THE EFFECT OF CULTIVATION ON SEDIMENT COMPOSITION AND DEPOSITION IN PRAIRIE POTHOLE WETLANDS

DAN B. MARTIN and WILLIAM A. HARTMAN

U.S. Fish and Wildlife Service, National Fisheries Contaminant Research Center, Field Research Station, Rural Route 1, Box 295, Yankton, SD 57078, U.S.A.

(Received April 14, 1986; revised October 16, 1986)

Abstract. Texture, major nutrient content, and deposition rate of sediments were compared for five prairie pothole wetlands surrounded by native grassland and seven otherwise similar wetlands surrounded by row crop and small grain farmland. Specific differences in the nature of the sedimentation cycle of cultivated and noncultivated watersheds were indicated. Flux of total inorganic material into sediments averaged 80 and 43 mg cm^{-2} yr^{-1} in cultivated and grassland wetlands, respectively. Cultivated sediments contained significantly higher clay percentages, but lower percentages of silt and sand than grassland sediments. Deposition rates of clay at cultivated sites averaged five times that of grassland locations. Enrichment ratios (the quotient of sediment concentration divided by upland soil concentrations) suggested that sand was selectively retained in equal proportions on uplands in both types of watersheds, that silt was selectively removed (although in different proportions) from uplands in both types of watersheds, and that clay was selectively retained only on grasslands. Total N and organic matter concentrations were significantly higher in both the soils and sediments of grassland watersheds, but there were no differences in total P concentrations with respect to land use. Sediment flux rates for total N and organic matter were similar in the two land use types; however, P was transported at nearly twice the rate to cultivated wetlands. Enrichment ratios indicated that N and P were selectively removed in similar proportions from upland soils in both types of watersheds.

1. Introduction

Prairie potholes are small, shallow, water-holding depressions of glacial origin (Sloan, 1972) that occur throughout 777 000 km^2 of prairie in the north central United States and south central Canada (Figure 1). Collectively, these potholes provide some of the most valuable wetland habitat for waterfowl in North America, producing about 50% of the continental duck crop in an average year, and more in bumper years (Smith *et al.*, 1964). Potholes are used extensively by other wildlife for water and habitat, and are important to man for flood control and groundwater recharge. In recent decades, numerous potholes have been eliminated by drainage for agricultural purposes. Conservation of the remaining habitat is essential if the benefits of pothole wetlands are to be sustained.

Potholes are typically interspersed within a rolling topography as a series of closed or poorly drained basins. Agriculture is the predominant land use throughout the prairie pothole region, and erosion of farmland by wind and water often results in the deposition of field soil directly into wetlands. The impacts of sediment on wetlands can be twofold: First, sediment can modify, reduce, and eventually eliminate wetland habitat through the filling of the pothole basin; and second, sediment may serve as a mechanism for the

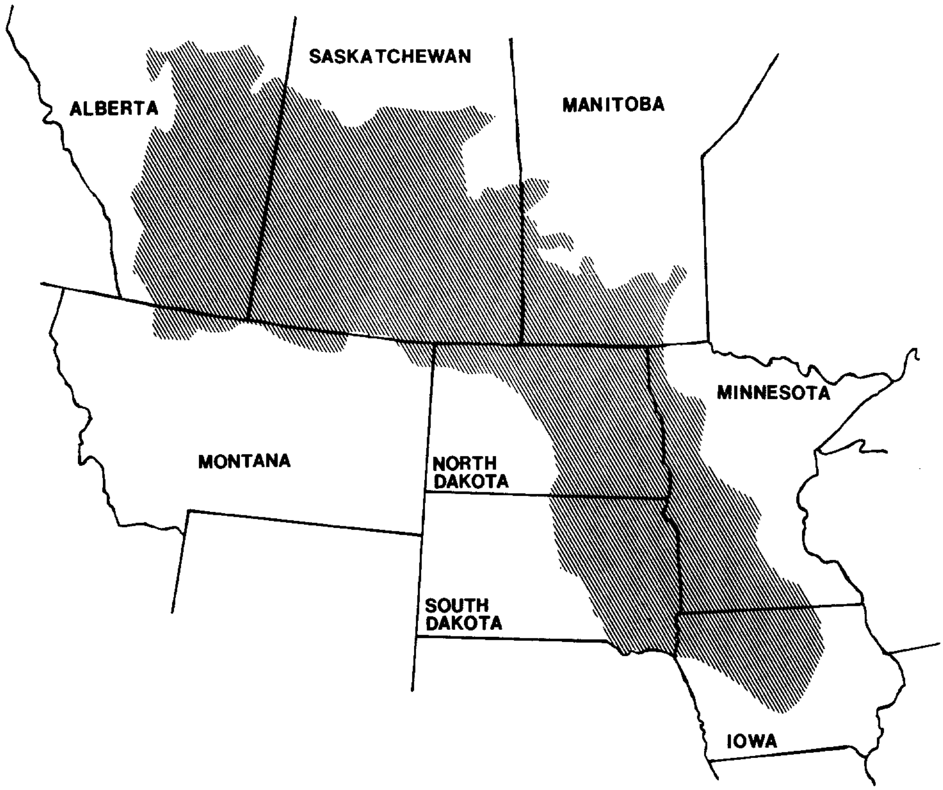

Fig. 1. Prairie pothole region of Canada and the United States.

transport of nutrients, pesticides, or other contaminants from the watershed to the wetland.

Our study compares the deposition rates and properties of sediment between potholes located in cultivated and non-cultivated watersheds to determine the basic impact of agricultural land use practices. This information should better enable resource managers to identify problem areas, understand biological effects of increased sediment yield, and evaluate feasibility and effectiveness of various measures to reduce adverse impacts.

2. Study Areas

Twelve pothole wetlands located in seven eastern South Dakota counties (Brookings, Clay, Day, Grant, Kingsbury, Lake, and Roberts) were selected for study. Five of the wetlands were located in watersheds that have never been cultivated and were thus surrounded by native grassland vegetation. The remaining seven wetlands were located in watersheds that were used for the production of corn, soybeans, oats, wheat, sunflowers, and alfalfa hay. Wetlands at all 12 study sites had similar surface areas (4 to 10 ha), maximum depths (<2 m), and vegetative composition. Each wetland would be classified as Type 4 (inland, deep, fresh marshes) in the system of Martin *et al.* (1953), or as Class IV (semipermanent ponds and lakes) in the system of Stewart and Kantrud (1971). The contributing watersheds were fairly uniform in size, ranging from about 20 to 80 ha. The maximum slope in each watershed varied from 17 to 38% at the grassland sites and from 4 to 14% at the cultivated sites. The soil-erodibility index (K) and the rainfall-erosion index (R) as defined by Wischmeier and Smith (1965) were similar for all 12 watersheds, ranging from 0.28 to 0.32 and from 100 to 125, respectively. The potholes are located in topographically high areas of stagnation or end moraine and probably formed as a result of stagnating and melting glacial ice following one of the several advances of Late Pleistocene (Wisconsin) glaciation. None of the potholes are part of an integrated drainage system, i.e., each is a closed basin, lacking a distinct inflow and outflow.

3. Methods

Soil and sediment samples were collected in January and February 1983. Soil profiles were collected with a 5-cm bucket auger from the highest point within each watershed at 10-cm increments to a depth of 20 cm in grassland and 30 cm in cultivated watersheds. Sediment profiles were collected with a 5-cm core sampler from the lowest point within each watershed (near the center of each wetland basin) at 10-cm increments to a depth well below that of ^{137}Cs incorporation. Ten replicate samples of soil and sediment at each location were frozen in the field, later sectioned in the laboratory, and then composited by 10-cm increments for analysis.

Samples were dried at 100 °C for 72 hr, ground with a mortar and pestle, and sieved through a 2-mm mesh screen. Organic matter content was determined colorimetrically following wet oxidation with potassium dichromate and H_2SO_4 (Carson and Gelderman, 1980). Soil separates (clay <0.002 mm, silt 0.002 to 0.062 mm, sand >0.062 mm) were determined by the pipette method (Guy, 1969). Total N and total P were determined by persulfate digestion (Raveh and Avnimelech, 1979; Ebina *et al.*, 1983). ^{137}Cs activity was determined at the U.S. Department of Agriculture, Water Quality and Sedimentation Laboratory, Durant, Oklahoma, by the methods of Ritchie and McHenry (1973).

Measurements of dry density (Buckman and Brady, 1960) were made on 14 sediment samples, these samples ranged from 1 to 25% organic matter, 4 to 57% clay, 28 to 78% silt, and 1 to 36% sand. A step-wise multiple regression analysis was used to derive the best equation for the data set, using density as the dependent variable and the other four sediment properties as independent variables. The resulting equation was:

$$p = -0.014\,(\mathrm{OM}) + 0.004\,(\mathrm{Clay}) - 0.011\,(\mathrm{Silt}) + 1.766\,,$$

where p is density in g cm^{-3}, and organic matter (OM), clay, and silt are expressed as percent of dry weight. This equation ($R^2 = 0.96$) was used to calculate dry density values for the remaining sediment samples.

The rate of accumulation (sedimentary flux) of any material (F in μg cm^{-2} yr^{-1}) can be calculated from the equation (Hamilton-Taylor, 1979):

$$F = R(1 - \phi)pC,$$

where R is the sedimentation rate (cm yr^{-1}), ϕ is the porosity, p is the dry density of the sediment (g cm^{-3}), and C is the dry weight concentration of the material (μg g^{-1}). Estimates of material flux were made for each pothole by using the appropriate data from this study. Porosity, which was not measured, was assumed to be constant at 0.865 (see Hamilton-Taylor, 1979).

Statistical methods (t-tests and correlation/regression) were taken from Steel and Torrie (1960) or LeClerg *et al.* (1962); all cases where $p \leq 0.05$ were considered significant. Textural classification and terminology for soils are from Buckman and Brady (1960). Enrichment ratios for each watershed were calculated by dividing the average dry weight concentration of a constituent in the sediment by the corresponding average value in the soil.

4. Results

Upland soils in the five grassland watersheds were all texturally classified as loams, whereas cultivated soils were more variable, consisting of loams, clay loams, and silt loams. Soils in grassland watersheds contained significantly more sand and significantly less clay and silt than soils in cultivated watersheds (Table I).

Mean total N and organic matter were significantly higher in grassland soils than in cultivated soils (Table I). The correlation between total N and organic matter was significant in cultivated soils (r = 0.96), but was not significant in grassland soils. Mean total P concentrations were not significantly different between grassland and cultivated soils and were not correlated with organic matter or total nitrogen in soils from either land use category.

Wetland sediments in all grassland watersheds were classified as silt loams, whereas sediments from cultivated watersheds were either silt loams or silty clay loams. Sediments in grassland watersheds were significantly higher in sand and silt, and lower in clay, than those in cultivated watersheds (Table I).

Mean total N and organic matter concentrations were significantly higher in sediments from grassland watersheds (Table I). Correlations between organic matter and total N were significant in both grassland (r = 0.95) and cultivated (r = 0.87) sediments. Concentrations of total P were not significantly different in sediments from the two land use categories, however, total P was significantly correlated with organic matter (r = 0.82) and total N (r = 0.74) in sediments from cultivated watersheds, whereas it was not correlated with either variable in grassland sediments.

^{137}Cs fallout measured at Vermillion, South Dakota, from 1957–1976 by the U.S. Atomic Energy Commission (1977), and continued in later years, yielded an estimate of total deposition since 1954 (the first year of significant worldwide fallout), corrected for decay, of 97 nCi m^{-2} by 1982. Mean concentrations of ^{137}Cs in grassland and cultivated soils were 98 nCi m^{-2} and 78 nCi m^{-2}, respectively, indicating no significant

TABLE I

Composition of upland soils and wetland sediments in cultivated and uncultivated watersheds[a]

Constituent	Upland soils				Wetland sediments			
	Uncultivated		Cultivated		Uncultivated		Cultivated	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Clay	20**	12–27	28	22–31	10**	4–16	30	23–40
Silt	40*	35–45	46	38–59	75**	69–76	60	47–67
Sand	40**	33–53	28	15–31	18*	10–22	15	3–16
Total N	0.18**	0.11–0.25	0.11	0.08–0.20	0.34**	0.25–0.48	0.22	0.17–0.34
Total P	0.05	0.034–0.056	0.05	0.038–0.060	0.069	0.046–0.092	0.072	0.053–0.096
Organic matter	6.3*	5.1–7.6	3.9	2.8–6.8	19.0**	13.8–24.2	9.0	5.8–12.4

[a] Asterisks opposite means for uncultivated values indicate a significant (*; $P \leq 0.05$) or highly significant (**; $P \leq 0.01$) difference from comparable means for cultivated values in the same row and corresponding column (upland soils and wetland sediments were treated separately).

TABLE II

^{137}Cs in upland soils and wetland sediments in cultivated and uncultivated watersheds

Constituent	^{137}Cs activity ($nCi\ m^{-2}$)			
	Uncultivated		Cultivated	
	Mean	Range	Mean	Range
Soil	98	61–133	78	33–114
Sediment	249	163–302	209	79–428
Enrichment ratio		2.5		2.1

difference between the two land use categories. The same was true for sediments, which had mean concentrations of 249 and 209 $nCi\ m^{-2}$ for grassland and cultivated watersheds, respectively (Table II).

Profiles of ^{137}Cs activity in wetland sediments indicated that recent vertical accretion rates (since 1954) ranged from 0.4 to 0.5 cm yr^{-1} in grassland watersheds and from 0.4 to 0.6 cm yr^{-1} at cultivated sites. Dry densities of wetland sediment in cultivated watersheds (range 0.969 to 1.316 g cm^{-3}) were significantly higher than those from grassland watersheds (range 0.631 to 0.829 g cm^{-3}) due to the lower organic matter and silt, and the higher clay content of sediment from the cultivated areas.

The flux of inorganic sediment in wetlands surrounded by cultivated land was about twice that in wetlands surrounded by grassland. Individual sites in the cultivated area ranged from 54 to 107 mg cm^{-2} yr^{-1} whereas in the grasslands they ranged between 34 and 56 mg cm^{-2} yr^{-1}. The average rate of sand accumulating in wetlands in the two land use types was similar, but rates of both silt and clay were significantly higher in cultivated watersheds (Table III).

TABLE III

Annual accumulation rates of inorganic sediment and selected constituents in wetlands of cultivated and uncultivated watersheds

Constituent	Uncultivated		Cultivated	
	Mean	Range	Mean	Range
Clay (mg cm^{-2})	5.4	2–9	25.6	14–40
Silt (mg cm^{-2})	31.2	26–41	45.9	34–54
Sand (mg cm^{-2})	6.9	5–9	9.1	2–17
Total P (μg cm^{-2})	29.5	21–46	57	32–77
Total N (μg cm^{-2})	140	116–193	174	122–271
Organic matter (g m^{-2})	74.8	62–87	69.7	59–76
^{137}Cs ($nCi\ m^{-2}$)	0.86	0.69–0.97	0.86	0.31–1.84

Accumulation rates of total N and organic matter were similar in wetland sediments from the two different land use categories, whereas accumulation rates of total P were higher in sediments of wetlands in cultivated watersheds than in grassed watersheds. Although average values for the accumulation of ^{137}Cs were identical for the two land use types, rates were more variable in cultivated watersheds (Table III).

5. Discussion

There are three interrelated aspects to consider when comparing sediment characteristics in cultivated and noncultivated watersheds: (1) the concentration of the various constituents in both the sediment and the watershed soil; (2) the rate of accumulation (flux) of materials from soil to sediment; and (3) the enrichment of materials from soil to sediment. These aspects need to be understood in both types of watersheds in order to assess the impacts of agricultural land use on wetland ecosystems.

In this study, concentrations of clay, silt, and sand all differed in soils from grassland and cultivated watersheds. This may be attributed to the effects of cultivation, or it may be due to inherent differences in the sites selected. Accumulation rates for total inorganic sediment and for clay and silt were significantly higher at cultivated sites than at grassland sites. The accumulation rate for sand was apparently not influenced by land use. The enrichment ratio for clay was less than 1.0 in all of the grassland watersheds, but consistently exceeded 1.0 in the cultivated watersheds. These data indicate that clay-sized particles are proportionally lower in sediment than in soil in grassland watersheds; the opposite condition exists in cultivated watersheds. Enrichment ratios for sand were less than 1.0 at all sites indicating that the larger particles are selectively retained on the uplands of both grassland and cultivated watersheds. Enrichment ratios for silt exceeded 1.0 at all sites, both grassland and cultivated, yet those from grassland watersheds were significantly higher than those from cultivated sites. This suggests that silt-sized particles were selectively removed from all uplands, but that the net effect of the processes involved differed in the two land-use types.

The same rationale regarding the concentration, flux, and enrichment of inorganic particles can be applied to the other constituents measured in this study. Concentrations of total N and organic matter were high in grassland soils and low in cultivated soils, undoubtedly as a direct result of differences in land use. These differences were apparently offset by differences in transport rates, so that accumulation rates of total N and organic matter were not significantly different in grassland and cultivated watersheds. The situation was somewhat reversed for total P. Both land use types had approximately the same concentrations of total P in the soils. The higher transport rates in the cultivated areas resulted in a significantly increased flux of total P from upland soils to the sediments of cultivated watersheds. Enrichment ratios for total N, organic matter, and total P were all greater than 1.0 at all sites and did not differ significantly between cultivated and grassland watersheds. This similarity suggests that sediments were enriched in proportion to the amount present in upland soils regardless of land use, and that concentrations in wetland sediments reflect concentrations in the contributing watersheds.

The situation with ^{137}Cs deserves special consideration. Cesium-137 is broadcast uniformly on the surface of the watershed from atmospheric fallout. In this regard, it is similar to a number of other aerially applied materials such as agricultural pesticides or trace substances found in precipitation. Once ^{137}Cs comes in contact with the soil surface, its fate becomes related to land use. In grassland watersheds, most of it remains on the surface and is readily available for transport. In cultivated watersheds, it is incorporated into the tillage layer and becomes less available for transport. In our study, the average specific activity of ^{137}Cs in the 0 to 10 cm layer of soil was 0.92 pCi g^{-1} in grassland watersheds and 0.44 pCi g^{-1} in cultivated watersheds. Similar differences in depth distribution of ^{137}Cs for cultivated and noncultivated soils have been reported by others (McHenry and Ritchie, 1980; Ritchie and McHenry, 1975). The flux of ^{137}Cs to the wetland sediments is a function of soil concentration and transport rate. In our study, the average accumulation rates for grassland and cultivated watersheds were equal, indicating that the higher concentrations of ^{137}Cs in grassland watersheds were offset by higher transport rates in cultivated watersheds.

Information on the movement of ^{137}Cs may be useful in assessing the impacts of future land use practices in prairie pothole watersheds. Farmers are being encouraged to use more conservation tillage. The desired result of conservation tillage is a reduction in runoff and sediment transport from watersheds. These practices may call for increased use of pesticides. Changes in patterns of pesticide use and tillage operations may affect the amount of pesticide transported to pothole wetlands. As suggested by Ritchie and McHenry (1978), a model to predict movement of ^{137}Cs within ecosystems should have additional application in the prediction of movement of many nonpoint source pollutants.

References

Buckman, H. O. and Brady, N. O.: 1960, *The Nature and Properties of Soils*, 6th ed., The Macmillan Co., New York, 567 pp.

Carson, P. and Gelderman, R.: 1980, *Soil Testing Procedures in Use at the South Dakota State Soil Testing Laboratory*, Plant Science Pamphlet No. 55, South Dakota State University, Agricultural Experiment Station, Brookings, SD, 45 pp.

Ebina, J., Tsutsui, T., and Shirai, T.: 1983, *Water Res.* **17**, 1721.

Guy, H. P.: 1969, 'Laboratory Theory and Methods for Sediment Analysis', Chapter C1, Book 5, *Laboratory Analysis, Techniques of Water-Resources Investigations of the United States Geological Survey*, U.S. Geological Survey, Washington, DC, 58 pp.

Hamilton-Taylor, J.: 1979, *Environ. Sci. Technol.* **13**, 693.

LeClerg, E. L., Leonard, W. H., and Clark, A. G.: 1962, *Field Plot Technique*. Burgess Publishing Co., Minneapolis, MN, 373 pp.

Martin, A. C., Hotchkiss, N., Uhler, F. M., and Bourn, W. S.: 1953, *Classification of Wetlands of the United States*, U.S. Fish and Wildlife Service, Special Scientific Report – Wildlife No. 20, Washington, DC, 14 pp.

McHenry, J. R. and Ritchie, J. C.: 1980, 'Dating Recent Sediments in Impoundments', *Proceedings of the Symposium on Surface Water Impoundments*, American Society of Civil Engineers, pp. 1279–1289.

Raveh, A. and Avnimelech, Y.: 1979, *Water Res.* **13**, 911.

Ritchie, J. C. and McHenry, J. R.: 1973, *Int. J. Appl. Radiat. Isotop.* **24**, 575.

Ritchie, J. C. and McHenry, J. R.: 1975, *J. Soil Wat. Conserv.* **30**, 283.

Ritchie, J. C. and McHenry, J. R.: 1978, *J. Environ. Qual.* **7**, 40.

Sloan, C. E.: 1972, *Ground-Water Hydrology of Prairie Potholes in North Dakota*, U.S. Geological Survey, Professional Paper 585-C, Washington, DC, 28 pp.

Smith, A. G., Stoudt, J. H., and Gollop, J. B.: 1964, 'Prairie Potholes and Marshes', in J. P. Linduska (ed), *Waterfowl Tomorrow*, U.S. Bureau of Sport Fisheries and Wildlife, Washington, DC, pp. 39–50.

Steel, R. G. D. and Torrie, J. H.: 1960, *Principles and Procedures of Statistics*, McGraw-Hill Book Co., Inc., New York, 481 pp.

Stewart, R. E. and Kantrude, H. A.: 1971, *Classification of Natural Ponds and Lakes in the Glaciated Prairie Region*, U.S. Fish and Wildlife Service, Resource Publication 92, Washington, DC, 57 pp.

U.S. Atomic Energy Commission: 1977, *Health and Safety Laboratory Fallout Program*, HASL-329, New York.

Wischmeier, W. H. and Smith, D. D.: 1965, *Predicting Rainfall-Erosion Losses from Cropland East of the Rocky Mountains*, U.S. Department of Agriculture, Agricultural Research Service, Agricultural Handbook No. 282, 47 pp.