradation process in intensively cultivated, sloping lands. By tilling the soil at shallower depths, tillage erosion and C loss can be significantly reduced. While the relative contribution of tillage erosion and water erosion needs to be further developed and understood, results suggest that the combination can result in soil variability that enhances yield variability across an eroded landscape depleted of soil C. The direction of historic tillage in this field was generally in an E–W direction and resulted in substantial translocation of the soil that affected the distribution of soil properties and grain yield (Schumacher et al., 1999; Schumacher et al., unpublished). This spatial variation along with the temporal variation based on weather-related factors presents a very complex picture of the spatial variation in sloping fields and their ultimate effect on yield and climate change. Additional work is required to provide a clearer picture on the relative contribution of tillage to soil degradation from erosion and C loss. Both contributed to significant degradation that created a large amount of soil variability across the landscape.

4. Conclusion

In summary, these results demonstrate a large loss of CO_2 immediately following MP that was substantially greater than that from CP along the same transects across this eroded landscape. The short-term rate CO_2 loss was partially dependent upon soil position within the landscape. The ability to characterize the spatial variability can be critical in field studies where the soil properties under investigation are not uniformly distributed. The large spatial variation and low correlation coefficients and large standard errors of regression preclude significant conclusions on this limited data set. In this work, past tillage erosion was a significant contributor to the spatial variation and soil degradation on the eroded knolls; however, the relation of tillage-induced CO_2 losses and surface soil organic C were not significant. The temporal variation and the factors that control associated processes are complex and difficult to quantify. Quantifying positional trends for spatially distributed parameters will require further work to provide policy makers with the quantitative data for environmental quality decisions.

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