EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **44**, 1091–1099 (2019)

Published online 7 January 2019 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.4557

High precision tracing of soil and sediment movement using fluorescent tracers at hillslope scale

R.A. Hardy,[1] J.N. Quinton,[1*] M.R. James,[1] P. Fiener[2] and J.M. Pates[1]
[1] Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK
[2] Institute of Geography, University Augsburg, Augsburg, Germany

Received 25 May 2018; Revised 23 October 2018; Accepted 22 November 2018

*Correspondence to: J. N. Quinton, Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK. E-mail: j.quinton@lancaster.ac.uk

ESPL
Earth Surface Processes and Landforms

ABSTRACT: Generating high resolution spatial information on the movement of sediment in response to soil erosion remains a major research challenge. In this paper we present a new tracing method that utilises LED (light emitting diode) light to induce fluorescence in a sand-sized tracer, which is then detected, using a complementary metal oxide semiconductor (CMOS) sensor in a commercial digital camera, at mm-resolution without the need for removal of soil material. First, we detail two complementary, but independent, methods for quantifying the concentration of tracer from images: particle counting and an intensity based method. We show that both methods can produce highly resolved estimates of particle concentrations under laboratory conditions. Secondly, we demonstrate the power of the method for collecting spatial information on soil redistribution by tillage, with mm precision, over an approximately 50 m hillslope and vertically down the soil profile. Our work demonstrates the potential to collect quantitative time-resolved data about soil movement without disturbing the soil surface which is being studied, and with it the possibility to parameterise or evaluate dynamic distributed soil erosion models or to undertake fundamental research focused on particle movement that has been impossible to conduct previously. © 2018 The Authors. Earth Surface Processes and Landforms Published by John Wiley & Sons Ltd.

KEYWORDS: tracer; sediment; soil erosion; digital imaging

Introduction

Soil moves: it is eroded by wind, water and tillage and its movement can lead to on-site and off-site problems. On-site the movement of soil can reduce the soil depth in some parts of the landscape, reducing productivity, and increase it in others boosting crop yields. Not all the soil is retained in the field and some may move into surface waters, where the effects of sediment are long lasting and far reaching. These effects may include pollution due to the sediment itself (Bilotta and Brazier, 2008), sediment associated contaminants (Quinton and Catt, 2007) and pathogens (Tyrrel and Quinton, 2003), sedimentation of waterways, leading to increased flood risk (Yin and Li, 2001), and phosphorus transport, leading to the eutrophication of surface waters (Catt *et al*., 1998, Haygarth *et al*., 2005). It is estimated that in the UK alone the erosion of soil costs an estimated £108 million y^{-1} (Graves *et al*., 2015). Given the impact of soil erosion both off-site and on-site it is not surprising that scientists have expended considerable effort in trying to identify where sediment originates, its transport pathways and the rates of sediment movement.

Monitoring soil erosion dates to 1917 when the first erosion plot experiments took place at the Missouri Agricultural Experiment Station in Columbia, Missouri (USDA-ARS, 2016). Since that date many studies have determined sediment loss from a landscape by monitoring sediment fluxes at the outlet of a field plot, hillside or catchment. This has the drawback of only providing information at the sampling point. Little is revealed about the transport pathways taken by the sediment and, through the installation of infrastructure on a hillslope or channel, the act of measuring may disrupt the very system being monitored.

To help understand the rates and spatial patterns of sediment movement considerable research effort has been put into sediment tracing: see Guzmán et al. (2013) for a review focused on water erosion and Fiener *et al*. (2018) for a comparison of different tracers for evaluating tillage erosion. Sediment tracers can be split into two groups: native and exotic tracers.

Native tracers rely on a relationship between distinct characteristics of the source material and the sediment. When multiple native tracers are studied in combination, this method is often referred to as sediment finger-printing. Typical sediment properties that can be used for finger-printing are fallout radionuclide concentrations, magnetic properties, and chemical and biological composition. These native tracers allow the integrated erosion pattern to be determined over long time-scales, from decades to centuries.

Exotic tracers rely on the application of particles to a hillside or catchment with characteristics that make them easy to identify, but which behave in a similar way to the native sediment. Using exotic tracers has the advantage of providing control over the initial conditions, as tracer(s) can be applied in known concentrations at different spatial locations on a hillside (Stevens and Quinton, 2008) or small catchment (Polyakov *et al.*, 2004). Exotic tracers can take the form of microtracers (diameter < 2 mm) or macrotracers (> 2 mm). Microtracers include rare-earth oxides (Polyakov *et al.*, 2004; Stevens and Quinton, 2008) and magnetic particles (Zhang and Li, 2011), while macrotracers have included coloured stones (Turkelboom *et al.*, 1997) and metal cubes (Lindstrom *et al.*, 1990). Sampling the area following erosion allows the spatial redistribution of the sediment to be estimated (Polyakov *et al.*, 2004), and further sampling allows changes to be tracked through time (Kimoto *et al.*, 2006). However, both approaches require field samples to be taken for analysis, with the resolution of the sediment redistribution data generated limited by the spatial density of sampling. Therefore, acquiring high resolution spatial information on the movement of sediment in response to soil erosion requires significant time and resources and remains a major research challenge.

Fluorescent particles offer significant potential for tracking sediment without the need to physically sample the soil or sediment. Advances have been made in hydrology, where buoyant fluorescent particles, which can be excited by ultra-violet light, have been used to estimate surface water flow velocities in overland flow and small streams (Tauro *et al.,* 2012a, b). There have also been small-scale studies utilising particles with densities similar to that of soil and sediment particles with a fluorescent coating: for example, the real-time tracking of clay (Hardy *et al.,* 2016) and sand particles (Hardy *et al.,* 2017) across a laboratory soil flume (350 mm by 500 mm) under simulated rainfall. However, to the best of our knowledge, to date there have been no studies on hillslope sediment transport processes using materials which have the same density as quartz-dominated soil materials.

In response to difficulties in gathering spatial distributions of sediment redistribution, and the lack of work on fluorescent tracers at field scales, we present a new non-invasive tracing method that utilises LED (light emitting diode) light to induce fluorescence in a sand-sized tracer, which is then detected using a complementary metal oxide semiconductor (CMOS) sensor in a commercial digital camera, at mm-resolution without the need for removal of soil material. First, we detail two complementary, but independent, methods for quantifying the concentration of tracer from images (laboratory study); and second demonstrate the power of the method for collecting spatial information on soil redistribution by tillage over an approximately 50 m hillslope and vertically down the soil profile (field study).

Methodology

Quantifying tracer concentrations

Tracer

The tracer used throughout was a commercially-available fluorescent tracer (Partrac Ltd, UK), green in colour, consisting of natural quartz particles coated with a fluorescent pigment (Figure 1(a)). In the laboratory study, particles with a D50 of 250 μm were used, whereas in the field study a smaller tracer with a D50 of 70 μm was used. The D50 selection was arbitrary since our focus was on testing the tracer rather than mimicking the characteristics of the study soils. The tracer has been used widely in estuarine and marine studies, and to a lesser extent in terrestrial systems, and is known to be non-toxic and stable in a variety of environments (Black *et al.*, 2013; Collins *et al.*, 2013).

Lighting and image acquisition

Correct lighting is critical to successful image acquisition. The lighting must be uniform (both spatially and temporally), of narrow and fixed wavelength corresponding to the wavelength at which the tracer fluoresces, and of the correct intensity. For field work (Figure 1(c)), portability, ease of use and robustness must also be considered. Custom made lights using LEDs offered the best solution at minimal cost. Two LED lamps (nominal wavelength 450 nm) with diffusing plates fitted were used.

For the laboratory study (Figure 1(b)), images were recorded using a Canon 500D DSLR camera, and for the field studies a Lumix GH4 camera was used. A 490 nm longpass filter (Knight Optical) was fitted to the lenses to prevent the camera from detecting the LED light. The Canon 500D DSLR was controlled manually with a wired shutter release. The Lumix camera was controlled remotely using a tablet (Google Nexus 9) running the corresponding software (Panasonic Imaging App). In both

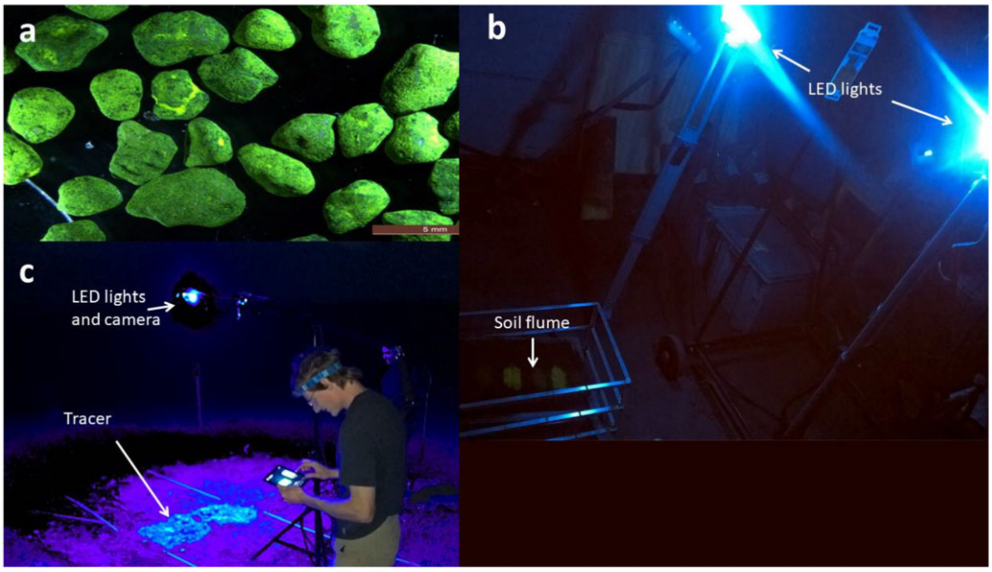

Figure 1. (a) Quartz grains coated with fluorescent coating (image courtesy of Partrac Ltd). (b) Laboratory setup showing position of LED lights and soil flume. (c) Field setup showing LED lights and camera position, the fluorescent tracer on the soil surface and remote control of the camera via a tablet. [Colour figure can be viewed at wileyonlinelibrary.com]

cases, images were recorded at the highest possible resolution in JPEG format, to ensure that the data file size was reasonable and easily accessible by a wide range of software. Post-processing was carried out using a custom written script (Hardy, *et al*., 2017) in Python (Python 2.7, SPYDER[2]).

Image interpretation

We used two methods to analyse the amount of tracer in the images: an intensity based method, similar to that of Hardy *et al.* (2016) and a particle counting method, as in Hardy *et al.* (2017). The intensity based method used the pixel values from the green colour channel in the camera. As each pixel is treated as an individual data point, each image was considered as a large matrix data set. If the average tracer concentration was desired, the median or mean value of the whole matrix was used without regard for the position of each data point. Alternatively, if the total amount of tracer in a given area was desired, then the sum of all pixels in that area was used. As the pixel data are stored as a matrix, the user can design their own analysis techniques to suit a task, for example, some tasks may favour using the geometric mean rather than the arithmetic mean. As we do not know the exact shape of the pixel intensity–sensor count relationship we prefer to present the intensity data without units. This is because we are uncertain as to the form of the intensity data produced by the camera and JPEG algorithm, we expect that it is non-linear with parts of the scale stretched and others contracted.

The second approach was to count the number of individual particles present in a given area, which is less sensitive to changes in lighting intensity and camera position than the intensity-based approach. The tracer particles are significantly brighter than the background when illuminated and can be detected even when they occupy a space smaller than a pixel. Thus, if the tracer concentration is low, the size of a pixel, commonly referred to as resolution, is not a limiting factor for their detection. The particles were located using bespoke software, drawing on the Python trackpy library (Hardy *et al*., 2017). This software also returned a parameter relating to the intensity of the located particle, permitting filtering of false positives, which are common due to the search algorithm used.

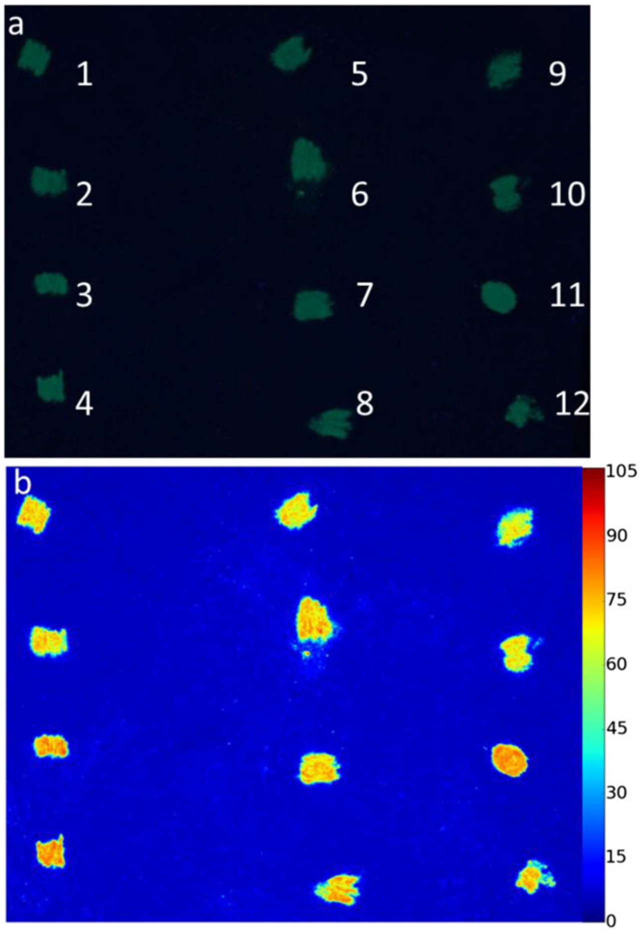

Figure 2. (a) A true colour orthophoto of the soil surface (*c.* 1.5 m^2) with 12 tracer spots (100 g kg^{-1} tracer concentration) acquired to estimate spatial variation within and between patches. (b) Image (a) after processing. The colour bar shows intensity of individual pixels. The nominal range is 0–254. Scale truncated at 105 for clarity. For analytical work the data are stored as a matrix, and are visualised here as a false colour image. [Colour figure can be viewed at wileyonlinelibrary.com]

Laboratory validation

Intensity-based method

To test the reproducibility of the tracing system performance a series of laboratory experiments were conducted. The same loam textured soil was used throughout. A 1.1 m × 1.3 m soil covered area was prepared using soil sieved to 1 mm. Tracer–soil mixtures were prepared by sieving the soil to 1 mm and combining it with the fluorescent particles in varying concentrations (see below). The tracer–soil mixture was placed on the soil surface in 0.04 to 0.065 m^2 patches, according to the specific experiment.

The following questions were then investigated:

(i) Do patches with the same tracer concentration result in the same intensity and is the intensity of each patch internally uniform?
(ii) Can the tracer be imaged reproducibly in terms of intensity?
(iii) Can different tracer concentrations be clearly differentiated?
(iv) Can the tracer concentrations be expressed as a function of intensity?

To address questions (i) and (ii), 12 patches (0.2 m × 0.2 m) of soil–tracer mixture (100 g kg^{-1}) were applied to the soil surface and images (Figure 2) acquired as described above. To answer questions (iii) and (iv), soil–tracer mixtures containing 3.97, 11.51, 19.85, 44.60 and 93.57 g kg^{-1} (concentrations A, B, C, D and E) were applied to the soil surface in patches (~ 0.25 m × 0.25 m) as a complete random block pattern and images collected as described above.

Particle counting method

To test the particle counting method, four counting test samples (CTS) were prepared in petri dishes, each containing a different number of particles (~20–200). Repeated images of the samples were captured and analysed as described above.

Field trial

To demonstrate that the method works under field conditions, we applied the tracer and our image acquisition methods during a soil tillage experiment, conducted on rolling arable farmland in north-eastern Germany (Fiener *et al*., 2018). The soils at the study site were developed from glacial till and vary in characteristics with respect to their location in the landscape. Extremely eroded Calcaric Regosols (IUSS, 2015) are located at the summit due to high tillage erosion, moderately to strongly eroded Luvisols can be found along the slopes and Colluvic Regosols, partly influenced by groundwater, are found at concave downslope areas (Sommer *et al.*, 2008; Gerke *et al.*, 2010). The plot size was 10 m × 50 m, but we focused on a 2 m × 50 m subsection of this area, because other investigations were being carried out simultaneously. A full account of this experiment can be found in Fiener *et al.* (2018). The field plot was orientated down the fall line of a gentle slope (5 to 16%) and tilled in the downslope direction only. Seven tillage events were carried out. Each tillage event consisted of a first pass with a harrow and a second pass with a roller, carried out by a local farmer under conditions that are broadly representative of tillage practices in the area, but at a lower velocity of 6 km h^{-1} instead of 15 km h^{-1}, as we were concerned that the tracer may not be recoverable at higher tillage velocities.

Prior to tilling, the tracer was placed in a 1.0 × 0.3 × 0.3 m deep trench, 12 m from the top of the plot. Once the tillage was complete, imaging markers were placed down the plot at approximately 1 m intervals, without walking on the plot, and were precisely located using a total station. The markers were used as reference points to aid analysis of the images. The images were taken from directly above the area of interest at approximately 2 m from the soil surface. Image collection started 5 m above the original tracer location and extended 10 m downslope and occurred at night to minimise the amount of background light. To analyse the images, a 400 by 400 pixel area was taken starting at the corner of each marker.

To investigate the vertical profile of the tracer, five soil pits were dug to a depth of approximately 35 cm (well below the tillage implement depth). These pits were photographed using the same type of lighting as for the horizontal tillage redistribution imaging, but with reduced intensity. The camera was placed in the pit approximately 40 cm from the pit wall on a small tripod with one LED to illuminate the pit face. The pit was covered with black plastic to prevent natural light from entering and the camera operated remotely using the tablet as described above. These images were collected during the day.

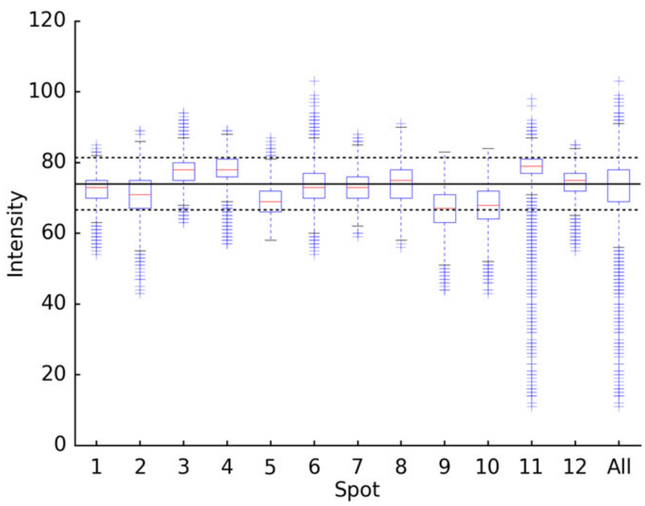

Figure 3. Variation within spots of tracer (1–12) compared with variations between spots (All). The red bar represents the median, the box represents the interquartile range, the whiskers represent the range and the crosses represent the outliers. The solid black line shows the median of all the data and the dashed lines showing ±10%. Note how all the median values are within this band with 7 below and 5 above the median. For nine spots (1, 2, 3, 4, 6, 7, 8, 11, 12) the entire interquartile range (50% of data) is within this band. Each box plot represents approximately 10 000 data points. [Colour figure can be viewed at wileyonlinelibrary.com]

Results

Laboratory validation

Intensity-based method

Figure 2(a) shows that it was possible to capture the desired area in a single photograph (~ 1.5 m × 1.5 m), while retaining a high degree of fine detail (mm resolution). A false colour image (Figure 2(b)) shows variations in tracer concentration that are not visible in the original. The data set consists of the nominal intensity of each pixel in the image.

Statistical testing of the difference between spots was not carried out as the data distribution (i.e. the amount and direction of skew) varied between tracer spots. The median intensity of the spots ranged from 67 to 79, the median of all the data points was 74.0 and the mean 73.4. All the median spot intensities fell within ± 10% of the median of the whole data set (Figure 3). Thus, we can have confidence that we can reproducibly evaluate the intensity of the tracer at a given concentration, considering all sources of variability, such as variations in lighting intensity, distance from the camera and the heterogeneity of the soil–tracer mixture.

Furthermore, the within spot intensity variation appears to be low, i.e. the interquartile range for each spot is narrow relative to the overall spread of the data (Figure 3). Some variation between spots was seen; one explanation could be that some spots were located closer to the camera than others and would therefore appear brighter or that the tracer was not perfectly mixed with the soil.

There was a small, but consistent, amount of variation in intensity between repeated images of the same spot (~ 3%), probably due to the JPEG compression process. Therefore, it is expected that using RAW images would reduce this uncertainty, but doing so would make the image analysis process more computationally intensive, due to increased file size.

Figure 4 compares the intensity of tracer patches of different concentrations. For each concentration, the interquartile ranges (representing 50% of the data points) for each discrete spot overlap, demonstrating that the intensity was reproducible between tracer spots across a range of tracer concentrations. In addition, there is no overlap of the interquartile ranges for the different tracer concentrations tested, demonstrating that they can be distinguished from each other. The small number of outliers and the tight interquartile ranges suggest that using the median is a reasonable measure of the tracer concentration in a given area.

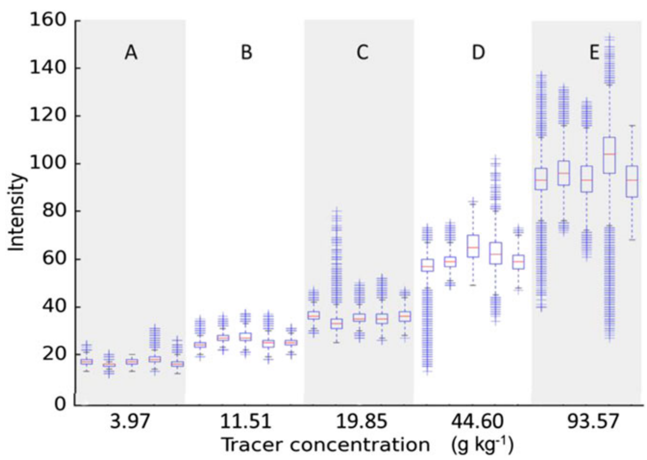

Figure 4. The variation between tracer spots of the same concentration compared with tracer spots of different concentration. Each box plot represents approximately 10 000 data points. [Colour figure can be viewed at wileyonlinelibrary.com]

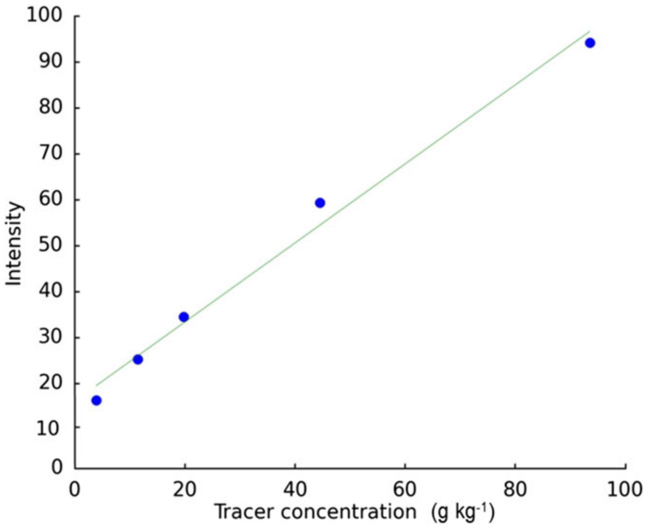

Figure 5. The relationship between the tracer concentration (g kg^{-1}) and the amount of light emitted from it. Each data point is the arithmetic mean of all data points from spots with the same concentration. The green line represents a linear line of best fit (R^2 = 0.99, y = 0.86x + 16). The offset is due to the background. [Colour figure can be viewed at wileyonlinelibrary.com]

Using a linear approximation between the mean treatment tracer concentration and intensity gives a strong linear relationship (R^2 = 0.995) (Figure 5) with some evidence of a small deviation at concentrations below 10 g kg^{-1}. Furthermore, the intensity for a zero concentration of tracer is 16, which suggests that use of the relationship below 10 g kg^{-1} may result in an over-estimation of the tracer concentration.

Particle counting method

Figure 6 shows some example images of the counting test samples (CTS) (petri dishes, containing increasing numbers of particles), indicating the locations of the identified particles. Overall, there was little to no variation between the number of particles counted in each of the 11 images of the individual CTS plates. The smallest variation was seen in CTS a (Figure 6 (a)–(e)), in which 21 particles were found in every image, and the largest variation was for CTS d (Figure 6 (d)/(h)), where the particle count ranged from 168 to 172, with a mean of 170 and a mode of 171. There appears to be a weak positive relationship between the number of particles counted and the uncertainty of the count number. When more particles are present, there is a greater chance that they will be touching, and hence may be counted as either 1 or 2 particles (as seen, for example, in Figure 6(d)) which is probably due to the shallow depth of field on the camera. Nonetheless, the images are still useable, and the software was able to easily identify the particles, suggesting that the software is reasonably insensitive to image quality.

Field trial

The purpose of the field experiment was to give insight into the type of data that is likely to be collected from tracer application, and to show how it might be analysed. Therefore, we focus on methodological issues, rather than using the data to investigate physical processes which are further explored in Fiener *et al*. (2018).

Preliminary surface results

The redistribution of the tracer downslope can be clearly seen in Figure 7, giving a truly visual representation of soil movement in response to tillage. Figure 8 shows how the tracer intensity varies downslope. Tracer intensity increases to a peak at 13 m then declines. It is likely that the sampling point near 16 m is artificially low as it was in the tractor's wheel track, something which can be clearly seen when examining the photo-mosaic of the transect (Figure 7). Using the intensity-based method, it is possible to detect tracer up to 8 m from the original tracer location and to the end of the slope using the particle counting method. The intensity-based method is simpler to execute and is computationally less intensive than the particle counting method; at this scale the former approach is less prone to sampling artefacts and additionally produces data that are commensurate with the scale of the study. The particle counting approach would be more appropriate when studying the fine detail of soil movement over mm to cm scales, as in Hardy *et al*. (2017), or where the tracer concentration becomes very low. Nonetheless, the use of two separate automated analysis methods combined with visual analysis of the images gives a high degree of confidence in the data.

Vertical distribution of tracer

Figure 9 shows one of the images clearly showing the depth distribution of the tracer. Tracer profiles were generated by determining the mean intensity across every row of pixels, such that the vertical resolution is one pixel, with approximately 50–100 data points per vertical centimetre (depending on exact camera distance from the soil face). The data collected from each slope position were interpolated to produce Figure 10 which illustrates the profile of the tracer as a function of depth and slope length. As may be expected, the tracer intensity decreases, with distance downslope. The depth of tillage (15 cm) can be clearly identified.

There is a high degree of variability within small spatial areas (both vertically and horizontally) within the soil profile (Figure 9). Part of this variability is caused by the presence of small stones, which appear as patches of moderately high intensity compared with the background soil. We have made no attempt to correct for the presence of these features, however, adjustments to the image acquisition (e.g. f-stop, ISO and shutter speed settings) would reduce their contribution. Additional image post-processing could potentially remove them altogether if necessary.

Discussion

Limits of detection and quantification

When the concentration of tracer becomes low then the intensity-based method may not return useful results because the background noise in the image is larger than the fluorescent signal, however, there is no clear point at which this occurs. The intensity-based method is dependent on several experimental factors including tracer size, camera resolution and lighting intensity, which will vary from experiment to experiment, making it hard to quantify an absolute limit of detection outside a given experimental set-up. The maximum concentration of tracer in an area also influences the limit of detection, as a bright area will saturate the camera sensor before it is able to register the duller areas with lower tracer concentrations, i.e. part of the image will be overexposed. However, removing

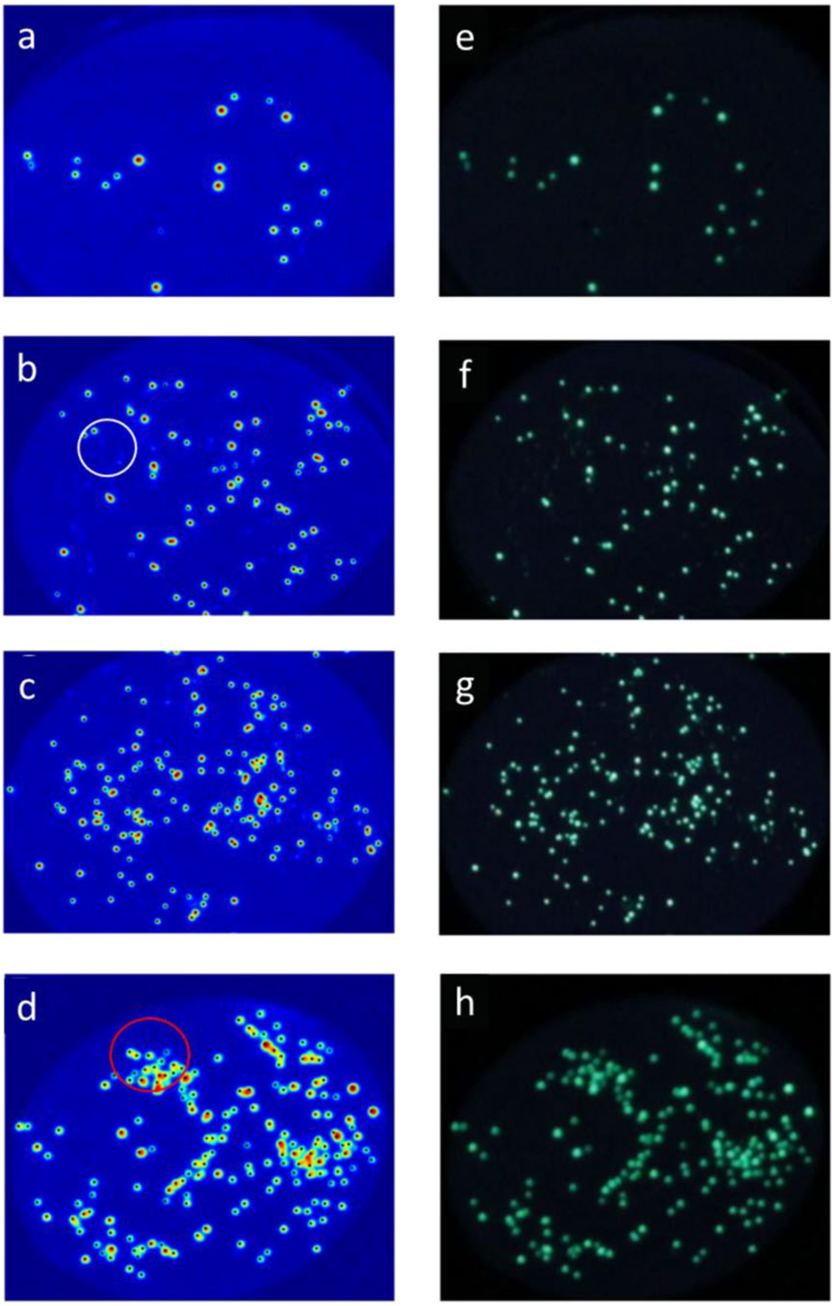

Figure 6. True and false colour images of the counting test samples (CTS a-d). (a)–(d) are false colour heat maps showing the green channel of the image and the black dots show the location of counted particles. (e)–(f) are the corresponding original images captured. Note how in some images (e.g. (b)) there is some background noise (white circle) and where there are large numbers of tracer particles (as in (d) and (h)) the particles fluorescence merges (red circle). [Colour figure can be viewed at wileyonlinelibrary.com]

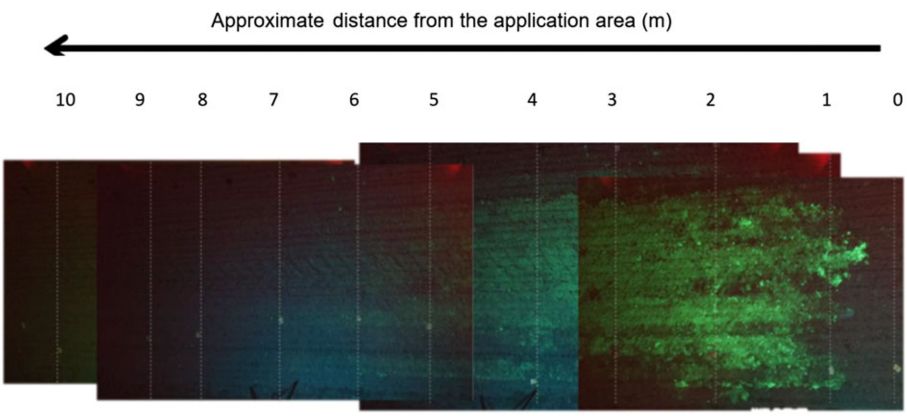

Figure 7. Photo mosaic of tracer distribution. [Colour figure can be viewed at wileyonlinelibrary.com]

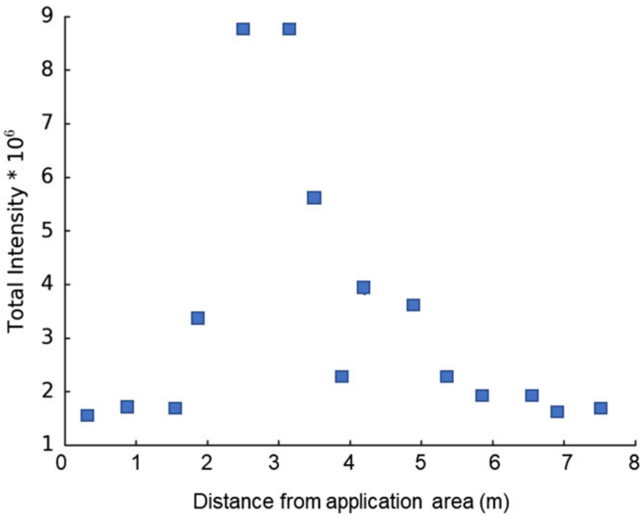

Figure 8. The total intensity of tracer in 400 × 400 pixel areas near markers approximately 1 m apart going down the slope. [Colour figure can be viewed at wileyonlinelibrary.com]

the bright area, either physically through shielding or through the image acquisition method (e.g. using high dynamic range methods, or zooming in on the lower intensity area), overcomes this issue. Thus, if required, it is recommended that the limits of detection and quantification are experimentally determined, as in Figure 4, for the circumstances under which an experiment is run.

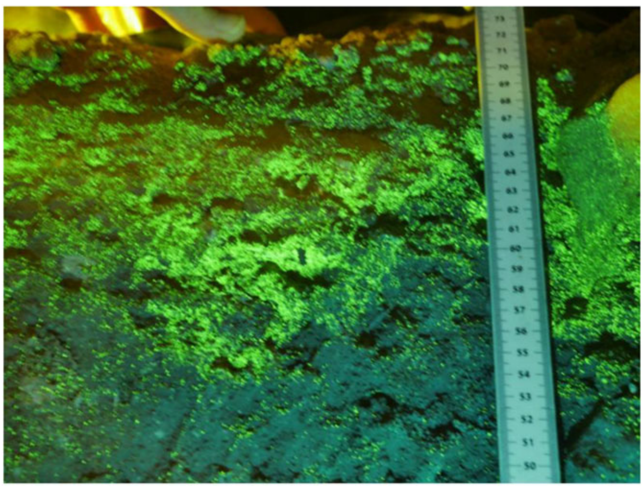

Figure 9. Photograph of the redistribution of the tracer through the soil profile following tillage close to the tracer source. [Colour figure can be viewed at wileyonlinelibrary.com]

If insufficient fluorescence is present to use the intensity-based method, it may be possible to count the individual particles. This technique has a nearly infinite limit of detection as a single particle can be detected in any sized area. Practically, the user will define the point at which the images contain so little tracer that the results are not meaningful.

Comparison of the two quantification techniques

There are relative advantages and disadvantages to using the intensity-based method rather than the particle counting method. One major advantage of the counting technique is that no calibration is required: the number of particles present are simply counted. In contrast, the intensity-based method requires the use of a calibration curve to translate intensity into other units, such as kg m^{-2}. However, the particle counting method is only useful when working at low concentrations of tracer and requires greater computing power due to the way that the particles are located, making this method much slower than the intensity-based method. The speed of the particle counting method scales geometrically with area, compared with a linear increase for the intensity-based method, making the latter approach preferable for large areas. The intensity-based method is also simpler, as only the area to be analysed needs to be defined, whereas the counting method requires the selection of parameters relating to particle size, as well as filtering of the results to remove false positives. While this process is relatively simple, the user's skill has a great effect on the time required to identify the optimum parameters for a given image set.

Field trial

As far as the authors are aware this is the largest tracing study using fluorescent imaging of a tracer that has been undertaken. It conclusively demonstrates that this methodology is usable in plot-scale outdoor studies under environmentally-relevant conditions. There were very few problems in scaling-up from the soil box used in Hardy *et al*. (2017) to plot scale, and we cannot foresee any reason that this method cannot be used on larger areas if desired.

One significant advantage of this non-destructive sampling approach is that data are acquired from the whole study area, at a scale that is not achievable through conventional destructive sampling methods and within a time-frame that would not be possible from high-resolution spot measurements. In addition, the resolution of the data is such that the images can be magnified and fine-scale details (mm to cm) can be detected. In other words, a single image, taking no more than 15 minutes to acquire, can be analysed at meter to millimetre scale,

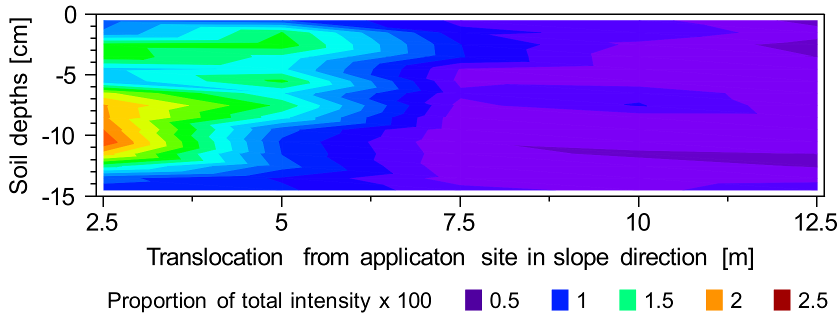

Figure 10. Translocation of the tracer downslope following seven tillage passes (adapted from Fiener *et al*., 2018). [Colour figure can be viewed at wileyonlinelibrary.com]

facilitating insights that are not otherwise achievable. For reference, the data presented in Figure 7 took approximately 2 hours to collect. Furthermore, we were able to review each image in the field as soon as it had been taken. Humans are very adept at intuitively judging the quality of an image, providing constant reassurance that we were collecting usable data (and an opportunity to take additional images where needed). This *in situ* quality control is not usually associated with traditional sampling techniques. Finally, the ability to review tracer distribution in the field allows the experiment to be adjusted and adapted according to your observations.

Advantages of fluorescent tracking

One of the major benefits of this technique is the removal of the need to physically sample the soil, which has multiple impacts. First, the lack of disturbance to the soil system while collecting data allows a truer impression of soil movement to be gained. Second, the temporal and spatial resolution of this technique is nearly infinite. Cooper *et al*. (2012) offer one of the few examples of high resolution tracing experiments that have been undertaken, sampling an approximately 14 m × 6 m area using a 0.3 m × 0.3 m grid to evaluate a new soil erosion model. This study, utilising the native tracer ^{137}Cs, required over 600 samples to be taken by hand, making this approach impractical for studies of larger areas. The model produced spatially-resolved results of a similar type to those produced during the field work we report on here, which suggests that the type of data produced here could be helpful in the design, development and testing of existing and future soil erosion models. It would also allow for these measurements to be taken without the need for laborious hand sampling and subsequent analysis.

Guzmán *et al*. (2013) conclude that rapid and inexpensive sampling is a requirement of future tracing techniques. We argue that the technique presented here satisfies this demand and has the additional benefits of being both non-destructive and carried out *in situ*.

Limitations of fluorescent tracking

This method was designed to enable investigation of the movement of soil particles across a soil surface, particularly due to rainfall and tillage. It was also used to trace particle movement vertically through the profile in response to tillage, on a face of a soil pit. The method can only detect particles that are both exposed to blue light from the LEDs and are able to emit green light back to the camera. If sufficient water covered a particle, or that water was very turbid, then that particle would not be detected. Additionally, images can only be taken in darkness, as natural light overwhelms the signal from the tracer. Thus, in the field, the surface work must be carried out at night (it is relatively easy to exclude daylight in the laboratory or from soil pits).

Conclusions

This paper described the collection of a unique data set on sediment movement with exceptional temporal and spatial resolution providing a method that can be used in studies of sediment redistribution on hillsides. The technique relies on consumer grade digital cameras, inexpensive filters and LED lights, and image analysis together with a commercially available fluorescent tracer. Due to the speed at which images can be acquired and the ability to integrate the information into existing methodologies, such as photogrammetry, it is possible to investigate much larger areas at higher resolution than has previously been possible.

The technique offers a significant advance on existing methodologies which rely on the removal of soil from the study area and opens the possibility to collect quantitative time-resolved data about soil movement without disturbing the soil surface which is being studied. Thus, there is potential to parameterise or evaluate dynamic distributed soil models or to undertake fundamental research focused on particle movement that have been impossible to conduct previously.

Acknowledgements—The authors would like to acknowledge the help and support of Dr Kevin Black (Partrac Ltd) and logistical support from Institute of Soil Landscape Research at the Leibniz-Centre for Agricultural Landscape Research ZALF e.V., Müncheberg, Germany. The study was supported by the Terrestrial Environmental Observatory TERENO-Northeast, of the Helmholtz Association. Robert Hardy was funded by a joint UK Natural Environment Research Council – Analytical Chemistry Trust Fund studentship (NE/J017795/1).

REFERENCES

Bilotta G, Brazier R. 2008. Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research* **42**: 2849–2861.

Black K, Sloan J, Gries T. 2013. Everything goes somewhere; tracking the movement of contaminated sediments in an industrialised estuary using dual signature sediment tracers. In *Tracer 6 - the 6th International Conference on Tracers and Tracing Methods*, Haugan A (ed). EDP Sciences: Cedex A.

Catt JA, Howse KR, Farina R, Brockie D, Todd A, Chambers BJ, Hodgkinson R, Harris GL, Quinton JN. 1998. Phosphorus losses from arable land in England. *Soil Use and Management* **14**: 168–174.

Collins AL, Zhang YS, Duethmann D, Walling DE, Black KS. 2013. Using a novel tracing-tracking framework to source fine-grained sediment loss to watercourses at sub-catchment scale. *Hydrological Processes* **27**: 959–974. https://doi.org/10.1002/hyp.9652.

Cooper JR, Wainwright J, Parsons AJ, Onda Y, Fukuwara T, Obana E, Kitchener B, Long EJ, Hargrave GH. 2012. A new approach for simulating the redistribution of soil particles by water erosion: a marker-in-cell model. *Journal of Geophysical Research - Earth Surface* **117**. https://doi.org/10.1029/2012jf002499.

Fiener P, Wilken F, Aldana-Jague E, Deumlich D, Gómez JA, Guzmán G, Hardy RA, Quinton JN, Sommer M, Van Oost K, Wexler R. 2018. Uncertainties in assessing tillage erosion – how appropriate are our measuring techniques? *Geomorphology* **304**: 214–225.

Gerke HH, Koszinski S, Kalettka T, Sommer M. 2010. Structures and hydrologic function of soil landscapes with kettle holes using an integrated hydropedological approach. *Journal of Hydrology* **393**: 123–132. https://doi.org/10.1016/j.jhydrol.2009.12.047.

Graves AR, Morris J, Deeks LK, Rickson RJ, Kibblewhite MG, Harris JA, Farewell TS, Truckle I. 2015. The total costs of soil degradation in England and Wales. *Ecological Economics* **119**: 399–413. https://doi.org/10.1016/j.ecolecon.2015.07.026.

Guzmán G, Quinton JN, Nearing MA, Mabit L, Gómez JA. 2013. Sediment tracers in water erosion studies: current approaches and challenges. *Journal of Soils and Sediments* **13**: 816–833. https://doi.org/10.1007/s11368-013-0659-5.

Hardy RA, James MR, Pates JM, Quinton JN. 2017. Using real time particle tracking to understand soil particle movements during rainfall events. *Catena* **150**: 32–38.

Hardy RA, Pates JM, Quinton JN, Coogan MP. 2016. A novel fluorescent tracer for real-time tracing of clay transport over soil surfaces. *Catena* **141**: 39–45. https://doi.org/10.1016/j.catena.2016.02.011.

Haygarth PM, Condron LM, Heathwaite AL, Turner BL, Harris GP. 2005. The phosphorus transfer continuum: linking source to impact with an interdisciplinary and multi-scaled approach. *Science of the Total Environment* **344**: 5–14.

IUSS. 2015. World reference base for soil resources 2014. Update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO: Rome

Kimoto A, Nearing MA, Shipitalo MJ, Polyakov VO. 2006. Multi-year tracking of sediment sources in a small agricultural watershed using rare earth elements. *Earth Surface Processes and Landforms* **31**: 1763–1774. https://doi.org/10.1002/esp.1355.

Lindstrom MJ, Nelson WW, Schumacher TE, Lemme GD. 1990. Soil movement by tillage as affected by slope. *Soil Tillage Research* **17**: 255–264.

Polyakov VO, Nearing MA, Shipitalo MJ. 2004. Tracking sediment redistribution in a small watershed: implications for agro-landscape evolution. *Earth Surface Processes and Landforms* **29**: 1275–1291.

Quinton JN, Catt JA. 2007. Enrichment of heavy metals in sediment resulting from soil erosion on agricultural fields. *Environmental Science and Technology* **41**: 3495–3500. https://doi.org/10.1021/es062147h.

Sommer M, Gerke HH, Deumlich D. 2008. Modelling soil landscape genesis – a 'time split' approach for hummocky agricultural landscapes. *Geoderma* **145**: 480–493. https://doi.org/10.1016/j.geoderma.2008.01.012.

Stevens CJ, Quinton JN. 2008. Investigating source areas of eroded sediments transported in concentrated overland flow using rare earth element tracers. *Catena* **74**: 31–36.

Tauro F, Grimaldi S, Petroselli A, Porfiri M. 2012a. Fluorescent particle tracers in surface hydrology: a proof of concept in a natural stream. *Water Resources Research* **48**: W06528. https://doi.org/10.1029/2011WR011610.

Tauro F, Grimaldi S, Petroselli A, Rulli MC, Porfiri M. 2012b. Fluorescent particle tracer for surface flow measurements: a proof of concept in a semi-natural hillslope. *Hydrology and Earth System Sciences* **16**: 2973–2983.

Turkelboom F, Poesen J, Ohler I, VanKeer K, Ongprasert S, Vlassak K. 1997. Assessment of tillage erosion rates on steep slopes in northern Thailand. *Catena* **29**: 29–44.

Tyrrel SF, Quinton JN. 2003. Overland flow transport of pathogens from agricultural land receiving faecal wastes. *Journal of Applied Microbiology* **94**: 87S–93S.

USDA-ARS. 2016. *USLE History*. US Department of Agriculture.

Yin H, Li C. 2001. Human impact on floods and flood disasters on the Yangtze River. *Geomorphology* **41**: 105–109. https://doi.org/10.1016/S0169-555X(01)00108-8.

Zhang JH, Li FC. 2011. An appraisal of two tracer methods for estimating tillage erosion rates under hoeing tillage. *Environmental Engineering and Management Journal* **10**: 825–829.

