Identification of ditches and furrows using remote sensing: Application to sediment modelling in the Tana watershed, Kenya

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Abstract

Ridge-tillage is an agricultural practice where crops are planted on elevated ridges, with furrows in-between. Ridge-tillage has been shown to significantly reduce erosion from croplands, but data on the presence of ridge-tillage is sparse and challenging to collect at the landscape scale. Thus, water quality models often do not account for ridge-tillage in a spatially-explicit manner, potentially overlooking the important impacts of this practice. We have developed a novel method that exploits the spectral, radiometric and linearity shape characteristics to identify both drainage ditches and ridge-tillage furrows using remote sensing of 0.5 m satellite data. We applied the method to the Sasumua watershed in Kenya, where we had false positives in only 3% of randomly selected polygons, and we detected the majority of ditches in 59% of randomly selected polygons. We then assessed the potential value of including these data in sediment modelling, showing that representing these practices could reduce sediment export in the study area by roughly 80%. Being able to readily identify the presence of ditches and furrows could enable the development of more accurate water quality models, and help identify priority areas for intervention to improve water quality (and possibly crop yields) through changing agricultural practices or policies.

Keywords: drainage ditches; ridge-tillage; feature extraction; soil erosion; remote sensing

Introduction

Erosion from croplands impacts both surface water quality (Pimentel et al. 1995) and contributes to soil degradation (Walling 2009), which in turn leads to declining agricultural productivity (Lal and Moldenhauer 1987; Lal 2001; Bindraban et al. 2012). Off-site economic effects of erosion include damage to civil structures, siltation of reservoirs, and additional costs involved in water treatment (Lal 1998).

In the United States ridge-tillage has been shown to reduce sediment export relative to conventional tillage by 82-90% (Reeder 1990; Wang et al. 2008). There is also evidence that ridge-tillage can reduce subsurface export of pesticides (Fawcett, Christensen, and Tierney 1994) and nitrates (Lowery et al. 1998). Ridge-tillage is primarily used by farmers to improve crop yields in poorly-drained soils (Eckert 1987; Fausey 1990), although in well-drained or moderately drained soils ridge-tillage can lead to a modest decline in crop yields (Pikul et al. 2001; Wilhelm and Wortmann 2004) and water infiltration (Lal 1997). Even where yields decline after adoption of ridge-tillage, over the long-term reduced erosion may eventually provide superior yields relative to long-term conventional tillage (Wilhelm and Wortmann 2004).

Vegetated agricultural drainage ditches can improve water quality by trapping sediment and nutrient from agricultural storm runoff (Bennett et al. 2005) and reducing declines in yield (Lutz, Pagiola, and Reiche 1994). In some cases drainage ditches have been found to reduce the impact of herbicides (Crum, Aalderink, and Brock 1998), reduce nonpoint-source pesticide pollution (Schulz and Peall 2001) and improve water quality (Meuleman, De Bruin, and Beltman 1990). However, non-vegetated drainage ditches connected to streams can in some cases substantially increase sediment export (Grace III 2002; Nieminen et al. 2010). In this paper, we review the benefits provided (in reducing sediment transported to streams) by both drainage ditches and furrows from ridge-tillage (an agricultural practice where crops are planted on elevated ridges, with furrows in-between which are generally not connected to streams or ditches). We then demonstrate a novel method to map these ditches and furrows using high-resolution satellite imagery, and evaluate the impact of including these data in sediment models.

Drainage ditches (which can look similar to furrows from ridge-tillage, but are often connected to other hydrologic features) serve as links between croplands and receiving waters (Moore et al. 2001). They can perform various hydrologic functions (Levavasseur et al. 2012) and exfiltration to ditch networks by lowering the water table, infiltration from the ditch toward the groundwater, and conveyance of water toward downstream areas.” In some instances, drainage ditches are also filled with irrigation water during the dry season. The magnitude of each hydrologic function depends on the location of the drainage network in the landscape, as well as climate, topography and soils. This explains why drainage ditches may have different or even opposite effects at the watershed scale, depending on the spatial and temporal context. For example, drainage ditches may convey more direct runoff during storms, resulting in higher peak flow and total runoff volume, while also promoting water infiltration during drier periods, thereby reducing flow velocity and total runoff volume at those times. These trade-offs also apply for sediment transport, with a reduction in erosion being observed due to lower surface runoff during dry periods, but possible higher transport of sediment coming from upstream of the ditch, during heavy rain events (Needelman et al. 2007). Unfortunately, while they function differently both drainage ditches and furrows from ridge-tillage look similar on satellite imagery (if they are visible at all).

The complexity of these processes mean that often sophisticated hydrologic models are needed to understand the effect of drainage ditches on catchment hydrology. Several models have been developed, often adapting existing hydrologic models to incorporate man-made infrastructure (Moussa, Voltz, and Andrieux 2002; Duke et al. 2006; Levavasseur et al. 2012). These models are typically spatially-explicit to account for the topology and location of the network in the landscape and consequently often have high data requirements (e.g. (Carluer and De Marsily 2004)). Integrating landscape features allows the primary flow paths of water, sediment and nutrient transport to be identified. Conversely, failing to account for the presence of drainage ditches could mean that models may be over-calibrated to fit calibration data, leading to models that appear correct but for the wrong reasons (Kirchner 2006).

Despite the importance of incorporating drainage ditches in hydrologic models, data on the location of these ditches is often unavailable. A method to detect furrows (which appear very similar to drainage ditches on satellite imagery) from high-resolution imagery was recently proposed that focused on developing a segmentation algorithm, enhancing image contrast, and thresholding to map furrows (Le Hegarat-Mascle and Ottle 2013). In this manuscript, we demonstrate an alternative approach using off-the-shelf software (as opposed to developing a novel algorithm) to using satellite imagery to map dominant management practices (ditches for drainage / retention / infiltration, as well as furrows from ridge tillage) in an agricultural area of Kenya with the aim of incorporating them into a hydrologic model. As our data was unable to distinguish between these different features, hereafter we collectively refer to them as "ditches and furrows" when describing our remote classification. We evaluated the impact of ditches and furrows on predicted sediment yield in an agricultural watershed, illustrating the significance of such dataset for watershed-scale sediment modelling. Our focus here is on the remote sensing method; our sediment model is relatively simple and is only intended to show the potential impact of accounting for the presence of ditches and furrows.

Study area

In January 2015, a new research project began with the aim to improve the design and facilitate implementation of the Upper Tana water fund (a financial tool where water users pay for upstream conservation to retain sediment and increase flow). The focal area within the Upper Tana watershed (which provides drinking water to Nairobi, Kenya) was the Sasumua region where annual vegetable crop production is concentrated. The study area in the Sasumua region covers 124.51 km^2, and is characterized by relatively flat to moderately sloped terrain and small field size with high spatial heterogeneity in cropping practices across the landscape.

During the rainy season, water treatment costs increase by about 30% according to the Nairobi City Water and Sewerage Company (Hunink and Droogers 2015; Vogl et al. 2016). Erosion from cropland has led to sediment deposition in reservoirs, and thus a loss in the volume of water stored by reservoirs (Masinga reservoir has lost 10% of its capacity since 1981, and Kamburu reservoir has lost 15% of its capacity since 1983 (Hunink and Droogers 2015).

One aspect of this new research project involved the use of high-resolution satellite imagery to more accurately map the agricultural landscape (land cover and agricultural practices). In the production of the land cover map a pan-sharpened multispectral Pléiades image composite was created, appropriate shape representation in the supervised classification tool were set, and areas that could complicate the classification process and lengthen the processing time were masked and the post processing options (e.g. aggregating / removing small / big regions or smoothing shapes) were specified in Feature Analyst (Textron Systems, 2016) tool. While we first produced a high-resolution land cover layer, the more innovative aspect of our work (and our focus of this paper) was to map conservation agriculture practices for use as input to hydrologic process models. Farmers in Kenya use ditches and furrows primarily to drain excess water during the rainy season, and in some cases, also use them for irrigation during the dry season (WOCAT 2016). As observed on high-resolution image, in plots of relatively similar land slope (on average 5%), ditches and furrows on clay and silty clay loam soils are spaced more narrowly (at about 8 - 8.4 m apart, or a density [length of ditches and furrows per unit area] of 0.1 m m^{-2}) than on clay loam soils (spaced 13 m apart, with a density of 0.08 m m^{-2}), while on loam soil ditches and furrows only exist around the perimeter of farm plots rather than within the plots.

Field visits established the prevalence of some form of ridge-tillage throughout the study area (and especially in the wettest areas), as well as the presence of drainage ditches in some areas (along roads, within fields, and around the edges of fields). Some of the ditches and furrows were bare soil while others were fully vegetated, and the depth and width varied considerably (Figure 1). While normally ridge-tillage involves a furrow between each crop row (one row per ridge), in Sasumua there are several rows of crops on each relatively wide / flat ridge with furrows in between. In preparation for harvest the entire field is generally cleared rather than leaving crop residue in the furrows. For the dominant crops (vegetables such as cabbage, potato, carrots, arrowroot, beans, etc.) in the study area, there are typically 3-4 plantings each year, with the soil fully tilled prior to each new planting (although some relatively common crops like maize have a longer rotation). As such, the potential for erosion from these fields during the rainy season is high despite the relatively flat landscape.

Figure 1: Four examples of what detected ditches and furrows look like on the ground (*a*) an in-field ditch, (*b*) a shallow channel along a roadside, likely not functioning as a ditch, (*c*) vegetated furrows in a wet area (the brighter green grasses are in the furrows which also had standing water visible), (*d*) a large ditch in a well-drained field (roughly ½ m deep, no water visible).

Methods

Our analysis consisted of five steps: 1) conducting field work to identify ditches and furrows on the ground (plus ground control points for image rectification), 2) acquiring and processing high-resolution satellite imagery, 3) classifying ditches and furrows from the imagery using Feature Analyst, 4) assessing the accuracy of the classification, and 5) conducting an exploratory analysis of how accounting for these ditches / furrows may affect sediment transport in the landscape (to determine whether or not it significantly alters model results).

Field work

Field work was conducted June 9-17, 2015 to identify the presence (or absence) of ditches and furrows in fields within the study area. At each of 236 sampling points (187 on farmland, 49 on pasture), the GPS coordinates of the observation point was recorded, along with photographs, and notes about land cover and agricultural management practices adjacent to the point (including but not limited to drainage ditches and ridge-tillage). An additional 13 points used for ortho-rectification were collected using a more precise RTK GPS unit.

Imagery acquisition and processing

Pléiades satellites imagery with panchromatic (0.47 to 0.83 μm) and multispectral (Red-Edge, Green, Blue and NIR) bands were collected at 0.5 m and 2 m resolution, respectively for June 22, 2015 (the closest available date to the field work with mostly cloud-free imagery). The imagery was supplied with standard radiometric calibrations and adjustments. The image was rectified using the platforms Rational Polynomial Coefficient (RPC), coordinates for ground control points (GCPs) collected at the field and ERDAS IMAGINE's in-built Digital Elevation Model (DEM) and then re-projected to the area coordinate. An ortho-rectification error of 4 to 7m was observed. A Gram – Schmidt pan-sharpening method was used to generate a 0.5 m resolution raster of the multispectral bands. Details of how the transformation works are provided by Laben and Brower (2000). The pan-sharpened images were used in extracting the agricultural ditches and furrows in the study area.

Classification of ditches and furrows

Feature extraction exploits objects' attributes (e.g. size, shape, width, direction, intensity, shape, texture, and context) to define them (Suetens, Fua, and Hanson 1992). The appearance of linear features (e.g. canals, ditches, furrows, roads, etc.) in imagery is dependent on sensor spectral and radiometric characteristics and image spatial resolution. In lower spatial resolution image (e.g. Landsat), large visible linear features (e.g. canals, highways) appear as lines (and smaller features are not visible at all). In higher resolution imagery (< 2m), ditches still look linear but show a bit more variation (with the key property being that they are long and mostly homogeneous regions with consistently narrow width, (Baumgartner et al. 1999)). The most pronounced characteristics of ditches and furrows is their appearance as an elongated parallel linear feature in an agricultural field. Ditches and furrows filled with water (or with higher subsurface moisture) and having less vegetation appear darker and more homogeneous, whereas ditches and furrows that are more dry but have more weeds in them appear lighter and more heterogeneous (but both are still linear features contrasting with the colour and texture of the adjacent field).

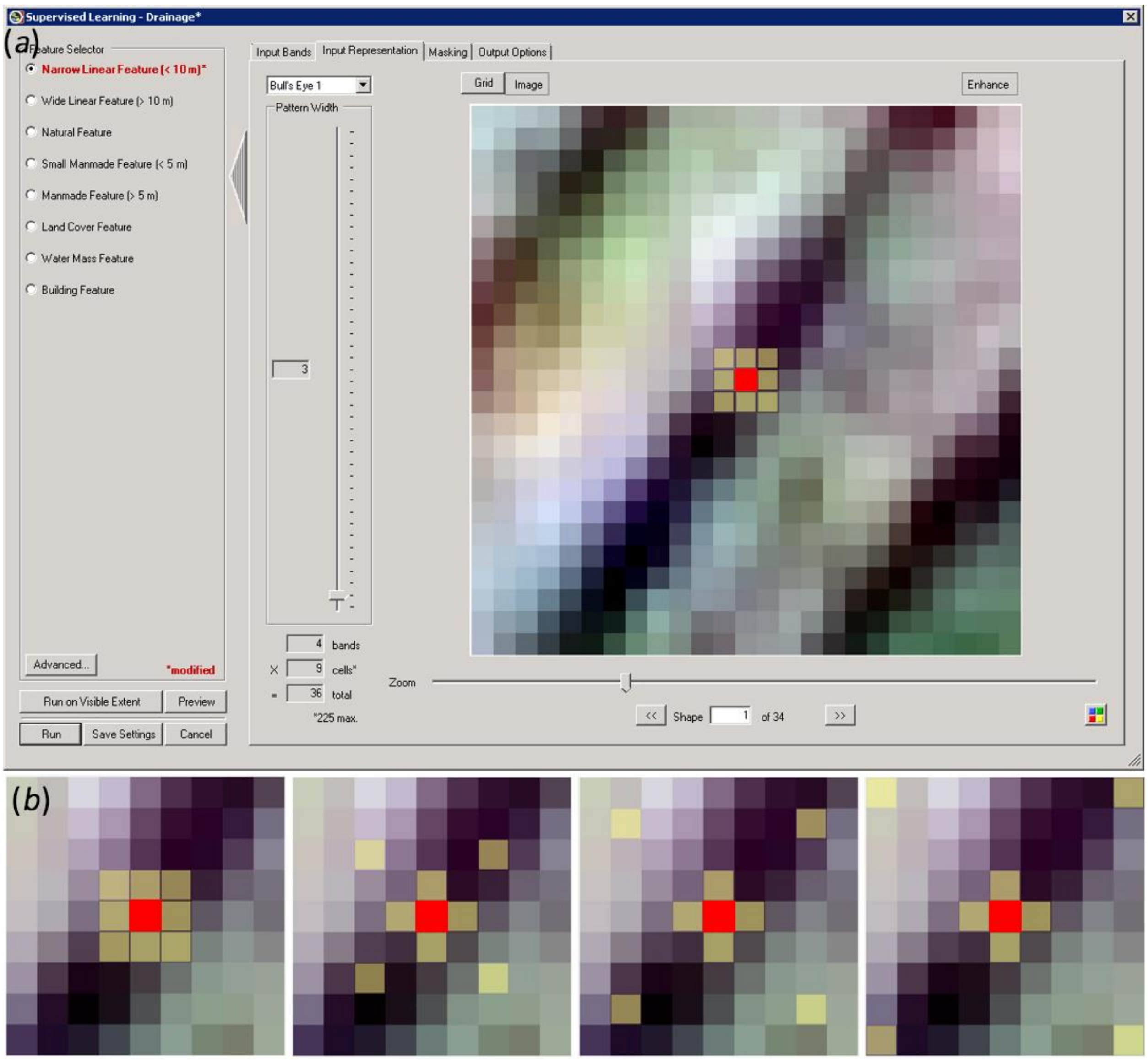
These characteristics, combined with field observations of the presence of ditches and furrows (the only place we directly utilized our field data), were employed to map ditches and furrows using Feature Analyst (Textron Systems, 2016), an automated user trained feature extraction tool that identifies objects based on training samples. The training samples provided the spectral and contextual basis for the classification algorithm to identify similar objects via a learning process. While various learning process (e.g. artificial neural network, decision trees, Bayesian learning, K-nearest neighbour) may be used, Feature Analyst uses multiple processes to obtain better predictive performance than can be obtained using a single algorithm (Opitz and Blundell 2008). The spectral and spatial / contextual characteristics obtained from these predictors are used by the tool to identify similar features in the imagery provided.

In our case we exploited the low albedo characteristics of water on a multispectral image to identify ditches and furrows filled with water (Wang and Weng 2013). Nevertheless, at the image acquisition date the ditches and furrows were filled to a varying degree, thus exhibiting a varying contrast. We addressed such variations by applying three supervised classification runs using three training samples created to represent wetter (filled or partly filled with water), intermediate, and drier ditches and furrows. This helps to maintain minimum variation in the spectral signature of features and to simplify the refinements through hierarchical learning.

A supervised learning setup includes five steps: *selection of feature shape*, *input bands* (reflectance, discrete, texture or elevation), *input representation method* as well as *masking* and *post processing* options. In the feature shape selection, feature attributes (e.g. width) and shape attributes (e.g. linear) were set and the feature shape selector was set to “Narrow Linear Feature (<10m)” (Figure 2 (*a*)). The pan-sharpened images were selected in the input bands selector. The emissivity layer generated based on the vegetation proportion (Sobrino, Jiménez-Muñoz, and Paolini 2004) was used to represent texture (local contrast). A slope raster could have helped the training algorithm associate flat slopes to prevalence of “Narrow Linear Feature,” but this would have required a DEM of comparable resolution which we did not have.

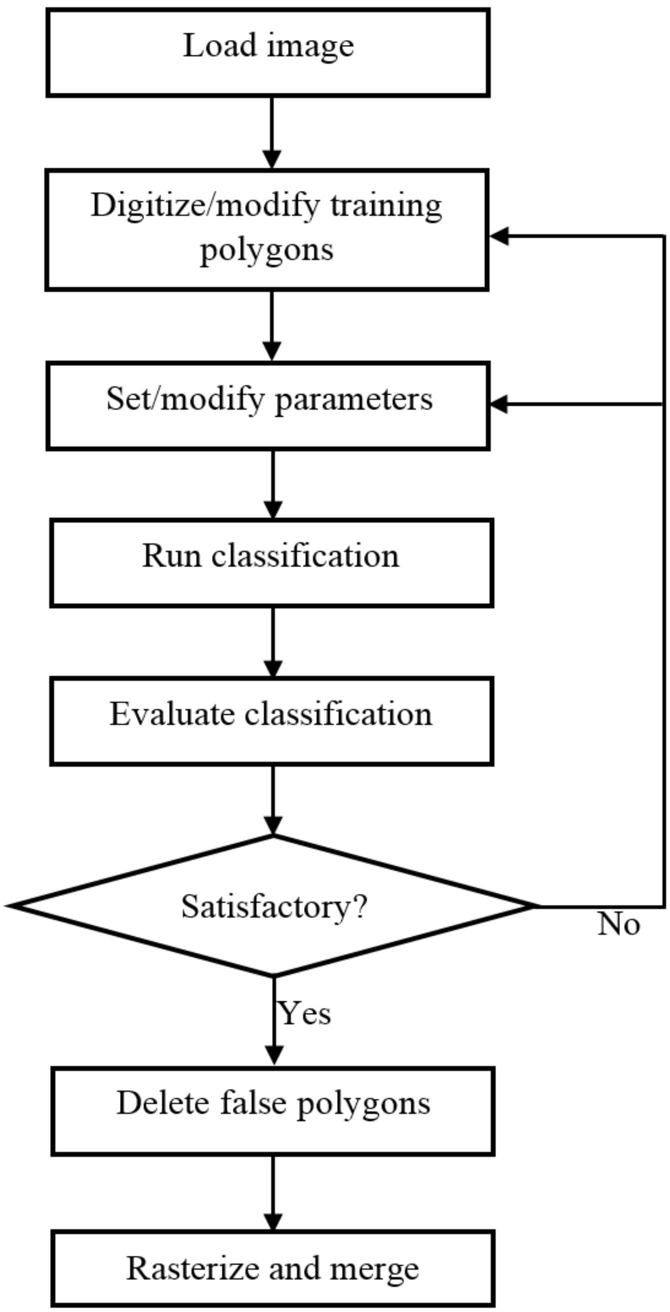
Defining the spatial context of the target feature class is a crucial step. For example, ditches and furrows filled with water could have a similar spectral signature to that of ponds. However, the spatial context of each target is different. The ditches and furrows exhibit a roughly equally spaced occurrence with alternate vegetation in between them, whereas a pond is a relatively isolated feature randomly scattered on a given scene. For input representation Feature analyst provides seven built-in (Square, Circle, Manhattan, and Bull’s Eye 1 to 4) and two user defined patterns along with an option to set the pattern width (Figure 2 (*b*)). The default Bull’s Eye 1 representation with 3-pixel pattern width was used to capture the narrower ditches and furrows (~1.5m) and the 5-pixel pattern width was used for wider ditches and furrows. The ditches and furrows classification runs were applied on a single image.

Figure 2. (*a*) A screenshot of a typical Feature Analyst setup for "Narrow Linear Feature" classification with a 3 by 3 window input representation pattern and (*b*) a 3, 5, 7 and 9 pattern widths representations where yellow boxes are learning pixels that the algorithm to predict the centre pixel shown in red.



The land cover map produced was used to restrict the classification run to agricultural areas (cropland and pasture) to minimize the time required for a single classification run and to reduce false positives in areas where ditches and furrows should not be present (like forests or urban areas). Each classification run produced cluttered polygons having a length not typical of ditches and furrows. The post processing settings help remove these small polygons using an aggregation / removal and smoothing threshold area set for each round of classification. As the aggregation / removal setting impacted the classification result considerably, further post processing was based on removal of cluttered polygons using an area threshold outside the Feature Analyst working environment. Generally, all the supervised learning parameters were set on a trial basis and evaluated within a zoom level that allowed visual identification of ditches and furrows; the set parameters were then run on the visible extent and visually evaluated for accuracy. Once a satisfactory setting was attained the classification was run on the entire image masked to the land cover raster other than the agricultural land. The resulting raster were merged to create the final ditches and furrows classification layer. The flow chart in Figure 3 outlines the work procedure followed. Note that every classification run generates an automated feature extraction (AFE) files which could be used to extract similar features on series of images without re-doing the learning settings.

Figure 3. Work flow diagram for classification of ditches and furrows



Accuracy assessment

We conducted three independent accuracy assessments, which collectively serve to describe the performance of our classification. First, we compared our classified ditches and furrows to manually digitized ditches and furrows on 16 plots across different soil types to compare our method to a simple manual classification (both results and effort). Second, we conducted a more comprehensive assessment on 200 sample grids (90 m^2 each, 100 grids classified as having no ditches and furrows, and 100 grids classified as being more than 5% covered by ditches and furrows) to identify the prevalence of both false negatives and false positives in our classification. Finally, we had access to data collected from a spatially explicit household survey in our study area which asked farmers whether they used ridge-tillage or drainage ditches on their farm (see Masuda et al In Review), so for 540 farm plots we compared our classification of ditches and furrows to the survey data reporting whether or not the farmer reported ditches and furrows being present.

First, we randomly selected 16 plots split across dominant soil types (clay, clay loam and silty clay loam), manually digitized visible ditches and furrows, and calculated the average density of ditches and furrows in the study area. We also compared the time needed for manual digitization as compared to using Feature Analyst. This manual digitization is insufficient as an accuracy assessment. It had a very small sample and would only be valid if ditches and furrows had the same density and prevalence throughout the study area. Given that field work showed how heterogeneous ditches and furrows were (both across the landscape, and on individual farm plots), we continued with two more thorough accuracy assessments as described below.

Comprehensively assessing the accuracy of the detection of ditches and furrows was challenging; a pixel level assessment is inappropriate as the metric of interest is whether a given area (e.g. a farm plot) has ditches and furrows present and if so, at what density. Getting that right does not require every pixel to be perfectly located, only that we detect the essential features. Similarly, simply recording the presence or absence of ditches and furrows within a sample grid could lead to a grid with only one very small ditch or furrow (but mostly un-drained) being classified as a false negative if no ditch or furrow was detected (which is very different from missing most or all of the ditches and furrows in an area). Given this challenge, we took a more qualitative approach for our second accuracy assessment as described below.

As it was not possible to collect field data evenly across the study area (due to lack of roads, flooded roads, and other obstacles), we used a pseudo-ground-truthing approach for our accuracy assessment. We first established using our field data on the presence and density of ditches and furrows that we could reliably identify ditches and furrows by visually examining the imagery, which was successful. We then used visual inspection of the imagery as pseudo-ground truthing to substitute for the lack of actual field data throughout the study area. We began by breaking the entire study area up into a series of sample grids of 30 m by 30 m (3600 pixels each, 90 m^2), and for each grid calculated the proportion covered by pixels classified as ditches and furrows. To identify false negatives, we visually inspected 100 sample grids picked randomly among the grids which had 0 classified ditch and furrow pixels in them. For each one, we visually inspected the imagery to determine whether any ditches and furrows were in fact present; ditches and furrows visible but missed by our classification represent false negatives. These detected features had to be substantial (at least one actual linear ditch or furrow and not just a small fragment of a ditch or furrow - e.g. a ditch or furrow 95% in another plot but with a meter or two extending into the sample grid).

To identify false positives, we repeated the process with 100 sample grids picked randomly among the grids which had >5% of the area classified as ditches and furrows (a subjective threshold found to indicate that substantial drainage was present). As with the prior 100 grid, we visually inspected the imagery to determine whether actual substantial ditches and furrows were apparent in the imagery, and whether the majority of classified ditches and furrows were visible in the imagery. Grids with no substantial ditches and furrows visible in the imagery (despite having been classified as containing them) indicated a false positive. We also tested whether the majority of ditches and furrows visible in the imagery were detected by the classification (to identify areas where we under-detected ditches and furrows).

Finally, using complementary data from a related research project we were also able to compare the results of our remote sensing classification method to an alternative approach: using household surveys to identify ditches and furrows. Masuda *et al*. 2016 surveyed farmers about the agricultural practices they used on their farm plots within our study area in Sasumua (including but not limited to ridge-tillage, drainage ditches within their fields, and drainage ditches around their fields). They also had farmers delineate the spatial boundaries of their plots using ArcGIS Collector and the ArcGIS World Imagery base map, which was successfully completed for 80% of the surveyed plots. Enumerators showed farmers their location on the map from the GPS in the tablet, pointed out nearby features visible on the imagery like roads and plantations, and then assisted the farmers in drawing the boundaries of their plots.

This resulted in a sample of 744 successfully drawn farm plots with associated household survey data, of which 63 were covered by clouds, and 141 were outside of the area in which we had high-resolution satellite imagery (and classified ditches and furrows), resulting in 540 farm plots (with a mean size of 0.30 ha) that had household survey data, high-resolution imagery, and classified ditches and furrows. We used zonal statistics to calculate which of the farm plots had ditches according to our remote sensing classification (and what % of the area of each plot was covered by ditches), and compared that to the farm plots reported as having ditches by the survey respondents. We expected that the survey would be more accurate than our remote classification and thus could serve as another form of accuracy assessment for our classification.

Sediment retention modelling

To illustrate the effect of incorporating ditches and furrows in a hydrologic model, we applied the InVEST (Integrated Valuation of Ecosystem Services and Tradeoff) sediment delivery model (Hamel et al. 2015) to the Sasumua watershed. The InVEST sediment delivery model is a geospatial tool that aims to estimate sediment transport from each pixel of a landscape. The soil loss module is based on the revised Universal Soil Loss Equation (Renard et al. 1997) and thus subject to the well-known limitations pertaining to this approach (see e.g. Ch. 5 in Roose (1996)): the main limitation relevant to this study is that the equation was developed and tested mainly in the U.S. (see Discussion). The sediment transport is modelled through the sediment delivery ratio (SDR), a factor computed for each pixel based on upslope and downslope land use and topography. The readers are referred to previous work for a full description and sensitivity analysis of the model (Hamel et al. 2015), as well as applications around the world, including in Kenya (Chaplin-Kramer et al. 2016; Hamel et al. 2017).

Model inputs are summarized in Table 1. Of note, the modelling uses a 30 m DEM, such that all model inputs and outputs are aggregated at this resolution. After calibrating the model based on the work of Mwangi *et al.*, (2015), it estimated total sediment yield for the watershed at ~900 ton km^{-2} $year^{-1}$ from 1970 to 2010. Calibration consisted in changing the value of the calibration parameter k_b (which has no physical interpretation, but shifts the distribution of SDR factors throughout the landscape, see Figure 2 from Hamel *et al*., 2015): the parameter was increased until predicted sediment yield matched the estimate of Mwangi *et al*.,(2015), yielding a value of k_b=4. Of note, this calibration has little effect on the relative results presented below, but simply aims to adjust the sediment delivery ratio of the watershed (i.e. the ratio between sediment export and soil loss) to be representative of the area.

As noted in the introduction, ditches and furrows tend to reduce erosion by intercepting flows, which reduces overland flow runoff on downslope areas, and infiltrating flows, thereby reducing the volume of runoff reaching the stream. But when ditches and furrows are connected to the stream network, they may also increase runoff and enhance sediment transport (of particles that would otherwise settle on the land). Different types of ditches and furrows will call for different modelling approaches (Dunn and Mackay 1996; Levavasseur et al. 2012). Unfortunately, it is difficult to know which process is dominant over the long term in the Sasumua watershed; on one hand, the classification described above does not allow to determine with certainty whether the ditches and furrows are directly connected with the stream. In addition, to the authors' knowledge, no local study was available to inform a decision about the hydrologic behaviour of the ditches and furrows. Thus, we modelled two different hypotheses about the behaviour of the ditches and furrows: a) that ditches and furrows are all disconnected from the main stream network, their main impact being to intercept and infiltrate flow (more common for ridge-tillage furrows); b) that ditches close to the main stream network are connected to them (thereby increasing the amount of sediment delivered to the channel, more common for drainage ditches). In the following sections, "connectivity" refers to hydrologic connectivity, i.e. "Physical linkage of sediment through the channel system, which is the transfer of sediment from one zone or location to another and the potential for a specific particle to move through the system" (Hooke 2003).

For both hypotheses, we represented the interception by ditches and furrows by a change in the P and in the LS factors of the RUSLE, representing, respectively, the effect of agricultural practices (here, ridges), and the topographic characteristics (local slope and position on the hillslope). The change in the P factor was simply based on the RUSLE guidance (Table 6-15, (Renard et al. 1997)) for open-outlet drainage ditches. The reduction in the LS factor, which corresponds to the shortening of the slope length when ditches and furrows intercept runoff, depends on the slope length and the size of a pixel. For example, given our 30m DEM resolution (unfortunately this was the highest resolution DEM available, and using high-resolution stereo imagery to build a higher-resolution one was cost-prohibitive), the LS factor is reduced by a factor of 3.75 for 5% slopes, and by a factor of 4.5 for 10% slopes (values based on Table 4-2 in the RUSLE guidance, Renard *et al.*, 1997). For this application, we used an average value of 4 for all pixels, thereby simplifying the effect of runoff interception. This decision was made given the remaining knowledge gaps on these processes, which are not the subject of this paper (see Discussion on the use of empirical data if these were made available). To represent the change in slope length in InVEST, we changed the C factor instead of the LS factor: with this modelling artifice, we could compute the same reduction in soil erosion without modifying the source code (because the RUSLE output is the product of five factors, we correct one factor, C, instead of the other hard-coded one, LS).

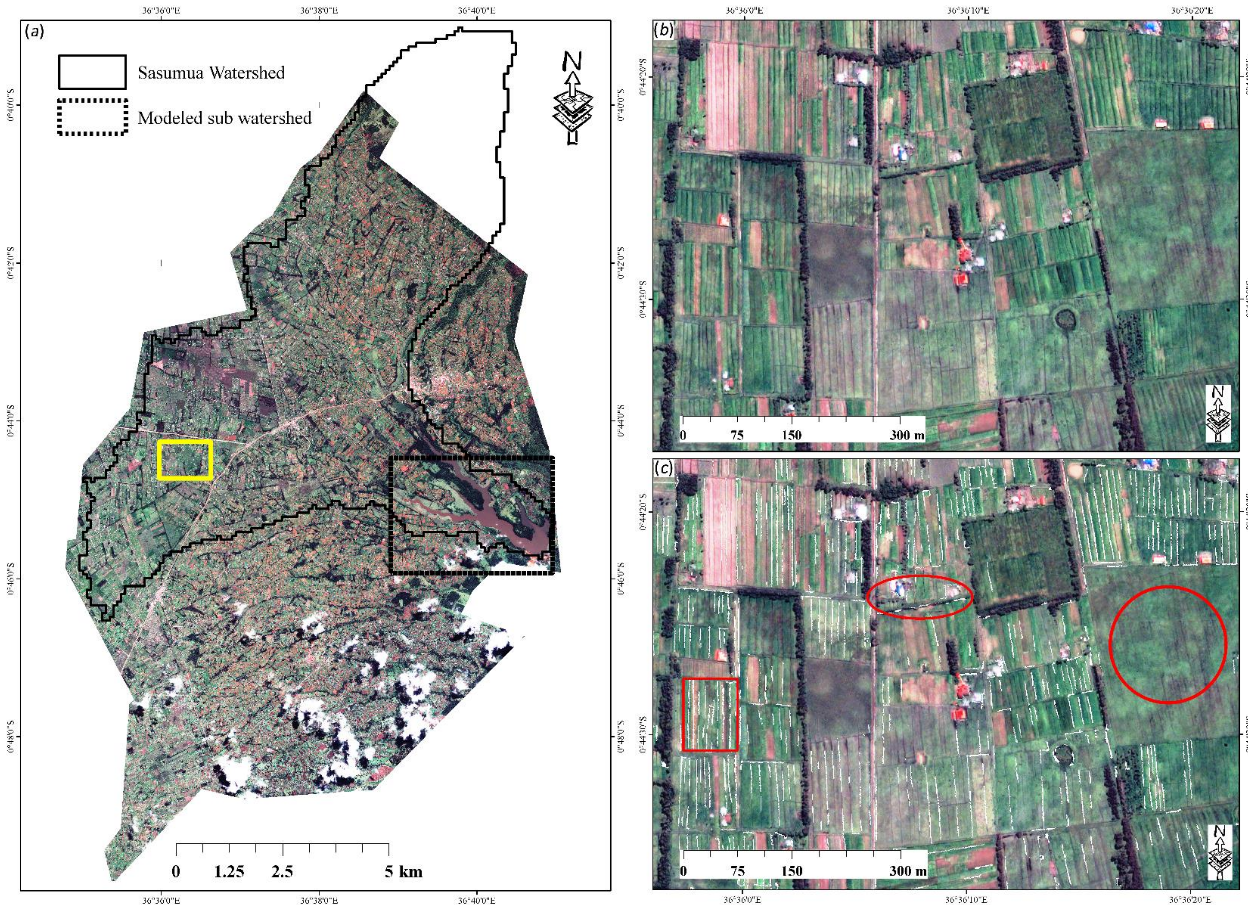
Finally, to represent the connected ditches and furrows (hypothesis b above), we assumed that all the ditches and furrows that were less than 90 m from the stream were hydrologically connected. In other words, sediment reaching these features are assumed to reach the main stream. The distance of 90 m (i.e. three pixels) was based on empirical knowledge on riparian buffers: the literature on riparian buffer modelling suggests that buffers less than 50 m may be too narrow to retain sediment (retention efficiency less than 90%, as suggested in reviews by (Liu, Zhang, and Zhang 2008; Zhang et al. 2010). We used this order of magnitude (rounded to the next pixel, i.e. 90 m) to create scenario b, thereby assuming that sediment generated outside this zone is efficiently retained by the riparian buffer. In practice, we implemented this hypothesis using the “Drainage layer” in InVEST, which allows to merge a layer of artificial drainage infrastructure (such as the studied ditches and furrows) to the stream network. Our layer of artificial drainage was created by masking out all areas outside a 90 m buffer from the stream network (delineated by the InVEST model from the 30m DEM).

Results

Classification of ditches and furrows

Our results revealed the presence of substantial amounts of ditches and furrows across the study area (Figure 4). A total of 1,785 km of ditches and furrows were detected over 22.48 km^2 of the agricultural lands within the study area.

Figure 4. (*a*) Overview map of the study area, with overlays of the overall watershed and the sub watershed in which sediment retention modelling was conducted (as shown in Figure 5). The yellow rectangle shows an example area highlighted in (*b*) only satellite imagery shown and (*c*) satellite imagery with classified ditches overlaid in white, and examples of correct classification (in red rectangle), false negatives (in red circle) and false positives (in red ellipse). Includes material © CNES 2015, Distribution Airbus DS Geo SA / Airbus DS Geo Inc., all rights reserved.



Accuracy assessment

The first assessment found that our classification had a ditch and furrow density of 0.08 m m^{-2}, slightly less than an average of 0.1 m m^{-2} ditch and furrow density estimated through manually digitizing ditches and furrows. Manually digitizing ditches and furrows within a total of 0.33 km^2 using the high-resolution imagery took about 35 minutes which, assuming consistent efficiency means the study area would have taken about 92 hours to manually classify. A single classification run confined to the agricultural area usually took about 2 hours (on a windows computer with dual 2.4 GHz cores, 24 GB of RAM, and an SSD USB 3 TB hard drive), although several runs were required to produce our final layer. Repeated classification runs are required to capture ditches and furrows with varying wetness, vegetation cover and adjacent ground conditions. Along with visual evaluation of each run and mosaicking outputs of each run to a single raster, the overall classification task was estimated to take up to 18 hours for the entire study area, considerably less time than a manual approach.

For the sample grids where we did not remotely detect any ditches and furrows, we had an accuracy of 62% (38 polygons were found to have at least one substantial ditch or furrow). For the sample grids where our classification identified the substantial presence of ditches and furrows, we found that 97% of the sample polygons had substantial ditches and furrows visible in the imagery, although only 59% of the polygons had the *majority* of visible ditches and furrows successfully classified. 80% of these sample grids had the majority of classified ditches and furrows also visible in the imagery. Collectively, this indicates that the classification was prone to false negatives: it completely missed visible ditches and furrows in sample grids 38% of the time, and when it detected some ditches and furrows it missed the majority of visible ditches and furrows 31% of the time. However, it had very few false positives: only 3% of sample grids with classified ditches and furrows had none visible in the imagery, and only 20% of sample grids had a majority of classified ditches and furrows that were not actually visible.

Finally, to compare our classification of ditches and furrows to the household survey data, we used zonal statistics to determine that out of the 540 farm plots drawn by participants in the household survey, 373 plots (69%) were found to have ditches and furrows based on our remote sensing approach, although some of these plots had only very slight overlap with ditch / furrow pixels. Looking only at plots with 5% or more of their area covered by ditches (subjectively determined to be a reasonable threshold to capture fields which definitely contain actual ditches and furrows), we found 226 plots (42% of the 540). However, only 14 plots (2.6%)

out of the 540 from the survey were identified by respondents as having drainage ditches or ridge-tillage (of those 14 plots, 11 were found to have ditches or furrows by remote sensing).

Given the measured accuracy of our remotely sensed data above (with only 3% false positives), this discrepancy revealed a problem with the accuracy of the household survey data. While we could not determine why the household survey so dramatically underreported ditches and furrows, possible explanations include survey respondents not understanding the terminology used, enumerator error, failure to draw the plots correction, or some other factor. Our results demonstrate the utility of measuring the presence of ditches and furrows remotely rather than relying on survey data (even if it were possible to obtain complete coverage of a study area via surveys, which would likely be prohibitively expensive). While our hypothesis that household survey data could be used as a reference to measure the accuracy of our remote classification was false, using a remote classification to assess the accuracy of household survey data appears to be promising.

There were several sources of error in the classification which reduced the accuracy independent of how it was measured. In some cases, ditches and furrows were insufficiently wet (or too covered by high dense vegetation) to show up in our classification. In other cases, we mistakenly identified other features as ditches and furrows, such as small streams, shadows caused by the border between a tall crop (e.g. mature Napier grass) and a short crop (e.g. cabbages), road edges, and small footpaths.

Sediment retention modelling

The representation of ditches and furrows in the InVEST sediment model greatly affected the sediment export predictions (Figure 5). Under the assumption that ditches and furrows less than 90 m from streams were hydrologically connected to the stream network sediment export was reduced by 71%; alternatively, if we did not modify the hydrologic connectivity of ditches and furrows then sediment export was reduced by 84% (Table 2). These results illustrate that the incorporation of the hydrologic effect of ditches and furrows has the potential to greatly affect sediment export predictions. Note that these results are also similar to the impact of ridge-tillage found in the literature (Reeder 1990; Wang et al. 2008). As discussed in the next section, further research is needed to ascertain the hydrologic effects of ditches and furrows (possibly distinguishing between the two) and improve model parameterization.

Figure 5. Map of sediment export at 30 m resolution, without (*a*), and with (*b*) ditches and furrows (i.e. under the assumption that ditches and furrows close to streams are hydrologically connected to the stream network)

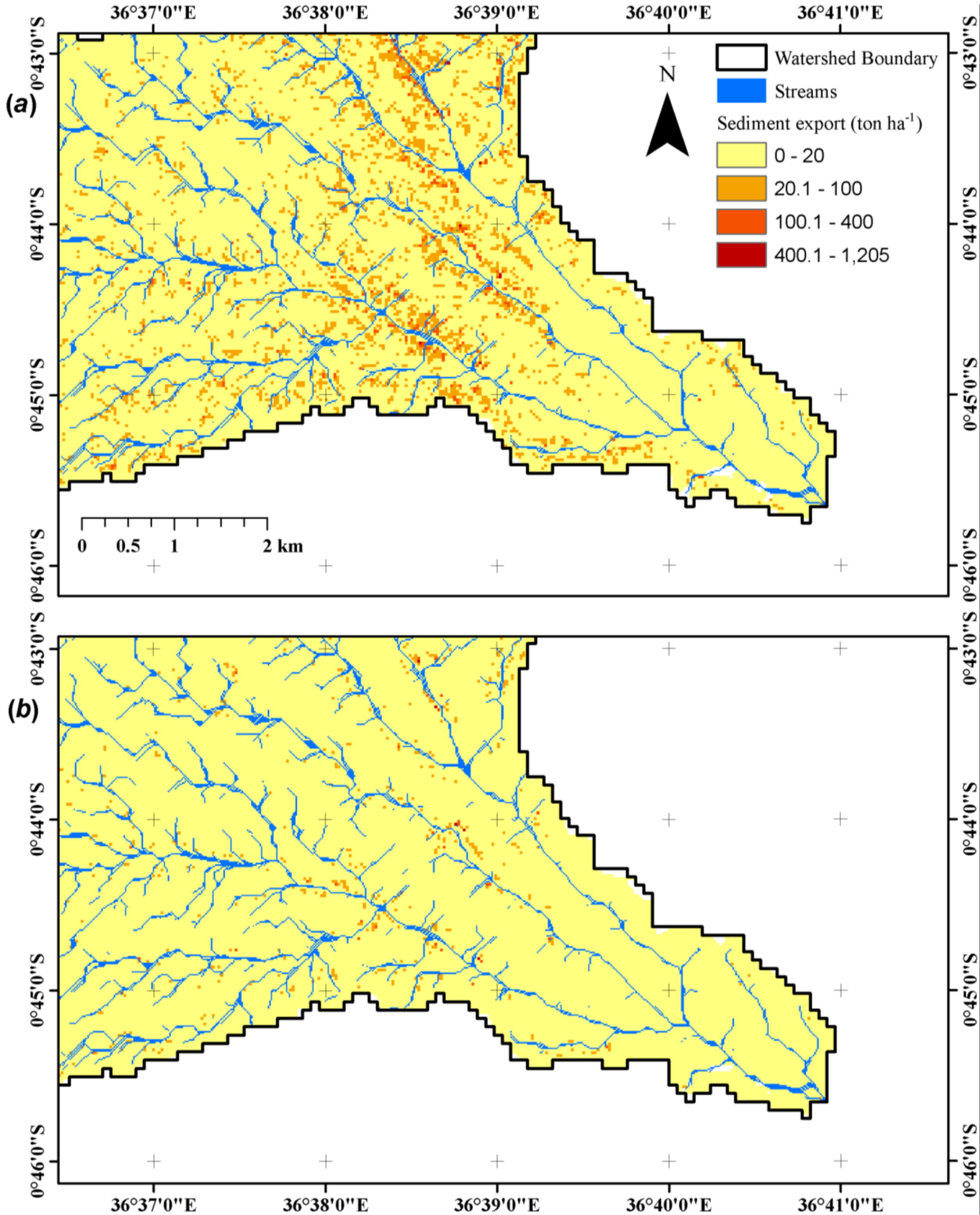

36°37'0"E
36°38'0"E
36°39'0"E
36°40'0"E
36°41'0"E
0°43'0"S
0°44'0"S
0°45'0"S
0°46'0"S
(a)
(b)
Watershed Boundary
Streams
N
Sediment export (ton ha-1)
0 - 20
20.1 - 100
100.1 - 400
400.1 - 1,205
0 0.5 1 2 km

Table 1. Data sources and parameter values for the InVEST sediment model

Input	Value (*indicates a mean value for raster data)	Source and processing
Erosivity layer	*3741 MJ mm ha^{-1} hr^{-1}	(Vogl and Wolny, 2015)
Erodibility layer	*0.017 t ha hr ha^{-1} MJ^{-1} mm^{-1}	(Vogl and Wolny, 2015)
Elevation layer	*1637 m	(Vogl and Wolny, 2015)
USLE *C* factor	Forest: 0.025 Plantation: 0.12 Grass: 0.03 Urban/Asphalt: 0.2 Ag: 0.4 Bare: 1.0	(Wischmeier and Smith, 1978) database
USLE *P* factor	1 for all LULCs for baseline 0.2	(Wischmeier and Smith, 1978)
Threshold flow accumulation (tfac)	100	(Vogl and Wolny, 2015)
Borselli calibration parameter k_b	4	Calibration based on (Mwangi et al. 2015)
SDR_{max} **Borselli calibration parameter IC_0**	0.8 0.5	Default value in (Hamel et al. 2015)

Table 2. Comparison of predicted sediment yields between the three modelling scenarios (numbers in parentheses are the percent differences with baseline, i.e. without ditches and furrows)

Scenario	Specific sediment yield (ton km^{-2})	Soil loss (ton km^{-2})
No ditches and furrows (baseline)	871	4417
Ditches and furrows with reduction in erosion	137 (-84%)	869 (-81%)
Ditches and furrows with reduction in erosion and hydrologic connection to the stream	254 (-71%)	869 (-81%)

Discussion

Classification of ditches and furrows

Our results indicate the importance of accounting for ditches and furrows in areas where these practices are common, although further work is needed to validate our estimates. Furthermore, our method of classification using high-resolution imagery is considerably easier and more scalable than field visits across a landscape or manually digitizing ditches, and is more reliable and scalable than using survey data.

There are some important considerations for future work. First, mapping will work best on non-vegetated ditches and furrows filled with clear water (with relatively high reflectance in the NIR band from crops contrasting with the adjacent water filled ditch or furrow with low reflectance), although this is most likely to be true during the rainy season when cloud-free imagery is scarce. Weak statistical relationships are expected in areas of reduced vegetation adjacent to the ditch or furrow pixels, lowered water level in the ditches and furrows, narrow ditch and furrow width and the increased complexity of the land cover immediately surrounding the ditches and furrows. Some of the mapped ditch and furrows edges fell short of representing the whole length of the ditch and furrows, especially when they were partly wet or weed filled (reinforcing that our approach underestimated ditch presence). Ditches and furrows filled with sediment are also less visible as they appear similar to the adjacent ground whereas those having bed slopes tend to appear shorter as sediment fill the lower edge of the ditch making it identical to adjacent ground. Future work may wish to take a less conservative approach (accepting more false positives to reduce the rate of false negatives); our approach was guided by a desire to not overstate the potential importance of ditches and furrows to sediment export. Finally, it would be useful to explicitly compare the accuracy of our method to the one outlined by Le Hegarat-Mascle and Ottle (2012) as in their study area they had only a 15% false positive rate, along with 10% false negatives.

We also found that a considerable amount of post-processing work is required to accurately classify ditches and furrows, and this approach relies upon imagery that costs a few thousand dollars (coarser free imagery having insufficient resolution to see ditches and furrows). The volume of post-processing work can be reduced (and the accuracy improved) by carefully planning the imaging time to coincide the best contrast between the water filled ditches and furrows and vegetated adjacent ground. While we took a conservative approach where we favoured false negatives over false positives (to ensure we would not overstate the prevalence of ditches in the landscape, and thus their impact on sediment), better timing of imagery and the use of imagery from multiple dates would make it considerably easier to reduce the rate of false negatives.

Sediment retention modelling

In the present application, we used a simplified modelling approach based on RUSLE and SDR approach to illustrate the potential implications of drainage detection for hydrologic modelling. As noted in a recent study of sediment retention (Hunink and Droogers 2015), there is limited access to water quality data for our study area, which limits the application of sophisticated sediment models. We used the work by Mwangi et al. (2015) to conduct a basic calibration and verification of the InVEST model performance. Here, the InVEST sediment delivery model was used for exploratory purposes (determining the order of magnitude of potential sediment reduction), rather than accurate predictions of a future landscape. This use of models for basic exploration is recognized in the literature (e.g. (Brugnach and Pahl-Wostl 2008)), and while it still requires thorough assessment of modelling assumptions, it does not require the same level of model validation as is required for prediction. Our findings were similar to other evaluations of the impact of ridge-tillage on sediment (Reeder 1990; Roose 1996; Wang et al. 2008), which suggest that erosion from agricultural plots is reduced by up to 80% compared to conventional fields.

The application of the model under two different assumptions provides insights into the model structural and parameter uncertainty, by representing distinct transport pathways for sediment on the landscape. It is likely that our predictions overestimate actual reductions in sediment yields due to ditches and furrows. Future work could involve the acquisition of empirical information on the hydrological behaviour of the ditches and furrows, including quantifying the degree to which ditches and furrows are connected across the landscape, and evaluating how often the ditches and furrows are vegetated in a given landscape. The distinction between un-vegetated and vegetated ditches in the imagery may lead to differential representation of ditches, with distinct effects on sediment or nutrient retention. Incorporating more thorough uncertainty analyses in sediment model predictions will help interpret such sediment yield estimates. This aspect was not further developed in this study, since the coarse representation of sediment transport processes by the InVEST model was sufficient for the illustrative purpose of this application.

Conclusions

Our methodology to map ditches and furrows using remote sensing was generally accurate, although somewhat prone to false negatives. Our exploratory analysis (using the InVEST sediment transport model) investigating the impact of incorporating ditches and furrows extracted from satellite imagery into sediment modelling found that doing so reduced estimated sediment transport from 71-84% depending on assumptions about hydrologic connectivity comparable to other analyses (Reeder 1990; Wang et al. 2008).

Mapping ditches and furrows in a highly heterogeneous landscape is challenging; future work on the classification of ditches and furrows could use additional post processing including manual segmentation to complete the ditches and furrows, removal of single pixel edges, and closing of gaps (important for modelling connectivity). The use of unmanned aerial vehicles (UAVs) in acquiring images (where legal and practical) would provide the flexibility of acquiring images at a very high resolution (even on cloudy days). Finally, water quality modelling investigating the impact of ditches and furrows should use a higher resolution DEM and collect data to validate the model.

Given the significant impact of ditches and furrows, remotely detecting them should serve to improve models which are being used to design interventions to improve water quality. Identifying the presence of ridge-tillage could also be used to improve crop yield estimates. With better understanding of the role of ridge-tillage and drainage ditches (ditches and furrows) in improving water quality and crop yields, better policies can be designed to promote these practices in the appropriate contexts.

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