The Use of Equivalent Quartz Size and Settling Tube Apparatus to Fractionate Soil Aggregates by Settling Velocity

Yaxian Hu[1], Wolfgang Fister[1], Hans-Rudolf Rüegg[1], Peter A. Kinnell[2], Nikolaus J. Kuhn[1]

[1] Physical Geography and Environmental Change Research Group, Department of Environmental Sciences, University of Basel, Switzerland (yaxian.hu@unibas.ch)

[2] Institute of Applied Ecology, University of Canberra, Australia

ABSTRACT: In a given layer of surface runoff, particle transport distance declines with increasing settling velocity. Settling velocity itself is determined by the size, density and shape of the particles. For sediment composed of aggregates, settling velocity does not only vary due to texture, but also due to aggregation, aggregate size and stability. Therefore, aggregation can strongly affect the transport distance of the sediment and the substance specific redistribution of the eroded material, such as organic matter. Understanding the effect of aggregation, for example, on redistribution of eroded organic matter is therefore essential for understanding local, regional and global carbon cycles. To capture and establish the relationship between aggregation, settling velocity and aggregate specific organic matter content, a settling tube apparatus, based on a previous design, was constructed and applied to fractionate soils by water stable aggregate size classes. To illustrate the effect of aggregation on settling velocity, the results were compared with mineral grain sizes after ultrasound dispersion. Five settling velocity classes were distinguished based on the Equivalent Quartz Size (EQS) of particles ≥ 250 μm, 125 to 250 μm, 63 to 125 μm, 32 to 63 μm, and ≤ 32 μm. Fractionation of a silty loam by settling tube illustrates that aggregation strongly affects settling velocities and should be considered in erosion models, as opposed to the texture of mineral grains. An analysis of sediment organic matter in the five settling velocity classes also showed that settling velocity is a suitable parameter to physically connect the redistribution of eroded soil organic matter to overland flow transport processes.

KEYWORDS: settling tube apparatus, settling velocity, transport distance, aggregate fractionation

Introduction

Soil particles displaced by erosion experience selective deposition along their flow paths across watersheds (Walling, 1983). Understanding the effect of this selective deposition on the redistribution of particle-bound substances (e.g. soil organic carbon, phosphorous or other contaminants) within watersheds requires a discrimination of particles and their properties by their respective transport distances. The transport distances of displaced soil particles are related to their settling velocities (Dietrich, 1982; Kinnell, 2001; Kinnell, 2005). For eroded soil particles composed of aggregates, settling velocities generally do not correspond to the average or median mineral grain size, because aggregates differ in size, density and shape from mineral grains (Johnson *et al.*, 1996; Tromp-van Meerveld *et al.*, 2008). The average or median grain size can be the same for a range of soils, but the aggregate size distribution can differ, e.g. when clay enhances the formation of aggregates. The distribution of settling velocities therefore can provide more accurate information on the quality and behavior of eroded and aggregated sediment than just texture (Loch, 2001). The distribution of settling velocities based on grain size classes has already been included into some erosion / deposition models (Morgan *et al.*, 1998; van Oost *et al.*,

2004; Fiener *et al.*, 2008; reviewed by Aksoy and Kavvas, 2005). However, inconsistencies such as over-prediction of clay in sediment fractions or under-prediction of sand and silt in sediment samples (Beuselinck *et al.*, 1999; van Oost *et al.*, 2004) are often present in their results, because soil particles are mostly eroded in the form of aggregates rather than as mineral grains (reviewed by Walling, 1988; Slattery and Burt, 1997; Beuselinck *et al.*, 2000). Aggregation potentially increases settling velocities and reduces transport distances. As a consequence, aggregation can lead to aggregate specific, rather than mineral grain specific, distribution of particle-bound substances across a landscape by selective deposition (Kuhn, 2007; Kuhn and Armstrong, 2012). The settling velocities of aggregates are therefore crucial to determine the effect of erosion on redistribution of substances (such as eroded soil organic carbon, phosphorous, nitrogen or metals) across landscapes, as well as their delivery into aquatic systems. By further identifying the lability of the eroded soil organic carbon, and quantifying the relative proportion mobilised into or out of different ecosystems, it also can substantially improve our understanding of the role of erosion / deposition on global carbon cycling.

The settling velocity of mineral particles is determined by their size, density and shape (Dietrich, 1982). For aggregated soils, their irregular shape, porosity, permeability, interaction with organic matter of low density, aggregation, and the relative fragility of wet aggregates (Dietrich, 1982; Le Bissonnais *et al.*, 1989; Johnson *et al.*, 1996; Tromp-van Meerveld *et al.*, 2008) can all affect their settling velocities. Therefore, a conceptual approach based on Equivalent Quartz Sizes (EQS), modified from the equivalent sand size used by Loch (2001), is developed to address the effect of aggregation on the potential redistribution of eroded soil organic matter across a hill-slope. EQS represents the diameter of a spherical quartz particle that would fall with the same velocity as the aggregated particle for which fall velocity is measured (Loch, 2001). Therefore, EQS represents an integrated index to indicate the settling behaviour rather than to represent the specific size of the soil particles. In this manner, our current understanding of the effects of mineral grain size on sediment behavior can be applied to aggregated sediment particles based on the concept of EQS. Although the accurate size of aggregated particles needs to be validated by field data, the accuracy of soil erosion models can also be largely improved by applying the distribution of settling velocities based EQS compared to grain size distribution.

Use of settling tubes to fractionate sediment particles

The settling tube (column) is a traditional technique used to measure the settling characteristics of aquatic solids (Droppo *et al.*, 1997; Wong and Piedrahita, 2000; Rex and Petticrew, 2006), but the settling tubes used in river and marine environment are often short and with small openings. Consequently, they are unable to allow coarse particles to pass through, so they cannot be directly applied to fractionate sediment that is often in the form of aggregates. Settling tubes, such as the 20 cm long example used in Johnson *et al.* (1996), cannot be used to fractionate the aggregated sediments either, because such a short settling distance is not capable of accurately distinguishing the velocities of fast settling particles.

In order to fractionate aggregated soils, Hairsine and McTainsh (1986) designed a top-entry settling tube apparatus (The "Griffith Tube"), which was adapted from the "Siltometer" developed by Puri (1934). In this design, soil samples were introduced into a 200 cm long vertical tube from the top by an injection barrel. After falling through the static water column by gravity, soil fractions were collected over predetermined time intervals into sampling dishes situated in a turntable under the widely-open bottom of the tube. This design was then improved by Kinnell and McLachlan (1988) using a more reliable injection barrel, and further by Loch (2001), who employed an electric motor to raise the tube and rotate the turntable. Unlike other physical fractionation methods, for instance, wet and dry sieving (Cambardella and Elliott, 1993; Christensen, 2001), where aggregates would inevitably experience abrasion, settling through a water column preserves fragile aggregates. However, such a technique has not been widely implemented, because the lack of details in describing the existing settling tube apparatus makes it very difficult to reconstruct one without detailed knowledge of their design specifications.

Such information could only be obtained by personally contacting the authors, which is often not possible. In particular, measurements linked to modeling the redistribution of organic carbon and their implications on the carbon cycle are missing (Kuhn, 2013). It is also noteworthy that soil particles depositing through a column of static water neglects the potential effects of, for instance, flow turbulence during transport processes. Other information (e.g. topography, and flow velocity) is required, therefore, in order to further calibrate the realistic transport distances of eroded soil particles.

Settling tube apparatus developed by Basel University

The settling tube apparatus built at Physical Geography and Environmental Change Research Group from Basel University consists of four components (Figure 1a): the settling tube, through which the soil sample settles (Figure 1b); the injection device, by which the soil sample is introduced into the tube (Figure 2); the turntable, within which the fractionated subsamples are collected (Figure 3); and the control panel, which allows an operator to control the rotational speed and resting/moving intervals of the turntable (Figure 4).
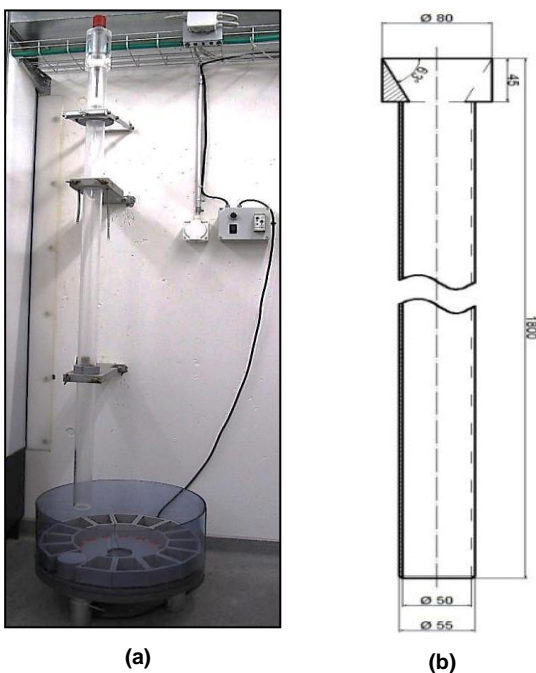

(a)   (b)

Figure 1. (a) Overview of the complete setup of the Basel University settling tube apparatus; (b) The settling tube. Measurement units in mm.

The settling tube

The settling tube is made of transparent PVC, has a length of 180 cm and an internal diameter of 5 cm (Figure 1b). The tube can hold approx. 4 liters of water, through which the soil sample is free to settle. In most cases, the soil particles are smaller than 2 mm in diameter, so the diameter ratio of the tube (50 mm) to a particle (< 2 mm) is greater than 25 to 1. According to Loch (2001), such a ratio largely eliminates concerns associated with edge effects and the variability introduced by wall effects is expected to be < 10%.

The injection device

An injection device is used to insert the soil sample into the top of the settling tube. It consists of a central chamber and a ca. 30 cm long metal rod connected to a Teflon cone at the lower end, a Teflon piston in the middle and a rubber plug attached to a handle at the upper end (Figure 2, based on the design of Kinnell and McLachlan, 1988).
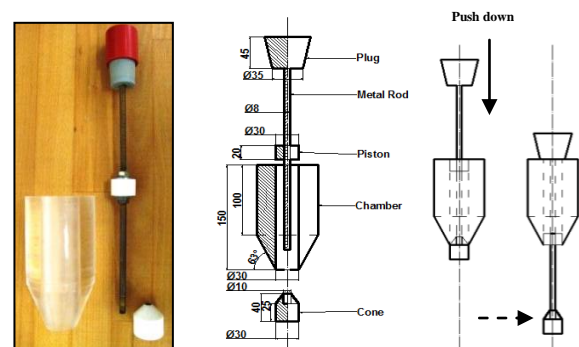

Figure 2. The injection device used in the Basel University settling tube apparatus. . Measurement units in mm.

The soil sample is placed into the central chamber before injection. The capacity of the injection chamber (ca. 80 cm^3) limits the mass of dry soil to 25 g. This leads to a soil concentration of approximately 6 g L^{-1} in the water column. Following Loch (2001), the concerns associated with particle interactions during settling are therefore minimal. The metal rod passing through the chamber opens the Teflon cone at bottom of the chamber, releasing the soil sample while the piston and plug keep the chamber sealed to prevent water flowing out at the bottom of the

pipe. Kinnell and McLachlan (1988) used a pin inserted into the rod to prevent the piston from moving downwards before release. In our injection device the deformation of the Teflon is used to seal the chamber and prevent the movement of the piston (Figure 2). This design seals the chamber more effectively; however, it requires a much greater force to open it. A slow opening of the chamber can lead to inaccurate settling times. It is also noteworthy that the cone frequently represents an obstacle in the pathway of falling particles and small amounts (< 1 g) have been observed on the surface of the cone. Further improvements on the design of the injection device are required in order to solve this problem.

The turntable

The turntable is placed under the settling tube and is used to collect the soil fractions that settle out of the tube. It consists of a circular tank (Figure 3a, PVC transparent), and a set of sampling dishes (Figure 3b, PVC grey). The circular tank is 50 cm in diameter, 20 cm deep, and has a volume of 40 L. The net volume of each sampling dish is ca. 290 cm^3. When settling, the water level in the tank must be higher than the bottom opening of the tube to prevent the water from flowing out of the tube. The turntable tank rests on a layer of plastic ball bearings placed in a tray beneath the tank. This tray rests on three pillars (Figure 3c). An electric motor, affixed to the pillars, enables a timed and stepwise rotation of the turntable and thus places each respective sampling dish precisely underneath the settling tube, e.g. at time intervals corresponding to the settling times of the EQS. Where motor installation is not available, manual operation to replace the sampling dishes is also feasible.

The control panel

A plug-in time delay relay (© Comat, RS 122-H) is used to control the rotational speed and resting/moving intervals of the turntable (Figure 4). The control panel primarily consists of three parts: the main switch, the speed-control knob, and the interval-control buttons.
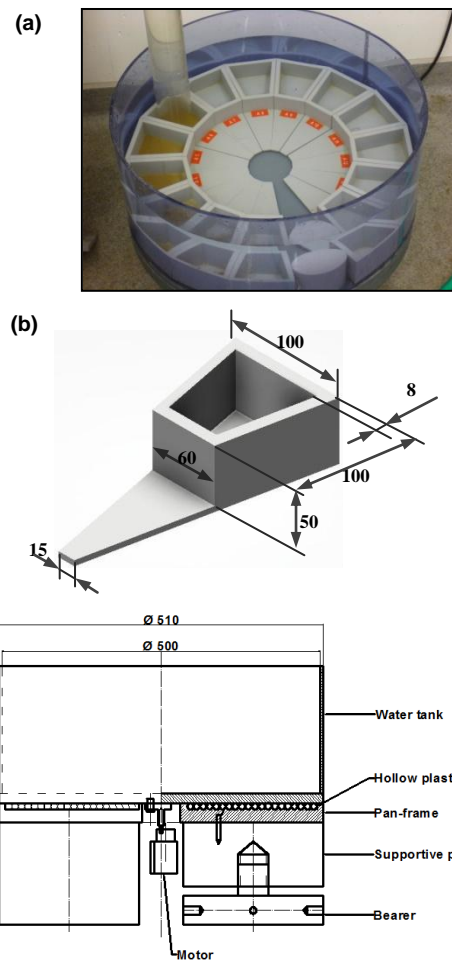

Figure 3. The turntable (a), the sampling dish (b), and the supporting frame. Measurement units in mm. (c) of the Basel University settling tube apparatus.
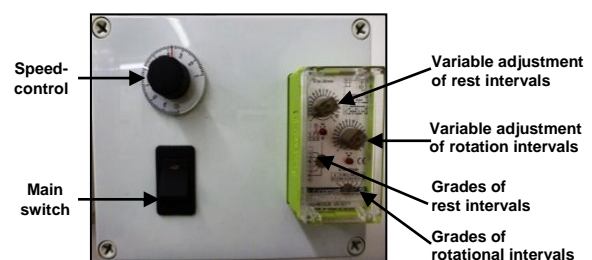

Figure 4. The control panel of the Basel University settling tube apparatus

Potential transport distance of eroded organic carbon based on texture and aggregation

Soil selection and preparation

A silty loam from Möhlin, in northwest Switzerland (47˚ 33' N, 7˚ 50' E) was used to compare the differences between the potential transport distance of eroded organic carbon predicted based on soil texture and

that predicted by aggregate fractionation. The soil was sampled from Bäumlihof Farm with a wheat-grass-maize rotation in August 2011. Sampling directly from the field, rather than from depositional sites after a certain extent of preferential transportation, provides an opportunity to evaluate the likely transport distance of all classes of eroded particles. Its total organic carbon concentration is 10.9 mg g^{-1}, and the aggregate stability (based on Nimmo and Perkins, 2002) is 66.85 %. This degree of aggregation and organic carbon content were considered appropriate to investigate the effects of aggregation onto the potential redistribution of eroded soil organic carbon by deposition across the landscape.

Calculation of Equivalent Quartz Size

Stokes' Law covers the range of the mineral grain sizes dominating the silty loam used for this study. Their terminal settling velocities can be calculated by:

$$V = \frac{h}{t} = \frac{d^2 g (D_s - D_f)}{18\eta} \qquad (1)$$

Where: V = settling velocity (m·s^{-1}), h = settling distance = 180 cm with this settling tube apparatus, t = settling time (s), d = diameter of settling particle (mm), g = gravitational force = 9.81 N·kg^{-1} , η = viscosity of water at 20° C = 1×10^{-3} Ns·m^{-2}, D_s = average density of the solid particles, for most soils = 2.65 ×10^3 kg·m^{-3}, D_f = density of water = 1.0×10^3 kg·m^{-3}.

The use of Stokes' Law to calculate EQS is, in the strictest sense, limited to particles < 0.07 mm (Rubey, 1933). For soils dominated by larger mineral grains, different relationships should be used (e.g. Ferguson and Church, 2004; Wu and Wang, 2006). Five size fractions were selected according to their likely transport distance once eroded (Starr *et al.*, 2000): ≥ 250 µm, 125 to 250 µm, 63 to 125 µm, 32 to 63 µm, ≤ 32 µm (Table 1).

Soil fractionation by settling tube and wet sieving

The soil samples were dried at 40 ˚C until constant weight was achieved and then gently dry-sieved with an 8 mm sieve to avoid over-sized clods. Prior to settling / wet-sieving, 25 g of dry soil were immersed into

50 ml tap water for 15 min. This fast-wetting emphasizes slaking and slight clay dispersion and simulates the destruction of aggregates during an erosion event (Le Bissonnais, 1996). For all tests, tap water was used. The electric conductivity of tap water was 2220 µs·cm^{-1}, which was five times higher than the rainwater in Basel (462 µs·cm^{-1}). In general, increased electric conductivity of tap water generally enhances dispersion during rainfall simulation tests (Borselli *et al.*, 2001). A comparative aggregate stability test (Wet Sieving Apparatus, Eijkelkamp, Netherlands) using tap water and rainwater from Basel had shown that tap water only had a minor effect on aggregates greater than 250 µm after 20 min of continuous up-and-down movement (67.24 % in rainwater, 73.59 % in tap water). Therefore, the use of tap water was considered to be acceptable.

Table 1. Settling times and velocities of the Möhlin silty loam, based on the Equivalent Quartz Size (EQS) classes, and the likely transport distance of soil particles once eroded and based on the conceptual function developed by Starr et al., 2000. The settling distance is 180 cm.

EQS (µm)	Settling velocity (m·s^{-1})	Settling time (s)	Likely transport distance
> 250	> 4.5×10^{-2}	< 40	Deposited across landscapes
125 - 250	1.5×10^{-2} - 4.5×10^{-2}	40 - 120	Deposited across landscapes
63 - 125	3.0×10^{-3}- 1.5×10^{-2}	120 - 600	Deposited across landscapes
32 - 63	1.0×10^{-3}- 3.0×10^{-3}	600 - 1800	Possibly transferred into rivers
< 32	< 1.0×10^{-3}	> 1800	Likely transferred into rivers

A 25 g of fast-wetted soil sample was fractionated using the Basel University settling tube apparatus into five settling velocity classes (Table 1). A typical settling pattern of soil particles in the water column is shown in Figure 5. The finest particles correspond to those that remain in suspension after 1800 s of settling (i.e. EQS < 32 µm). Fractionated samples were dried at 40°C and dry weights as well as total organic carbon concentration (by Leco RC 612 at 550°C) were measured.
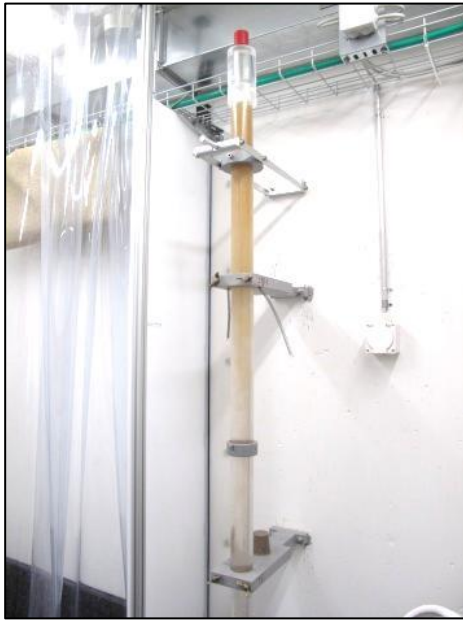
Figure 5. A typical settling pattern of soil particles through the water column: coarse particles settle fastest, while the fine particles stay suspension at upper part.

A second 25 g of fast-wetted soil sample was subjected to ultrasound using a Sonifier 250 from Branson, USA. The energy dissipated in the water/soil suspension was ca. 60 J·ml^{-1} (i.e. Energy = output power 70 W × time 85 s / suspension volume 100 ml) (North, 1976). According to Kaiser *et al.* (2012), although the aggregates were probably not thoroughly dispersed at this level of energy, the coarse mineral and organic particles (> 250 μm) were prone to be damaged if higher energy than 60 J·ml^{-1} was further applied. The dispersion energy level of 60 J·ml^{-1} was thus considered to be satisfactory, in the context of distinguishing the size distribution of aggregates from grains. The dispersed fractions were then wet-sieved into the five size classes corresponding to the five EQS classes used for the fractionation by settling tube. The weights and total organic carbon concentrations of each class were then measured in the same way as for the settling tube fractionated samples.

Effect of aggregation on settling velocity

The results of the two fractionation approaches are shown in Figure 6. The effect of aggregation on settling velocity is pronounced: 68.61 % of the aggregated soil behaved like particles of EQS greater than 63 μm (Figure 6a). The mineral particle size

distribution, on the other hand, shows that 89.65 % of soil grains were smaller than 63 μm (Figure 6a). This difference between proportion of EQS and corresponding mineral grain size classes illustrates that aggregation has a great effect on the particle settling velocity of the silty loam tested in this study.
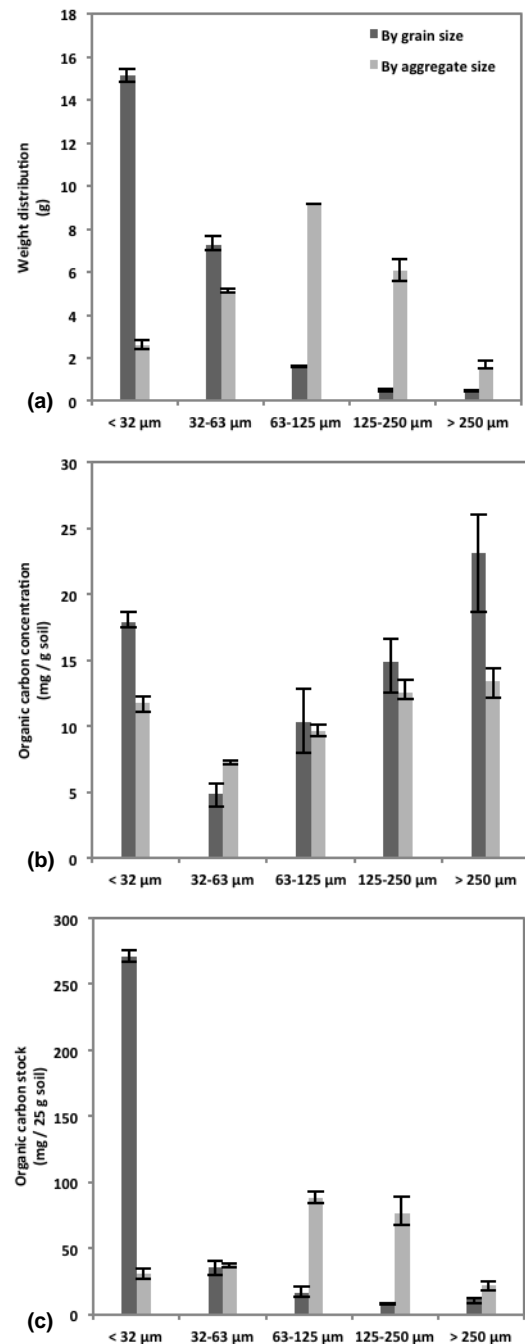

Figure 6. (a) Weight distribution, (b) organic carbon concentration distribution, and (c) organic carbon stock distribution of the Möhlin silty loam across aggregate size classes fractionated by the Basel University settling tube apparatus and across grain size classes dispersed by ultrasound. Error bars indicate the range of minimum and maximum values. n=3.

The relevance of this finding is further illustrated by the distribution of total organic carbon in aggregates and mineral grains. The distribution of total organic carbon concentration follows a similar pattern for both grain size and aggregate size classes (Figure 6b). However, multiplying the organic carbon concentration of each size class with its weight (Figure 6c) shows that 73 % of the organic carbon stock is contained in particles > 63 μm, while 79 % of the organic carbon stock was associated with grains < 32 μm. This implies that aggregation strongly affects the potential transport distance of the eroded organic carbon. Basically, the amount of deposition across the landscape would be tripled as the soil texture suggests. By contrast, the exportation of eroded organic carbon to watercourses would be reduced to a third. In consequence, the effect of aggregation on transport distances would fundamentally change our perspective on the environmental impact of eroded organic carbon as well as other nutrients and contaminants.

Conclusion and Implication

The settling tube fractionation provides settling velocity as a 'tool' to physically connect the redistribution of eroded soil organic carbon in an agricultural landscape with a soil transportability parameter used in current erosion models. While the initial test reported in this paper is very limited in its applicability to real erosion events, the results prove that a more accurate settling velocity of aggregated soil particles can be measured based on Equivalent Quartz Size than solely based on grain size distribution. The results also indicate that selective transport of aggregated sediment potentially has a great impact on the redistribution of eroded organic carbon in terrestrial ecosystems and its delivery to aquatic ecosystems. Such differentiation of sediment movement could, in turn, be highly significant for the effect of soil erosion on the global carbon cycle (Kuhn *et al.*, 2009). As a consequence of the results of the settling velocity fractionation procedure presented in this study, we conclude that the settling tube apparatus can be further applied to determine the realistic settling velocities of eroded soil generated in the field. The application of a settling tube to fractionate sediment particles according to settling velocities makes a significant contribution to our understanding of local, regional and global geochemical fluxes within terrestrial ecosystems, and also of their interaction with atmospheric and aquatic systems.

References

Aksoy H, Kavvas ML. 2005. A review of hillslope and watershed scale erosion and sediment transport models. *Catena* **64**: 247-271.

Beuselinck L, Govers G, Steegen A, Quine TA. 1999. Sediment transport by overland flow over an area of net deposition. *Hydrological Processes* **13**: 2769-2782.

Beuselinck L, Steegen A, Govers G, Nachtergaele J, Takken I, Poesen J. 2000. Characteristics of sediment deposits formed by intense rainfall events in small catchments in the Belgian Loam Belt. *Geomorphology* **32**: 69-82.

Borselli L, Torri D, Poesen J, Salvador Sanchis P. 2001. Effects of water quality on infiltration, runoff and interrill erosion processes during simulated rainfall. *Earth Surface Processes and Landforms* **26**: 329-342.

Cambardella CA, Elliott ET. 1993. Methods for physical separation and characterization of soil organic matter fractions. *Geoderma* **56**: 449-457.

Christensen BT. 2001. Physical fractionation of soil and structural and functional complexity in organic matter turnover. *European Journal of Soil Science* **52**: 345-353.

Dietrich WE. 1982. Settling velocity of natural particles. *Water resources research* **18**: 1615-1626.

Droppo IG, Leppard GG, Flannigan DT, Liss SN. 1997. The freshwater floc: A functional relationship of water and organic and inorganic floc constituents affecting suspended sediment properties. *Water Air Soil Pollut.***99**: 43–53, doi:10.1007/BF02406843.

Ferguson RI, Church M. 2004. A simple universal equation for grain settling velocity. *Journal of sedimentary Research* **74 (6)**: 933-937.

Fiener P, Govers G, Van Oost K. 2008. Evaluation of a dynamic multi-class sediment transport model in a catchment under soil-conservation agriculture. *Earth Surface Processes and Landforms* **33**: 1639-1660.

Hairsine PB, McTainsh, G. 1986. The Giffith Tube: A simple settling tube for the measurement of settling velocity of soil aggregates. School of Australian Environmental Studies, Griffith University, AES Working Paper 3/86.

Johnson CJ, Li XY, Loan BE. 1996. Settling velocities of fractal aggregates. *Environ. Sci. Technol.* **30**: 1911-1918.

Kaiser M, Berhe AA, Sommer M, Kleber M. 2012. Application of ultrasound to disperse soil aggregates of high mechanical stability. *J. Plant Nutr.Soil Sci.***175**: 521-526.

Kinnell PIA. 2001. Particle Travel distances and bed and sediment compositions associated with rain-impacted flows. *Earth Surface Processes and Landforms* **26**: 749-758.

Kinnell PIA. 2005. Raindrop-impact-induced erosion processes and prediction: a review. *Hydrology Process* **19**: 2815-2844.

Kinnell, PIA, McLachlan C. 1988. An Injection Barrel for the Top Entry Sedimentation Tube. Technical memorandum 43/1988, CSIRO Division Soils.

Kuhn NJ, Armstrong EK. 2012. Erosion of organic matter from sany soils: solving the mass balance. *Catena* **98**: 87-95.

Kuhn NJ, Hoffman T, Schwanghart W, Dotterweich M. 2009. Agricultural soil erosion and global carbon cycle: controversy over? *Earth Surface Processes and Landforms* **34**: 1033-1038.

Kuhn NJ. 2007. Erodibility of soil and organic matter: independence of organic matter resistance to interrill erosion. *Earth Surface Processes and Landforms* **32**: 794-802.

Kuhn NJ. 2013. Assessing lateral organic Carbon movement in small agricultural catchments. In: *Graf, C. (Red.) Mattertal - ein Tal in Bewegung. Publikation zur Jahrestagung der Schweizerischen Geomorphologischen Gesellschaft 29. Juni-1. Juli 2011, St. Niklaus.Birmensdorf, Eidg. Forschungsanstalt WSL*: 151-164.

Le Bissonnais Y, Bruand A, Jamagne M. 1989. Laboratory experimental study of soil crusting: relation between aggregate breakdown mechanisms and crust structure. *Catena* **16**: 377-392.

Le Bissonnais Y. 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *European Journal of Soil Science* **47**:425-437.

Loch RJ. 2001. Settling velocity – a new approach to assessing soil and sediment properties. *Computers and Electronics in Agriculture* **31**: 305-316.

Morgan RPC, Quinton JN, Smith RE, Govers G, Poesen JWA, Auerswald K, Chisci G, Torri D, Styczen ME. 1998. The European soil erosion model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. *Earth Surface Processes and Landforms* **23**: 527-544.

Nimmo JR, Perkins KS. 2002. Aggregate stability and size distribution. in Dane J.H. and Topp G.C., eds., Methods of soil analysis, Part 4-Physical methods. Madison, Wisconsin, *Soil Science Society of America*: 317-328.

North PF. 1976. Towards an absolute measurement of soil structural stability using ultrasound. *J.Soil Sci.* **27**: 451-459.

Puri AN. 1934. A siltometer for studying size distribution of silts and sands. *Punjab Irrigation Institute Research Publication* **2(7)**: 10pp.

Rex JF, Petticrew EL. 2006. Pacific salmon and sediment flocculation: nutrient cycling and intergravel habitat quality. *Sediment Dynamics and the Hydromorphology of Fluvial Systems* (Proceedings of a symposium held in Dundee, UK, July 2006) **306**: 1-8.

Rubey W. 1933. Settling velocities of gravel, sand and silt particles. *Am. J. Sci.* **225**: 325-338.

Slattery MC, Burt TP. 1997. Particle size characteristics of suspended sediment in hillslope runoff and stream flow. *Earth Surface Processes and Landforms* **22 (8)**: 705-719.

Starr GC, Lal R, Malone R, Hothem D, Owens L, Kimble J. 2000. Modeling soil carbon transported by water erosion processes. *Land Degradation and Development* **11**: 83-91.

Tromp-van Meerveld HJ, Parlange JY, Barry DA, Tromp MF, Sander GC, Walter MT, and Parlange MB. 2008. Influence of sediment settling velocity on mechanistic soil erosion modeling. *Water Resources Research* **44**: W06401, doi:10.1029/2007WR006361.

Van Oost K, Beuselinck L, Hairsine PB, Govers G. 2004. Spatial evaluation of a multi-class sediment transport and deposition model. *Earth Surface Processes and Landforms* **29**: 1027-2044.

Walling DE. 1983. The sediment delivery problem. *Journal of Hydrology* **65**: 209-237.

Walling DE. 1988. Erosion and sediment yield research – some recent perspectives. *Journal of Hydrology* **100**: 113-141.

Wong KB, Piedrahita RH. 2000. Settling velocity characterization of Aquacultural solids. *Aquacultural Engineering* **21**: 233-246.

Wu WM, Wang SY. 2006. Formulas for Sediment Porosity and Settling Velocity. *Journal of Hydraulic Engineering* **8**: 858-862.