Catena 91 (2012) 94–103

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Interrill erosion of carbon and phosphorus from conventionally and organically farmed Devon silt soils

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ARTICLE INFO

Article history:
Received 8 April 2009
Received in revised form 23 April 2010
Accepted 13 October 2010

Keywords:
Interrill erosion
Phosphorus erosion
Soil organic carbon
Carbon cycle
Organic farming

ABSTRACT

Globally, between 0.57 and 1.33 Pg of soil organic carbon (SOC) may be affected by interrill processes. Also, a significant amount of phosphorus (P) is contained in the surface soil layer transformed by raindrop impact, runoff and crust formation. In the EU, the P content of a crusted (2 mm) surface layer corresponds to 4 to 40 kg ha^{-1} of P on arable land (1.094 mil km^2). Therefore, the role of interrill processes for nutrient cycling and the global carbon cycle requires close attention. Interrill erosion is a complex phenomenon involving the detachment, transport and deposition of soil particles by raindrop impacted flow. Resistance to interrill erosion varies between soils depending on their physical, chemical and mineralogical properties. In addition, significant changes in soil resistance to interrill erosion occur during storms as a result of changes in surface roughness, cohesion and particle size. As a consequence, erosion on interrill areas is selective, moving the most easily detached small and/or light soil particles. This leads to the enrichment of clay, phosphorous (P) and carbon (C). Such enrichment in interrill sediment is well documented, however, the role of interrill erosion processes on the enrichment remains unclear. Enrichment of P and C in interrill sediment is attributed to the preferential erosion of the smaller, lighter soil particles. In this study, the P and organic C content of sediment generated from two Devon silts under conventional (CS) and organic (OS) soil management were examined. Artificial rainfall was applied to the soils using two rainfall scenarios of differing intensity and kinetic energy to determine the effects on the P and C enrichment in interrill sediment. Interrill soil erodibility was lower on the OS, irrespective of rainfall intensity. Sediment from both soils showed a significant enrichment in P and C compared to the bulk soil. However, sediment from the OS displayed a much greater degree of P enrichment. This shows that the net P export from organically farmed soils is not reduced by a similar degree than soil erosion compared to conventional soil management. The enrichment of P and C in the interrill sediment was not directly related to SOC, P content of the soil and soil interrill erodibility. A comparison of soil and sediment properties indicates that crusting, P and C content as well as density and size of eroded aggregate fragments control P and C enrichment. Due to complex and dynamic interactions between P, SOC and interrill erosional processes, the nutrient and C status of sediments cannot be predicted based on soil P content, SOC or interrill erodibility alone. Clearly, further research on crust formation and the composition of fragments generated by aggregate breakdown and their transport in raindrop impacted flow under different rainfall conditions is required. Attaining this critical missing knowledge would enable a comprehensive assessment of the benefits of organic farming on nutrient budgets, off-site effects of interrill erosion and its role in the global C cycle.

1. Introduction

1.1. Interrill erosion and the environment

Soil erosion by water is a complex, multifaceted process which involves a range of erosion processes, soil properties and interactions between soil surface, rainfall and running water (Römkens et al., 2001). Generally, linear erosion by concentrated flow on agricultural land is called rill erosion, while erosion by non-concentrated runoff, enhanced by the impact of raindrops, is referred to as interrill erosion. Where both processes occur at the same time, rill erosion is considered to be more damaging to the soil (Govers and Poesen, 1988). However, interrill erosion processes affect basically all arable land on Earth (14.2 mil. km^2, Kuhn et al., 2009). A soil layer comprising the volume of a rough, crusted soil surface at harvest time contains approximately 50 Gt of soil and 0.57 to 1.33 Gt of carbon (C) (Kuhn

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doi:10.1016/j.catena.2010.10.002

et al., 2009). On all arable land in the EU, this layer would contain an estimated 0.44 to 4.44 Tg of phosphorus (P), which is potentially mobilised by interrill processes annually (Table 1). Consequently, interrill erosion has significant on- and off-site effects. On-site effects include the loss of soil fertility due to the preferential erosion of nutrients, clay and C. The erosion of nutrients and C from agricultural land can lead to surface water eutrophication and disoxyfication (Levine and Schindler, 1989; Sharpley et al., 1994; Jordan et al., 2000; Withers et al., 2007). Interrill erosion has therefore been identified as one of the major processes contributing to soil and water quality degradation (Wan et al., 1996). As a result, it is becoming essential, in addition to monitoring the quantity of sediment eroded, to consider the P and C content of sediments in erosion risk assessments (van der Knijff et al., 2000). Furthermore, the interaction of this large volume of soil with rainfall and runoff, the potential erosion of P and the exposure of the soil organic carbon (SOC) to the atmosphere, require further study and a better understanding to assess its role within the global geochemical cycles (Quinton et al., 2001; IPCC WG 1, 2007).

1.2. Rainfall–soil interaction and interrill erosion

Interrill erosion is commonly understood to be a combination of two sub-processes: detachment and entrainment by raindrop impact, and transport by thin, non-concentrated raindrop-impacted flow (Meyer, 1981; Foster, 1990; Quinton et al., 2001). Resistance to interrill erosion varies as a result of inherent primary physical and chemical characteristics of soils as well as a number of important secondary properties such as soil structure (Bryan, 1968; Le Bissonnais, 1996). Among the key factors controlling soil detachment are rainfall intensity, runoff (Moldenhauer and Long, 1964; Meyer, 1981) and aggregate stability (Young and Onstad, 1978; Luk, 1979; Meyer and Harmon, 1984). Soil properties, such as texture, content of organic C, and clay content, are a key part of the stability of aggregates against interrill erosion (Le Bissonnais et al., 1995). In fact, some studies (e.g. Martinez-Mena et al., 2002) have suggested that the soil type and properties are more important in determining a hydrological and erosional response than factors such as the rainfall intensity. SOC is a particularly important property as it has been shown that soils with a greater SOC concentration are more resistant to the breakdown of aggregates as well as other processes such as slaking and dispersion (McDowell and Sharpley, 2003).

There are four processes of aggregate breakdown: mechanical breakdown, slaking, dispersion and liquefaction (Levy et al., 2007). Aggregate breakdown processes and their links to soil properties have been well documented. Rasiah et al. (1992) observed that clay content and C explained more than 80% of the variability in wet aggregate stability. The percentage of water stable aggregates (WSA) is also a good indicator of soil susceptibility to erosion, seal formation and compaction (Le Bissonnais and Arrouays, 1997). WSAs maintain the rate of infiltration and resist breakdown caused by raindrop impact, hence slowing surface sealing and crusting, reducing infiltration and thus ultimately increasing surface runoff and erosion (Unger et al., 1998). WSAs are strongly related to SOC in that the size and the stability of the aggregates in water are generally greater where there is a higher SOC (Tisdall and Oates, 1982; Bravo-Garza and Bryan, 2005). Therefore, WSAs are affected by the application of fertilisers. Soils with organic fertiliser inputs, such as legume green manure or animal manure, as can often be seen in organic farming, tend to have a higher organic matter (OM) input and thus more WSA than cropland where mineral fertilisers are applied (Whalen et al., 2003). This, in part, explains the suggested the benefits, such as reduced erosion rates of an organic farming management practices over conventional practices.

Resistance to erosion is not constant and secondary properties, such as the percentage of WSA, have a strong impact, particularly over a long period of time. Rainfall, runoff and erosion all change soil surface roughness, cohesion (crusting) as well as infiltration (sealing) and therefore affect the hydraulic properties of the soil surface. As a consequence, erosivity of raindrop impacted flow and the resistance of the soil surface to erosion change during rainfall events (Hairsine and Hook, 1995; Smith and Quinton, 2000). Aggregate breakdown and seal formation vary also with rainfall intensity, duration and temporal pattern of rainfall (Kuhn and Bryan, 2004) leading to a strong influence of event characteristics on interrill erosion and sediment properties (reviewed by Bryan, 2000). There is some discrepancy in the literature considering the relative importance of the role of rainfall characteristics on the selective removal of P depending on the soil and rainfall conditions observed. Fraser et al. (1999) report an increase in P concentrations with increasing discharge. On the contrary, Massey and Jackson (1952), Sharpley (1980) and Quinton et al. (2001) suggest that small erosion events are the most nutrient selective.

1.3. Soil management P and C erosion

Continuous farming with little or no inputs of OM and deep ploughing has been seen to drastically reduce organic C content of soils (Bowman et al., 1999). Such intensive management techniques are associated with the highest emissions of greenhouse gases from agriculture (IPCC, 1997 cited in Olesen and Bindi, 2002). Farming organically encourages the use of cover crops to reduce soil erosion and nutrient leaching as well as the application of farmyard manure rather than inorganic fertilisers, which have a more positive impact on SOC (Davis, 2002 cited in Fleiβbach et al., 2007). There is clear documented evidence that organic farming is beneficial – lower fertiliser application reduces CO_2 production, increases soil OM, improves soil structure, aggregate stability and ultimately reduces erosion and water pollution (Stockdale et al., 2001; Pulleman et al., 2003; Freibauer et al., 2004). However, due to the lack of pesticide application, organic farming often requires more tillage operations to limit weed growth (Bàrberi, 2002). In cultivated soils, tillage results in the breakdown of aggregates (Urioste et al., 2006), not only

Table 1
Estimate of P and C affected by interrill processes.

	Bulk density ($t\,m^{-3}$)	Surface area (mil. km^2)	Roughness effect on area	P and C content	Soil volume affected by interrill processes (mil. m³)	P and C affected by interrill processes per year globally	P and C affected by interrill processes ($kg\,ha^{-1}$)
Organic carbon conservative estimate	1	14.2	1	2%	28 400	0.57 Pg	400
Organic carbon high estimate	1.3	14.2	1.2[a]	3%	34 080	1.33 Pg	936
Phosphorus conservative estimate	1	1.094[b]	1	200 ppm	2 188	0.44 Tg	4
Phosphorus high estimate	1.3	1.094[b]	1.2[a]	1000 ppm	3 413.28	4.44 Tg	40.56

Figure adapted from Kuhn et al., 2009.
OS – organically farmed soil, CS – conventionally farmed soil.
[a] Based on laser scanning DEMS by Anderson & Kuhn (2008) and unpublished data collected at the University of Basel.
[b] Figures from Eurostat (2007).