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Quantifying soil movement by forest vehicles with corpuscular metal tracers

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ABSTRACT

Bulk soil movement caused by human impact is hard to quantify. In forestry the bulk soil displacement by passage with heavy machinery is virtually unknown. We present a new method to measure such soil movement with hollow corpuscular metal tracers (16 mm pieces of thin-walled metal pipes made of iron, aluminum, copper and lead) and a metal detector. The tracers are installed minimally invasive into the soil before and located with a metal detector after logging operations. To correctly interpret these measurements it is crucial to know about the accuracy and precision of the method, especially under varying soil moisture content or if different tracer materials are present. To address these questions a series of experiments under controlled conditions on soils with differing iron oxide concentrations were conducted. Best performance on all soils showed Al-tracers, whereas Fe-tracers are limited by increasing Fe-oxide concentrations. Cu and Pb failed. Material specific detection is limited to soils poor in Fe-oxides. Tracers were accurately detectable up to 15–20 cm depth depending on soil moisture. As the signals of the metal detector leave room for interpretation handling needs individual training to obtain unbiased results. In a case study from timber harvesting operations on sloping terrain in Central Europe the tracers where successively moved by each passage of the harvesting machines. After a complete operating cycle the histogram of displacement matched a heavy tailed distribution with a median of around 10 cm and a maximum of several meters. Displacement was reduced by the use of a traction supporting winch. However uncertainty remains whether tracer displacement exactly reflects bulk soil movement.

1. Introduction

Soil displacement due to use of heavy tools and machinery is well known in agriculture. The process termed tillage erosion has been identified as a major cause of soil losses from upper slope positions (Lobb et al., 1995) and often exceeds soil erosion by water (Quine et al., 1997).

Various approaches to quantify soil displacement in agriculture have been presented and tested in literature (Table 1). In this study we searched for a tracer especially applicable in the context of soil displacement by forest machinery. In forestry the effects of heavy machinery have usually been addressed on smaller scales evaluating soil compaction, the destruction of inter- and intra-aggregate pores and reduction of soil strength (Horn et al., 1995; Cambi et al., 2015). Horn et al. (2003) installed stress state transducers below machine paths to measure stress induced by forest harvesters and forwarders. Haas et al. (2016) used photogrammetry to asses rutting and surface soil displacement. On level terrain stress causes much more vertical than horizontal soil displacement (Horn et al., 2003). Operations leading to horizontal soil displacement here include dragging or skidding of trunks across the soil surface.

Largest horizontal soil displacements are found when machines working in steep terrain loose traction and wheel slippage occurs. To reduce extensive damages to forest soils modern reduced-impact logging (RIL) techniques (Putz et al., 2008) recommend to use a minimum number of planned machine tracks. While this limits damages to the area of the tracks the probability of continuous soil displacement and disturbed surfaces along tracks increases. For ergonomic and work security reasons machine tracks are oriented perpendicular to contour lines leading to a rise in downslope soil displacement. Additionally these damages promote preferred flow paths for surface runoff and soil erosion by water as infiltration capacities are even more decreased by shearing and smearing than by compaction. Shearing stress induced by wheel slippage can lead to crushing of soil macrostructure, even in soils with high structural stability, like Ferralsols (Schack-Kirchner et al., 2007). Just as much as wheel slippage is often neglected in agriculture (Lindstrom et al., 1992) it has rarely been addressed in forestry.

To asses soil displacement in forest soils several tracer approaches shown in Table 1 are ruled out. Tracers which have to be mixed with soil material, such as ^{137}Cs or the magnetic plastic beads presented by

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Table 1
Studies comprising of different approaches to quantify soil displacement.

Authors	Method	Detection
Tsara et al. (2006)	Historical vs. recent soil profile data (long-term displacement)	Field measurements
Ritchie et al. (1974), De Jong et al. (1982), Walling and Quine (1991)	Mapping of resident ^{137}Cs from nuclear tests or reactors (long-term displacement)	Laboratory measurements
Brown et al. (1995)	Mapping of cosmogenic ^{10}Be (long-term displacement)	Laboratory measurements
Govers et al. (1994)	Numbered plastic spheres with a metal core, 15 mm diameter, 1.75 g cm^{-3} density	Excavation of tracers
Thapa et al. (1999a), Nyssen et al. (2000)	Granite rocks, 3–4 cm size	Excavation
Zhang et al. (2004a), Zhang et al. (2004b)	Gravel	Excavation
Tsara et al. (2006)	Numbered Al cylinders, 10 mm diameter, 2.7 g cm^{-3} density (3 years in soil)	Metal detector and excavation
Montgomery et al. (1999)	Alphanumerical stamped washers, 13 mm diameter, 1.45 g cm^{-3} density	Metal detector and excavation
Lindstrom et al. (1992), Thapa et al. (1999b)	Labeled steel hexagonal nuts, 11–12 mm diameter	Metal detector and excavation
Zhang et al. (2009)	Mixing soil with magnetized kiln residues, 2.37 g cm^{-3} density	Magnetometer
Ventura et al. (2001)	Plastic beads coated with magnetite, 1.21–1.52 g cm^{-3} density (used for water erosion)	Magnetometer
Lobb et al. (1999)	Manually distributed chloride	Laboratory measurements
Lobb et al. (1995)	Manually distributed ^{137}Cs	Laboratory measurements
Ristolainen et al. (2003)	Acceleration sensors in subsoil	Field measurements

Ventura et al. (2001), would disturb natural forest soils and are highly laborious. Tracer materials with high densities such as solid aluminum cylinders or metal, stone, or ceramic goods would differ too much from the low densities of forest soils and behave physically rather like rocks. Other promising techniques involving tracers with magnetic properties at least result in high costs for detection devices and are difficult to remove.

As a consequence we propose a new less invasive method including corpuscular metal tracers and a metal detector. While in literature metal detection in soils is usually addressed in the context of land mines (Igel and Preetz, 2009) knowledge about accuracy and precision of the detection of smaller objects is very limited and not provided by manufacturers. We expect accuracy and precision of metal detection to depend on various factors such as soil moisture content, soil mineral composition, object depth and material, and its distance to a source of disturbance, like other metal objects.

To evaluate the method in terms of tracer material and accuracy and precision of tracer detection we pose the following questions:

1. Does tracer detectability decrease with increasing soil moisture content?
2. Does tracer detectability decrease with increasing contents of minerals with magnetic properties in soil?
3. Does tracer detectability decrease with increasing depth in soil?
4. Is the metal detector capable of distinguishing between two tracers of the same or of different materials?

To address these questions several experiments under laboratory conditions (in the following called bucket experiments) and under field conditions (in the following called field experiments) were conducted. Based on the findings from these experiments we furthermore present a case study from wood harvesting operations in steep terrain in Central Europe where soil displacement was evaluated with metal tracers. The question we pose here is:

5. Does the application of traction supporting technologies on forest vehicles reduce soil movement?

2. Materials and methods

2.1. Tracer materials and installation

The corpuscular tracers are pieces of metal pipes with 16 mm length and diameter and 1 mm wall thickness. The tracers are installed before treatment with minimum changes to soil properties and are located contactlessly with a metal detector after the surrounding soil was displaced. To cover a wide range of possible tracer materials we included four metals with different densities and magnetic properties: iron, aluminum, copper and lead. Besides finding the best tracer material we wanted to analyze the possibility of simultaneous use of different tracer materials to, for example, equip different installation depths. Iron, aluminum and copper pipes are easily available from hardware stores, while lead tracers had to be manufactured from sheet metal by a welder. For tracer installation into the ground a special tool was constructed. The tool and installation method are described in

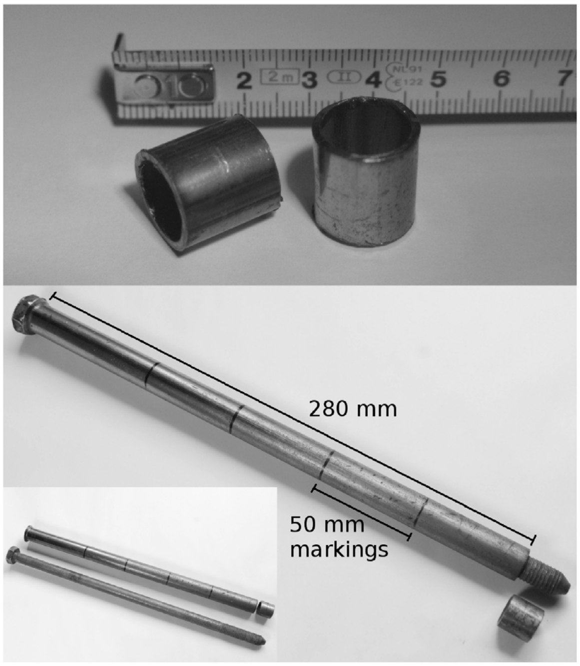

Fig. 1. Above: sections of cylindrical metal pipes with 16 mm length and diameter serve as corpuscular metal tracers. Below: The tool to install tracers is assembled from a 280 mm piece of iron pipe and a 300 mm bolt with a slightly smaller diameter than the inner diameters of pipe and tracers. The bolt would than be entered into the pipe and a tracer would be placed on the tip of the bolt. Assembled like this the tool would be placed on the desired spot and carefully hammered into the soil until the desired depth is reached. By first pulling out the bolt and then the pipe the tracer remains in place and soil material falls into the resulting hollow and the inside of the tracer cylinder. By filling the tracer with soil material the effective density of the tracers gets closer to soil density. To facilitate installation graduated markings for depth every 5 cm were painted onto the tool.