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Blake, William

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SPECIAL ISSUE ARTICLE

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Integrating land-water-people connectivity concepts across disciplines for co-design of soil erosion solutions

William H. Blake¹  | Claire Kelly¹  | Maarten Wynants¹  | Aloyce Patrick²  |
Shaun Lewin¹ | Joseph Lawson³ | Emmanuel Nasolwa² | Annabel Page¹ |
Mona Nasser⁴  | Carey Marks⁵ | David Gilvear¹  | Kelvin Mtei²  |
Linus Munishi²  | Patrick Ndakidemi²

¹School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, UK

²Nelson Mandela African Institution of Science and Technology, Arusha, Tanzania

³Arhwithrans Surveys Ltd, Oxford, Oxfordshire, UK

⁴Faculty of Ecological Design Thinking, Schumacher College, Totnes, UK

⁵Scarlet Design, Totnes, Devon, UK

Correspondence

William H. Blake, School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, UK
Email: william.blake@plymouth.ac.uk

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Abstract

Soil resources in East Africa are being rapidly depleted by erosion, threatening food, water and livelihood security in the region. Here we demonstrate how the integration of evidence from natural and social sciences has supported a community-led change in land management in an agro-pastoral community in northern Tanzania. Geospatial analysis of erosion risk and extent (based on a drone survey across a 3.6 km² sub-catchment) revealed that recently converted land had ca 12-times greater rill density than established slow-forming terraced plots (987 ± 840 m² ha⁻¹ vs. 79 ± 110 m² ha⁻¹). Slope length and connectivity between plots were key factors in the development of rill networks rather than slope per se wherein slope length was augmented by weak boundaries between newly formed plots. Erosion evidence, supported by communication of 'process' and 'structural' hydrological connectivity, was integrated with local environmental knowledge within participatory community workshops. Demonstration of the critical time window of hillslope-scale rill erosion risk during early phases of slow-forming terrace development catalysed a community-led tree planting and grass seed sowing programme to mitigate soil erosion by water. This was grounded in an implicit farmer understanding of the need for effective governance mechanisms at both community and District levels, to enable community-led actions to be implemented effectively. The study demonstrates the wide-reaching impact of integrated and interdisciplinary 'upslope-downslope' thinking to tackle global soil erosion challenges.

KEYWORDS

agro-pastoral, co-design, drought, erosion, land degradation, UAV

1 | INTRODUCTION

1.1 | Soil erosion challenges in East Africa

The East African region harbours rich natural resources across the landscape (Veldhuis et al., 2019). These areas are populated with varied

human and livestock densities and, while the landscape provides many ecosystem services, provision is hampered by human activity and land degradation that include soil erosion. Climate changes, ecosystem degradation, biodiversity losses and sociopolitical pressures all impact development, conservation and livelihoods of socio-ecological systems of which the majority of communities rely on across the region.

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Soil resources in East Africa are being rapidly depleted by erosion, threatening food, water and livelihood security in the region (Cobo, Dercon, & Cadisch, 2010; Oldeman, 1991; Wynants et al., 2019). While soil and land resources are progressively being depleted, the population, with associated needs for livelihoods, food, fibre and other resources is expanding (FAO, 2019). Agricultural intensification and economic diversification are hampered by a lack of available knowledge, skills and agricultural technology (Korotayev & Zinkina, 2015) and as a result, an increasing number of farmers are pushed to seek more land to establish agricultural operations, causing a marked shift from naturally vegetated landscapes towards agricultural landscapes (Jayne, Chamberlin, & Headey, 2014; Odgaard, 2002). Policies of sedentarisation, privatisation and confinement within administrative boundaries have impeded the mobility of previously nomadic pastoralist communities (Homewood, Coast, & Thompson, 2004). Moreover, pastoral communities are also experiencing internal pressures due to rapid changes in herd sizes and stocking densities (both expansion and contraction), shifts towards the need for external employment opportunities, increased competition over grazing resources and challenges presented by social inequality (e.g., gender) (Rabinovich et al., 2019; Rufino et al., 2013). A combination of all these and other factors have led to a tripling of the livestock numbers in the last 50 years (FAO, 2019) with increasing local densities of domestic grazers in many areas, leading to overgrazing and trampling of the soil (Little, 1996; Ruttan & Borgerhoff Mulder, 1999). Furthermore, the high reliance on natural vegetation as a source of fuel, construction materials and fodder in both the urban and rural populations is resulting in substantial exploitation pressures on forests and woodlands (Hiemstra-van der Horst & Hovorka, 2009). The conjunction of these multiple pressures has increased rates of surface runoff, soil erosion, gully incision and downstream sediment transport (Blake et al., 2018; Vanmaercke, Poesen, Broeckx, & Nyssen, 2014; Wynants et al., 2020). Furthermore, these processes are potentially amplified by natural rainfall variations (Ngecu & Mathu, 1999) and projected increases in extreme climatic events, for example, drought followed by extreme rainfall (Nearing, Pruski, & O'Neal, 2004). East-Africa's environments and ecosystems are highly dynamic in both time and space, posing substantial challenges to both the communities that are dependent on them and the development of sustainable land management plans.

1.2 | Integration of hydrological and socio-economic connectivity concepts in land management plans

Interventions to reduce overland flow and soil erosion range in spatial scale from the farm plot to hillslope and catchment level. The conservation agriculture (CA) approach (International Institute of Rural Reconstruction and African Conservation Tillage Network., 2005; Kassam, Friedrich, & Derpsch, 2019) centres around the mitigation of on-site soil erosion effects on cultivated land, where soil conserving cropping practices help reduce erosion and water run-off. Three key

interventions that are essential to CA; however, are applied to different extents and site-specific contexts. First, the minimum or no-tillage practice reduces soil disturbance, supports higher infiltration capacity and reduces the risk of overland flow. Second, the permanent cover of soil by vegetation and/or use of crop residues as mulch reduces rain splash and compaction/crusting of the soil surface. Third, crop rotations and intercropping, even though their main aim is to increase soil fertility and yield, consequentially improve soil organic matter content, increase soil aggregate stability and hence help reduce erodibility. Edge-of-plot attenuation features (e.g., vegetative barriers, ditches, bunds, buffers) mitigate both on-site impacts, through retention and capture of soil and nutrients in the farm, and off-site impacts, by impeding downslope water flow. East-African hillslope farms are often cultivated under slow-forming terraces (Kagabo, Stroosnijder, Visser, & Moore, 2013), where soil eroded up the plot congregates at the plot boundary, thereby reducing hillslope gradient. Downslope catchment measures include the use of check dams or other flow retardants in gullies and incised channels to slow down the water discharge response to the drainage network, reduce channel incision and stimulate sediment deposition. These offer win-win outcomes of landscape restoration and enhanced resilience to future climate threats such as extreme rainfall and drought. Successful implementation of these multi-scalar intervention opportunities can only be realised with a thorough and nuanced understanding of community-specific needs and priorities, as well as wider political and economic contexts, all set within a deep understanding of landscape hydrological processes and concepts in both 'structural' and 'process' connectivity (Bracken et al., 2013). In brief, the term 'structural connectivity' has been used to describe the distribution of landscape units and features, for example, topographic controlled, flow convergence lines, gully or track networks, that physically facilitate water and sediment transfers from hillslope to channel. Structural connectivity approaches are limited to supporting inferences of potential hydrological connectivity should overland flow be generated. In this regard, the concept of 'process connectivity' has greater relevance to tackling overland flow generation and soil erosion by water. This concept encompasses the actual processes that operate to produce fluxes of water and sediment and capture the evolutionary dynamics of how hydrological systems function (Bracken et al., 2013). For example, soil crusting reduces infiltration capacity leading to infiltration excess overland flow, which converges to form and feed rill and gully network structures. The concept refers to the activation of the potential pathways described within a structural connectivity framework, which is generally highly temporally discrete. To date, however, process and functional connectivity concepts in hydrology have not directly accounted for the human dimension in land management decision making an impact of soil hydrology nor the maturity of land conversion features that might over time increase soil retention efficacy. Furthermore, in the East African context, connectivity within hillslopes and river basins are dynamic in both space and time (Wynants et al., 2020) with marked changes in connectivity due to rainfall variations, river networks, rapid land-use change and positive feedback of gully incision and channel network expansion over

decadal scales—hydro-geomorphic processes that are still not well understood or quantified.

The complex spatial and temporal dynamics of overland flow, soil erosion and sediment conveyance downstream can be better understood by the scientific community within the framework of hydrological connectivity. However, stakeholders also have context-specific local in-depth knowledge of landscape processes, albeit generally through an agro-pastoral practitioner lens that encompasses social and economic facets (Wynants et al., 2019). As such, integrating scientific findings into locally led land management plans presents a challenge/barrier to research impact. The co-design of land management policy, which integrates local socio-economic and environmental knowledge and is tailored to the needs of specific communities is a credible pathway to sustainable change.

Participatory research in this context aims to evaluate not only the key environmental challenges affecting communities but also, and more critically, to understand the socio-ecological connectivity (Berkes, Folke, & Colding, 2000) between these environmental challenges and their integration in socio-economic processes at multiple spatial levels and temporal scales. Prior work has shown that understanding the linkages is vital to enable sustainable and equitable change and break the cycle of declining resilience to soil erosion (Pretty, 1995). In this East African context, soil erosion is a civic as well as a practical problem. Roads, trackways and community spaces are all exposed soil surfaces and thus the problem is not limited to those engaged in agriculture alone; it is a challenge for the whole community. From this perspective, every community member has a stake in contributing to the effort to find sustainable solutions; and every community member has an opportunity to take action to effect real and lasting change. Co-designing mitigation strategies with communities ensures that potential solutions are relevant, applicable and achievable, particularly where alternative livelihood strategies to support pathways to sustained change are applied. This is exemplified by Reed et al.'s 'bottom-up' participatory principles (Reed et al., 2017) where community-led planning is guided by the local ambitions of stakeholders alongside the strategic objectives of external agencies and state authorities, leading to equitable solutions with the much wider community 'buy-in' than those designed through top-down and non-participatory mechanisms (Pretty, 2003).

1.3 | Aim

This contribution demonstrates how an established interdisciplinary participatory approach (Figure 1) supported a community-led change in land management in an East African agro-pastoral community. It explores how the integration of drone survey data and geospatial analysis of erosion extent and risk, supported by communication of 'process' and 'structural' hydrological connectivity, with community participation, successfully underpinned and catalysed a community-led tree planting and grass seed sowing programme to mitigate soil erosion by water.

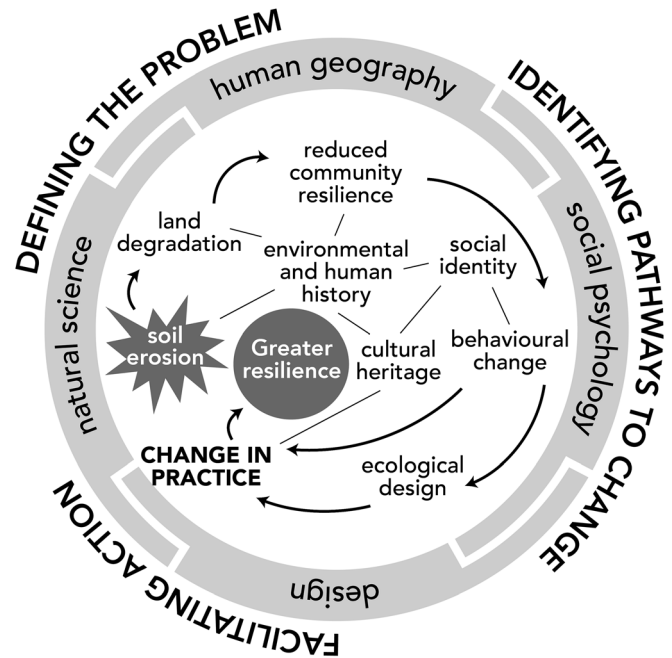


FIGURE 1 Interdisciplinary approach to linking evidence into action (Blake et al., 2018)

2 | MATERIALS AND METHODS

2.1 | Study area: Emaerete sub-catchment

The study site (Figure 2), 3.6 km² Emaerete catchment area, is located in the Monduli Highland area, east of the Northern Tanzanian Rift Valley, with an elevation ranging between 1746 and 2037 m. The geology is mainly rocks of volcanic origin and the soils have evolved to loamy clay Andosols on the upper slopes, and to the typical swelling clay Vertisols in the lower topographic swales. The mean annual rainfall (MAR) ranges from 800 mm in the lower areas to 860 mm for the higher areas and was obtained from the global climatologies at high resolution for the Earth's land surface areas ('CHELSA') dataset (Karger et al., 2017). The area has a typical bimodal wet season, with a short peak that occurs from November to December and a long peak between February and May, and one long dry season from June to October (Prins & Loth, 1988). Local and global climatic phenomena such as the El Nino Southern Oscillation and the Indian Ocean Dipole interlink to create a high interannual variation wherein the short rains can fail (droughts) or connect to the long rains (extended wet season) (Nicholson, 1996). The natural vegetation is mostly an elevation-defined transition between savanna bushland and afro-montane rainforest. The landscape in many areas is characterised by severe surface denudation in open grazing land with notable rill and gully erosion by overland flow (Figure 2a).

The communities are predominantly Maasai and have a long history of assimilation and reciprocal influencing with other ethnic groups such as the waArusha and waMeru. Livelihoods in these communities continue to transition from nomadic pastoralism to sedentary agro-pastoralism driven by factors such as population growth, social

and environmental human displacement. While traditional customs have gradually lost importance, they still exist, sometimes assimilated within local governance structures, or in parallel with formal governance. Much village land is still set aside for communal grazing; however, during the transition to agro-pastoralism, large areas of land have been entrained into different ownership processes, and used for mixed agriculture. The rights to these lands mostly belong to the

'original' Maasai people although some of these plots are also being leased to farmers from other regions in Tanzania who pay for their tenure in crop-shares. Both processes have resulted in a conversion of semi-natural grazing lands to cropland. The dominant cropping system is intercropping of maize with common beans. However, there are other crops grown in the area such as wheat and horticultural products. These croplands areas are mostly located in the upper

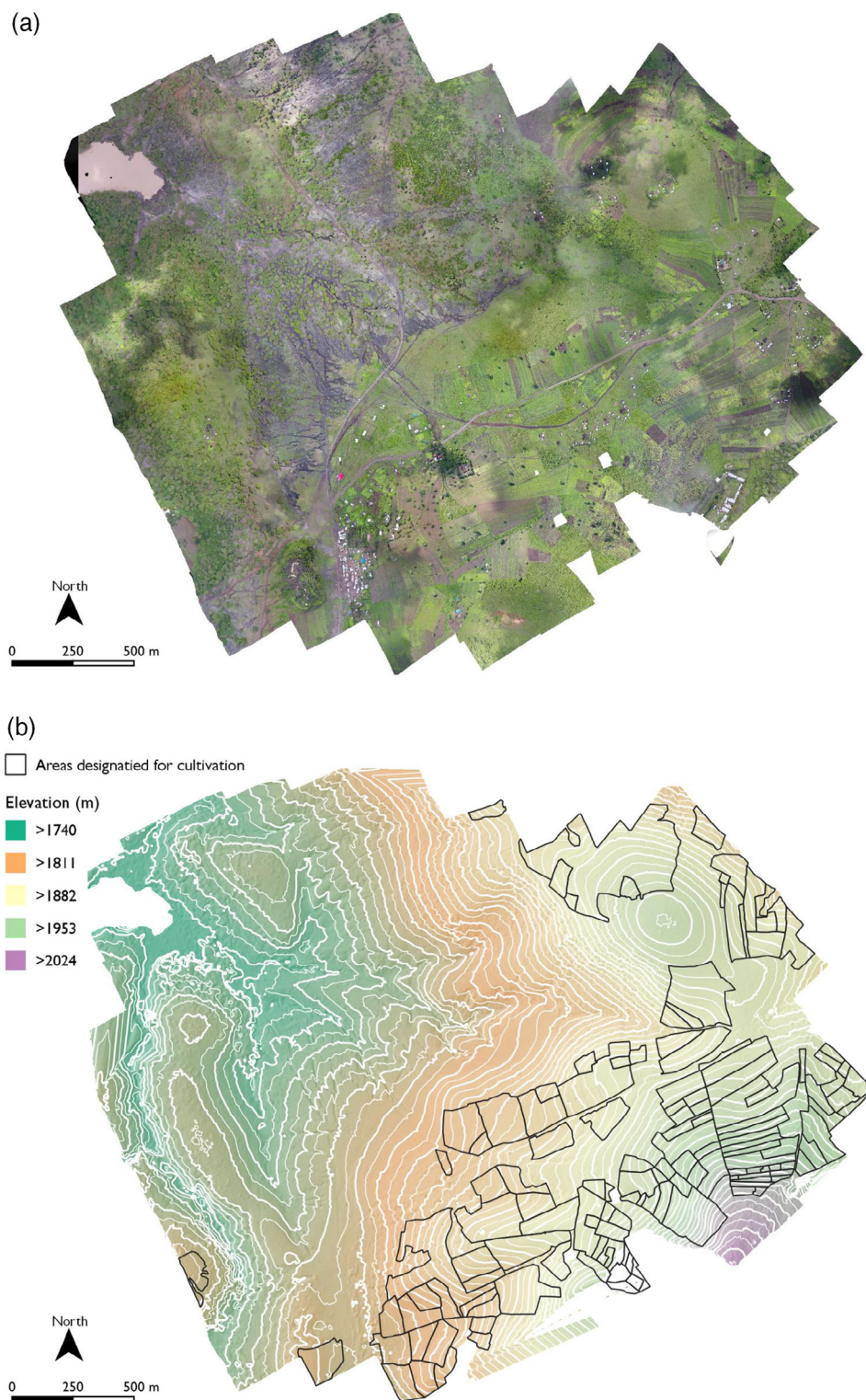


FIGURE 2 Emaerete catchment (a) broad land cover and (b) topography showing areas designated for agriculture (grey outline) where remainder is open land utilised for common grazing. Note areas of severe gully erosion and surface denudation [Colour figure can be viewed at wileyonlinelibrary.com]

slopes of the landscape, while the grazing lands are mostly located in the lower areas and topographic swales (Figure 2b).

2.2 | Drone survey and geospatial analysis

To develop a topographic digital surface model (DSM) of the study area using photogrammetry, a drone photographic survey was undertaken using a Phantom Potensic T25 drone equipped with internal GPS and a 1080p GPS digital red-green-blue (RGB) camera with an optimised 120° wide-angle lens. The flightpath was set to take photographs from an altitude of 400 m, reduced to 150 m over hill top areas that were obscured by cloud cover. The flightpath was set so that images had greater than 65% overlap. Twelve ground-based GPS reference points were made along the boundaries of the designated area to permit vertical alignment of relative elevations derived from the drone survey. A Digital Elevation Model (DEM) was created using photogrammetric routines within AGISOFT METASHAPE (Agisoft LLC) whereby building and tree interference was removed from the DSM by excluding points that had a steep (>80°) angle with an adjacent point.

The red, green and blue bands of a compile orthomosaic aerial image of the study area were used as the input for a maximum likelihood classification using the QGIS 3.4 Saga tool 'Supervised Classification for Grids'. Training data were generated through heads up digitisation of that aerial photograph. The output of this process successfully differentiated gullies and rills from other forms of ground cover but could not distinguish between the different vegetation communities present within the catchment. This high-resolution mapping of soil erosion features was therefore, supplemented with a conventional aerial photograph interpretation exercise carried out at a scale of 1:3000. In addition to the classification of broad land cover types within the study area, cultivated land use was subject to a further level of classification according to the direction of cultivation. This categorisation was undertaken as a simple aerial image interpretation (at a scale 1:500) with discontinuities in land management practices being recorded as separate features (land parcels) within the geographical information system (GIS) layer.

The 1 m DEM of the site was analysed in QGIS (version 3.10, qgis.org) to produce a model of potential surface flow, slope aspect and slope degree. In order to simplify subsequent analyses, the aspect of each 1 m pixel within the elevation model was categorised into one of the eight cardinal directions (N, NE, E, SE, S, SW, W, NW). These DEM derivatives were used as inputs in the following analyses. The mean slope degree and modal aspect were calculated for each parcel of cultivated land identified in the aerial photograph interpretation using QGIS's Zonal statistics tool. The direction of cultivation recorded in the aerial imagery interpretation was then compared with the modal aspect for each land use parcel and the relationship between the two described using these qualitative classes: cultivation along contours, cultivation with slope and intermediate cultivation—where the direction of cultivation had no strong relationship with the aspect of the field. The modelled surface flow was used for two purposes,

first to create a Strahler ordered model of potential overland flow convergence within the study area, and second to select those bare ground (interpreted as eroded) pixels within the landscape that were probably generated by the surface flow that is, rills and gully features (in the main visible in high-resolution photography). The selected pixels were then converted into point data and their density expressed as area (m²) per m² calculated to derive an independent index of observed erosion feature density.

2.3 | Community consultation and engagement

The village level is spatially the lowest statutory administrative unit in Tanzania and, as such, provides two key advantages for our participatory research approach. First; at this level, local environmental knowledge and understanding of farm-specific soil condition, water runoff and seasonal micro-climate are the most finely nuanced and second; planning and implementation of potential institutional and community responses have the highest chance of success because, in this study, those directly affected by the problems are also directly engaged in designing workable solutions (Blake et al., 2018). Previous co-design work with these communities has shown that strong participatory engagement and knowledge exchange, following the principles and theoretical framework of Pretty (1995) and Reed et al. (2017), has delivered a better understanding of the impact of social, cultural and economic drivers on soil management challenges. This approach underpins the model of engagement discussed in this paper. Participatory approaches enable affected stakeholders to jointly define the scale and nature of the problem, find common ground in determining impacts and identify relevant policy mechanisms and levers for reform. Our previous research has demonstrated that good soil management is needed, which necessitates farmers and land managers to be empowered to continue to innovate towards sustainable resource conservation. The ambition of participatory research is to catalyse the development of a culture of the mutual understanding of potentially competing interests, and willingness to support honest and open dialogue built around a shared understanding of the socio-economic and as well as the hydrological connectivity of the landscape (Brown, 2002; Moore & Westley, 2011).

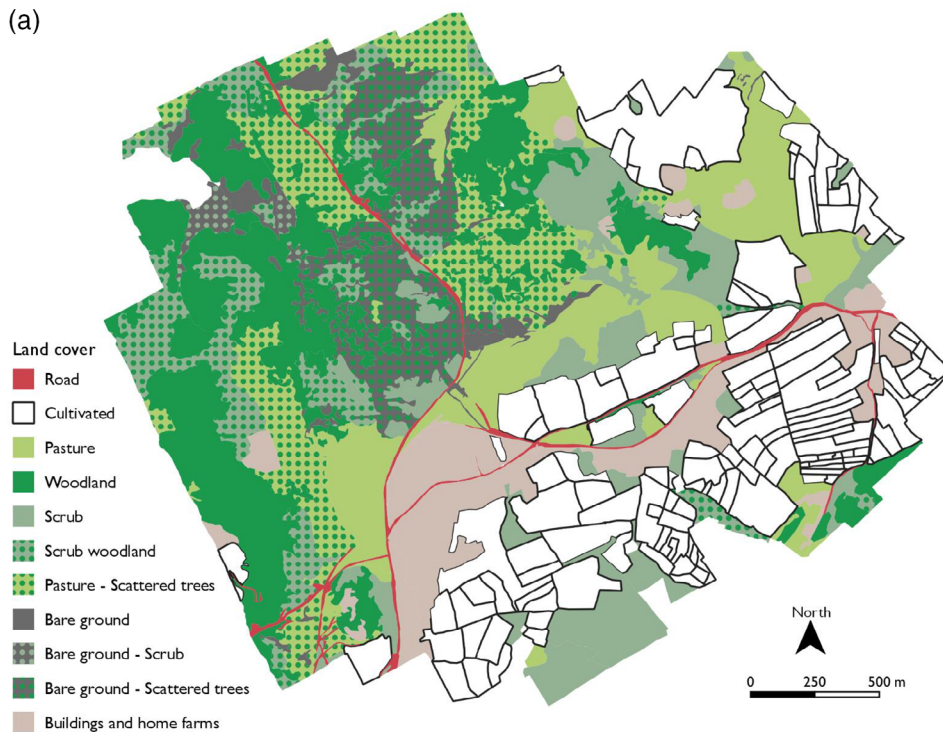
Building on previous participatory research carried out with the Emaerete community (Blake et al. 2018), a workshop was designed to bring the co-produced set of visual materials and associated results back to the community and to use them as a mechanism to explore key elements of local hydrological, biological and socio-economic connectivity in generating soil erosion issues. The workshop was held in the Emaerete community, attended by 20 participants from the Community and five District Government personnel who were further consulted on workshop outcomes (also following Reed et al., 2017). All discussions were conducted in Swahili, with facilitation by Tanzanian members of the research team, and with concurrent translation for English-speaking team members. Discussions were audio-recorded, subsequently transcribed and translated into English.

Following a brief introduction on the format of the workshop and the collaborative research activities to be completed, work was structured into two elements:

1. A short 'report back' and review session providing feedback on the wider Jali Ardhi Project research findings to date, (Blake et al., 2018; Rabinovich et al., 2019; Wynants et al., 2020; Wynants, Solomon, Ndakidemi, & Blake, 2018) and team learning from community experiences regarding erosion mitigation
2. Introduction and discussion of the drone survey aerial photo mosaic (one A0 scale copy for group discussion) and A2 scale copies for ease of handling by individual participants); an infographic tool highlighting soil erosion processes; and a set of previously produced local erosion impact photographs.

measures taken to date. Measures included demarcated livestock exclusion zones for gully rehabilitation; and community commitments to plant trees and shrubs; reduce vegetation cutting and change livestock grazing patterns.

(a)



(b)

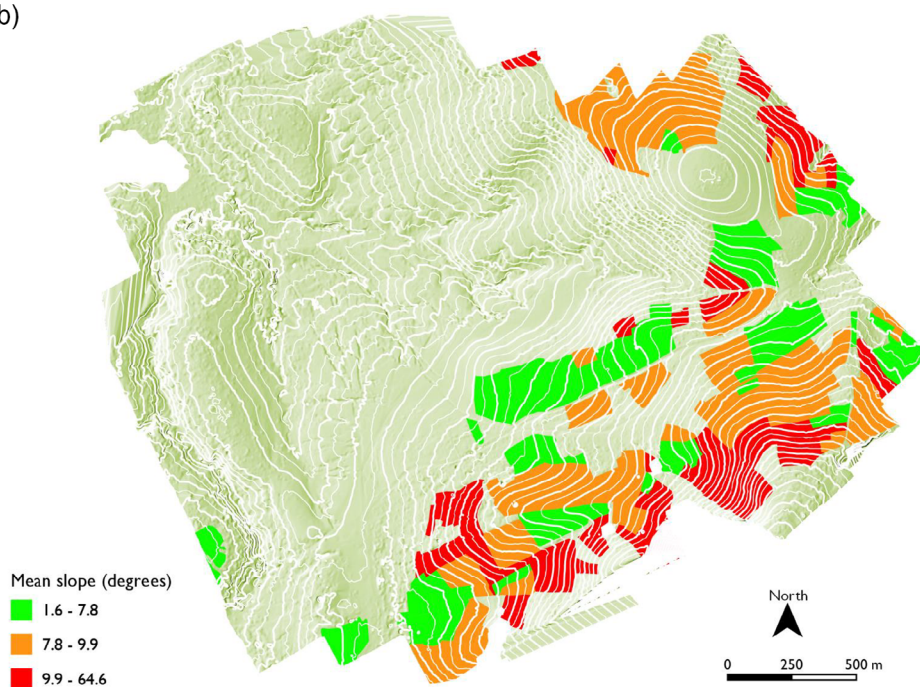


FIGURE 3 (a) Land cover classification and (b) derived mean slope (degrees °) for cultivated plots [Colour figure can be viewed at wileyonlinelibrary.com]

These visual tools were used by both the research team and participants in multiple ways to illuminate discussion points and trace hydrological connectivity within the landscape. Using visual methods, such as photographs and the DEM model, has the distinct advantage of creating a shared frame of reference and intuitive understanding despite the complex and abstract nature of the information. Visual methods using photographs and images are particularly helpful in supporting a process of joint learning, negotiation and reflection, around which soil erosion issues and associated connectivity can be identified. Image-elicitation is based on the use of one or a series of photographs or other images in a participatory research context, in order to reach a deeper understanding of something (Harper, 2002). Image-elicitation can stimulate empathetic understanding and draw out connections that might not otherwise be made. In this multi-stakeholder context, discussion alone faces the challenge of creating a trusting environment between participants from widely differing backgrounds and philosophical standpoints, and there is a need to 'bridge the gap'. Image-elicitation techniques can overcome these differences by offering a shared frame of reference (a composite image of the wider context, or of a particular issue, for example) on which to build trust and through which deeper insights can emerge than would otherwise be achieved through discussion alone (Collier & Collier, 1986).

3 | RESULTS

3.1 | Topography and land cover

Derived land cover classes (Figure 3a) were broadly spread across cultivated plots (26%), open pastoral land (30%) including homestead farm areas with sporadic tree and shrub cover and exposed soil surfaces in and around village buildings. Areas with patchy grass and rough shrub cover, often with intermittent soil loss and vegetation disturbance due to erosion, were classed as a scrub (10%). Areas of notable bare ground were observed in the severely eroded mid to lower slope region (Figure 4) that receives much of the concentrated overland flow from the hillslopes above.



The cultivated plots occupied the east and southeastern side of the catchment upland zone and hence represent potential overland flow contribution areas to the mid and lower slope gullied zones. The group of cultivated plots to the east of the system are the most recently converted (from open grazing to cultivation) land (ca 1–3 years prior to the survey) with boundaries set to shallow ditches and bunds akin to 'slow-forming' terrace approaches (Chapagain & Raizada, 2017; Dercon et al., 2003). Vegetation along these boundaries was largely immature grasses. The cultivated plots to the south were more established (over 7 years) with the notable establishment of edge-of-plot bunds and mature vegetation along boundaries. In both areas of cultivation, uppermost plots showed steeper slopes (Figure 3b) graduating to more gentle slopes towards and on the open pastoral land.

The cultivated land plots are interconnected with unmetalled trackways commonly used to drive livestock and for pedestrian and motorbike access. All tracks are incised to varying degrees with a notable incision on the downslope reaches of tracks from upper cultivated plots. Severe erosion of pastoral land originates from apparent overland flow spill over and concentration from the track in the centre west of the study area (Figure 3a; Figure 4). Severe gully erosion has resulted in upslope relocation of the track on more than one occasion.

3.2 | Structural connectivity framework and observed erosion

Comparison of potential flow pathways (grey convergence lines, Figure 5) and observed density of rills (white-grey-black shaded plots in Figure 5) reveal a disconnect in the potential and actual development of rill erosion in some plots. Plots coloured white have a low ($<0.0005 \text{ m}^2 \text{ m}^{-2}$) density of rill features observed in the drone survey and there are several notable examples where the topography-driven model predicts flow convergence but no rill erosion features were observed (e.g., northeastern sector, labelled A, Figure 5). Equally, however, there are plots where topography predicts flow convergence, which correlated with observations of high-density rill erosion ($>0.007 \text{ m}^2 \text{ m}^{-2}$) (e.g., southeastern sector, area B, Figure 5). Herein there is a notable strip plot showing no erosion features that had apparently been cultivated



FIGURE 4 Severely degraded pastoral land in the mid to lower region of the catchment (photos Carey Marks/University of Plymouth, taken March 2017) [Colour figure can be viewed at wileyonlinelibrary.com]

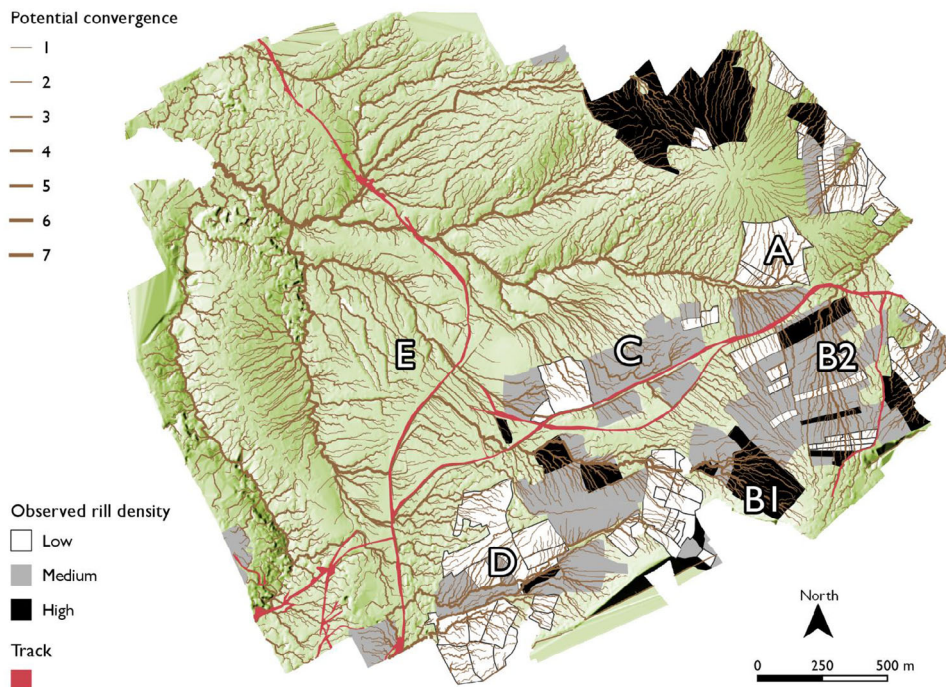


FIGURE 5 Potential overland flow convergence pathways, major trackways and summary first order observed rill density in cultivated plots [Colour figure can be viewed at wileyonlinelibrary.com]

shortly before the drone survey (see Figure 2a) highlighting potential limitation in the approach with respect to cultivation duration and timing prior to study. Area C is notable again for lack of erosion features given potential convergence line density wherein these fields also have limited potential for overland flow run-on given track along the upper slope. These areas can be compared to area E in the open pastoral land where severe erosion was observed, linked to overspill from the track (Figure 4). In comparison to area B, cultivated area D is notable for lack of erosion features given the potential for higher-order flow convergence routing wherein observational evidence of crop growth indicates potential rill features have not been cultivated out in this instance. It is also noteworthy that the area upslope of these plots remains under semi-natural vegetation cover compared to area B and that there is no major difference between area D and B in terms of slope angles (Figure 3b). In the more recently converted plots of area B, ca 90% of the area with potential for flow convergence showed moderate or high density of rill erosion features. In area D, the established agricultural plots, ca 40% of the area with potential for flow convergence showed moderate rill erosion density. Herein we note that the use of rills as an index for erosion intensity does not take into account the role of sheet and inter-rill erosion, which are often invisible to stakeholders within agricultural time-frames. Within this study, there is an implicit assumption that sheet erosion is occurring as a part of overland flow delivery to flow convergence lines where rills are forming but evaluating the relative intensity of this process in the different study contexts was beyond the scope of the methods used.

3.3 | Process connectivity framework and observed erosion

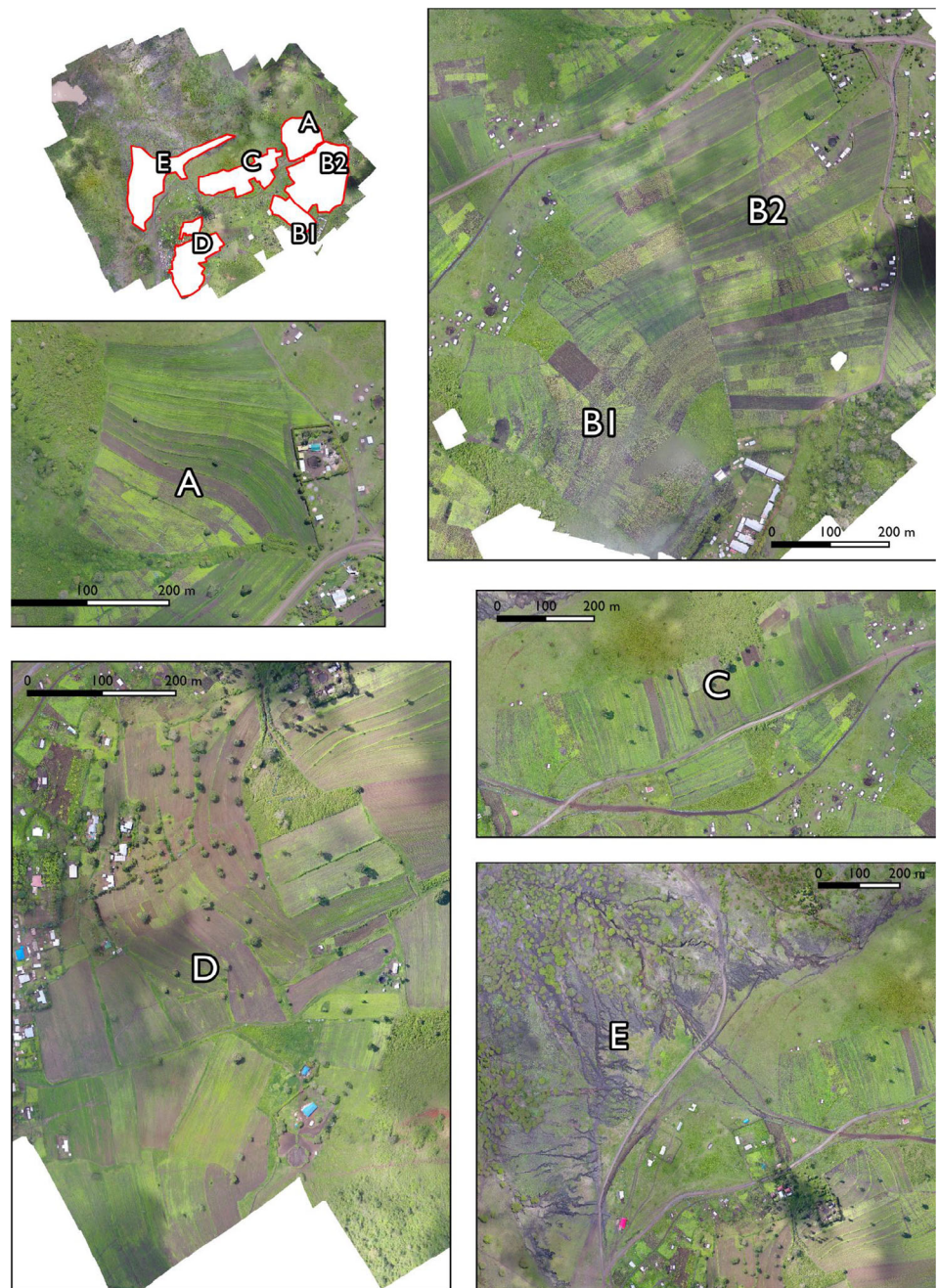
In terms of process connectivity overland flow enhancement factors, on-the-ground measures of soil infiltration capacity and soil erodibility

(aggregate stability) across the different agricultural plots were beyond the scope of this drone survey-based study. We hypothesised, however, that at a higher level, correlation of plot cultivation direction with a high density of rill erosion could be illustrative of cultivation controls on potential overland flow generation in the context of process connectivity concepts that encompass impacts on overland flow generation and slope length.

Zones of different time since plot establishment, configuration and within plot practice showed different degrees of rill density and network development (Figure 6). In zone B, where the greatest density of rill erosion was observed, there were two main rill networks (labelled B1, B2, Figure 7) connecting the upper slope to lower and discharging onto the main track running east to west/southwest, which ultimately spills across the pastoral land at E. The agricultural plots in B1 are orientated across the slope so boundaries traverse any potential flow lines in accord with local 'good practice' but cultivation lines within the plots are largely in the direction of slope (indicated by amber and red arrows, Figure 7), with the exception of the lowermost plots. On top of that, the higher plots are also developed on very steep slopes ($>12^\circ$). In zone B2, again the plots themselves are largely and appropriately orientated across the slope but within plots, there is a mosaic of cultivation directions. The rill network on this slope is well developed and crosses all cultivated plots connecting them to the main track way. It is also important to note that the slope length on these plots is also longer.

Zones A and D contrast with the situation of zone B. Both zones A and D show more moderate observation of rill density (Figure 6). In zone A, the plots are contoured around a valley head. Plots to the northern side have crop lines contoured with plot boundaries (green arrows, Figure 7) and little evidence of rill erosion. To the southern side, crop lines show some alignment to the slope (amber arrows, Figure 7) and there is moderate rill erosion in the lower plots

FIGURE 6 Aerial photographs of key illustrative zones showing field boundaries, cropping practice and incidence of rill erosion [Colour figure can be viewed at wileyonlinelibrary.com]



(Figure 6). In Zone D, plot boundaries are more exactly contoured to topography than zone B (Figure 6) and there is only one incidence of cultivation lines being with the slope, the remainder being intermediate or contoured. Rills in this area do not display the same level of development and connectivity as zone B. Zone C offers a different scenario where while cropping lines are contoured, moderate rill erosion was determined (Figure 7) and apparently concentrated along plot boundaries before overtopping edge-of-field bunds (Figure 6). The extensive erosion of gentle to moderately sloped pastoral land, zone E (Figure 6), occurred at the outlet of the track fed by extensive rill erosion in zone B with some contribution from zone C.

Geospatial observations can be evaluated in the context of the underpinning primary data that is, (a) plot slope ($^{\circ}$), (b) rill point density

(m ha^{-1}) and (c) potential flow convergence as modelled length (m) of potential overland flow pathways defined by topography, analysed in zone and cultivation practice categories. While a positive relationship between potential flow convergence and rill density would be expected under uniform conditions, across the full dataset from plots A to D, there was no correlation ($r = -0.07$) between these parameters. Comparison of these data within and between zones of cultivated land, however, (Figure 8a), reveals that while zone B1 has the greatest incidence of rill erosion, the greatest potential for flow convergence, based on topographic factors, was determined for zones A and D. While the range in slope angle overlapped across the zones, the median of C and D were ca. 0.75-times those of the other zones with notable outliers. Plots in the recently converted zone B were

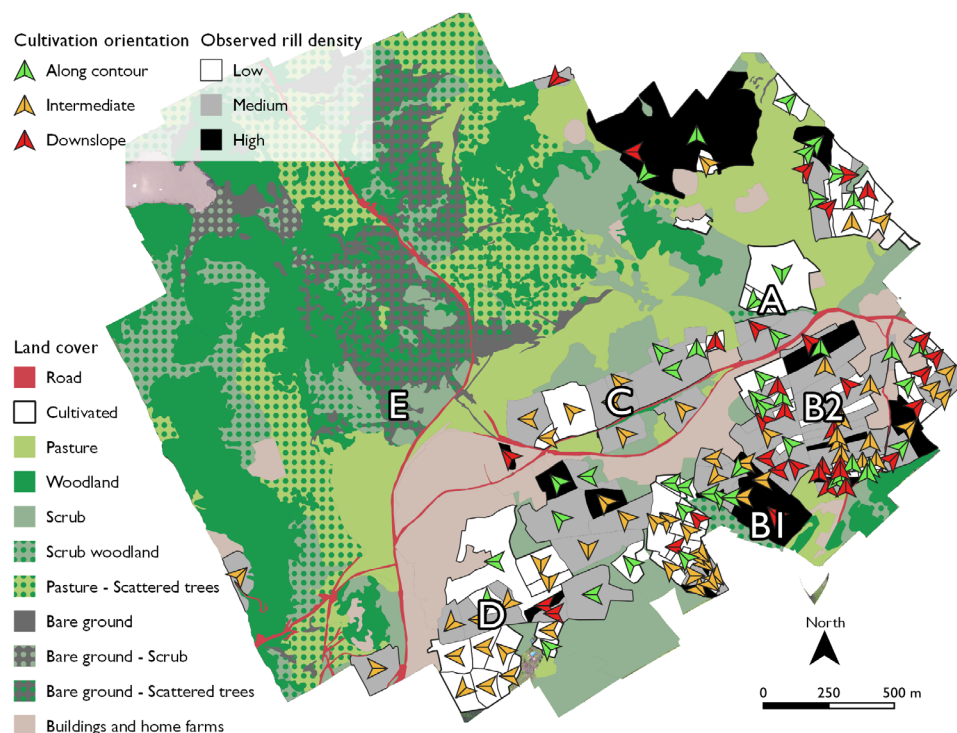


FIGURE 7 Comparison of first order rill density data and orientation of cultivation with respect to slope [Colour figure can be viewed at wileyonlinelibrary.com]

smaller in area than the other more established areas. Evaluation across the zones with categorisation by cultivation direction (Figure 8b), demonstrated that the range of rill density observations was similar for plots that were both cultivated across and with contours, not with standing some outliers.

3.4 | Infographic tool for dissemination of connectivity concepts

To support the dissemination of connectivity concepts an infographic tool (Figure 9) was developed based on a generic narrative of the consequences of land conversion/grazing on soil vegetative cover and soil surface degradation. The central part of the infographic focusses on reduced infiltration due to soil exposure and reduced infiltration linked to rain splash, aggregate breakdown with loss of soil organic matter and surface crusting. The wider narrative of the poster was designed to set the landscape in context, showing the destructive narrative of the erosion unfolding from the top to the bottom of the image. The tracks and pathways dissect the landscape, showing livestock and human traffic aggravating the initial stream channel incisions—and the structural connectivity, linking the upslope disturbance to downslope challenges—and inevitable result of enhanced overland flow.

We chose to create a visual style that would resonate culturally both within the Western and subSaharan diaspora. By developing a series of graphic devices, recognisable local iconography, a bright colour palette and lastly an abstraction of reducing the three-dimensional scenario into a two-dimensional illustration—the attempted result was to create an eye-catching and visually pleasing poster that encouraged

interaction and discussion with the researchers and stakeholders alike.

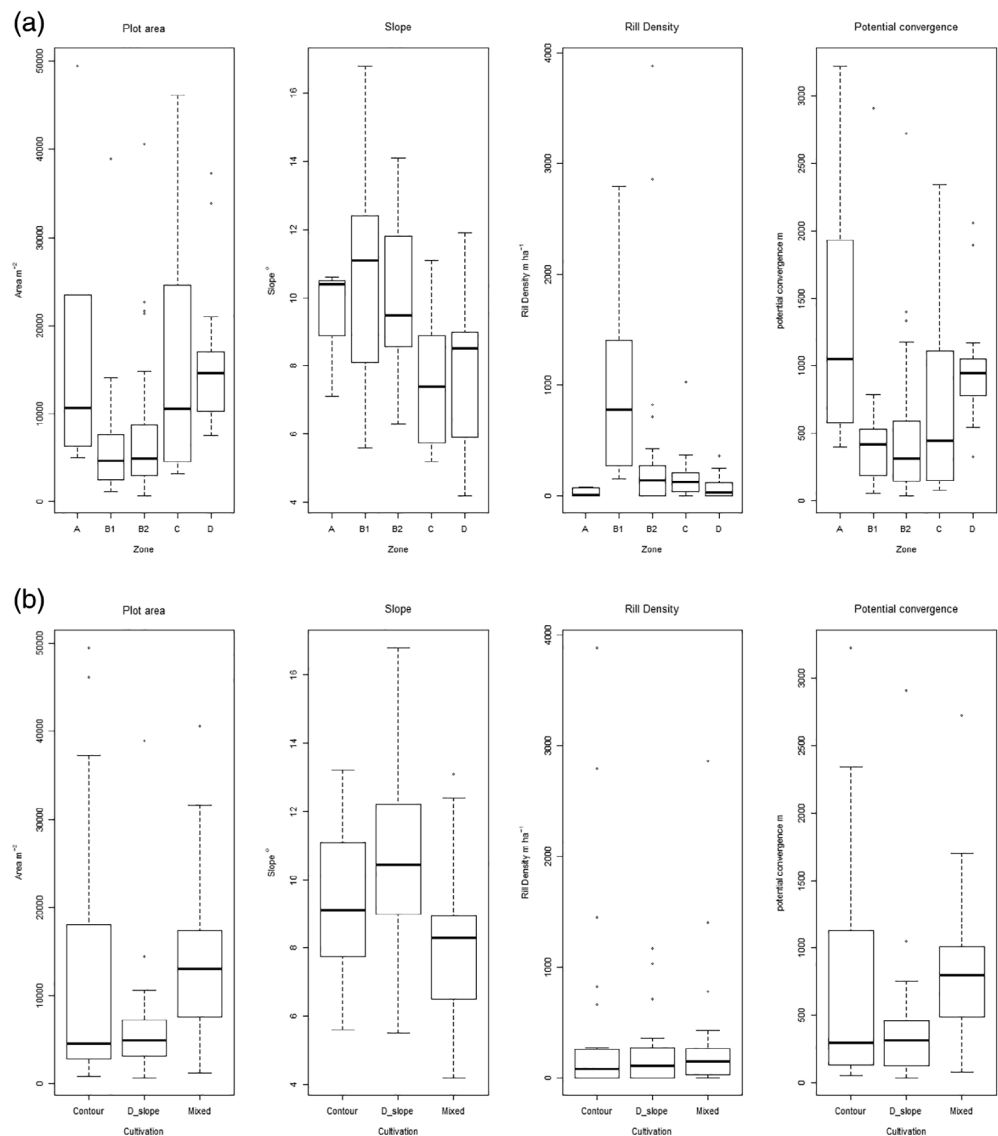
3.5 | Local environmental knowledge

The DEM image generated considerable interest among participants. The first step was to orientate the image to local landmarks, to enable those present to identify their own land on the DEM and situate their understanding of the real world three-dimensional landscape within the context of the two-dimensional aerial view. Once done, participants used the infographic tool to begin relating their understanding of water flow across their own land, and its associated connection to gullying downslope. This was the first time that local participants could see 'from above' how the complexity of landscape topography played a critical role in whether specific mitigation actions would have the planned effect:

VLG[villager]1: In order to fill gullies and look as what we see from the map, we have to plant grasses as it looks down there. This erosion occurs because when the rainwater flows from the upslope it lacks barriers, which protect soil from being washed away. So now as the water flows downslope it erodes soil and leave cracks on land surface. All we have to do is plant grasses and trees.

Although initial discussions centred primarily on how hydrological processes had created rapid overland flow leading to severe erosion and gullying downslope; the focus rapidly shifted towards the physical drivers (lack of effective terracing in upland farms to slow overland flow; lack of trees and vegetation upslope) and associated socio-economic drivers (lack of CA knowledge, skills or resources; lack of compliance) as this participant notes:

FIGURE 8 Key soil erosion factors measured across the study are categorised by (a) cultivated plot zones according to conversion year and practice (see text for details) and (b) cultivation direction with respect to contours



VLG8: "Some of the people living uphill there have not terraced their farms and when it rains water flows through their farms till down here."

Facilitator: "Why is it that some have not terraced their farms. Have they not been told or it's just that they do not want?"

VLG4: "It's because of ignorance because everyone has got their own knowledge and understanding. You can find someone lacks even the basic knowledge of doing something in order to prevent soil erosion."

Further discussion highlighted a particular issue on common land outside of private ownership, where less effort was made on soil erosion mitigation, and where water was directed towards, to avoid eroding private land. This resulted in faster flow along cattle trackways and paths, which were located on common areas. In order to deal with this specific issue, participants identified areas on the map, which could be zoned as priority areas to plant trees and shrubs in order to mitigate and slow hydrological flow. The DEM played a critical role in enabling participants to identify the areas for actions likely to have

most impact in slowing flow based on their overview of the topography; and supported a much more focussed debate regarding the specific actions (tree-planting; terracing; education) needed to suit the differing soil types in each area:

VLG6: "First of all, the places you see are fields that people grow crops. Although people farm, there is a difference in soil between one zone and another. Where you see there is erosion, is the newly cultivated farming area and the other side, which is uneroded is the uncultivated area. And areas you see as eroded are cultivated areas. Erosion takes place downstream there. But what causes erosion downstream is the difference in soil between down here and up there. Therefore, as water flows from upstream it does not erode as it does down here."

Using the DEM, participants also reflected on the relative success of the demonstration plots set up with the community during the original Jali Ardhi Project. These areas highlighted the close coupling between institutional factors, such as the commitment of village leadership to maintain these areas as livestock exclusion zones. As a result

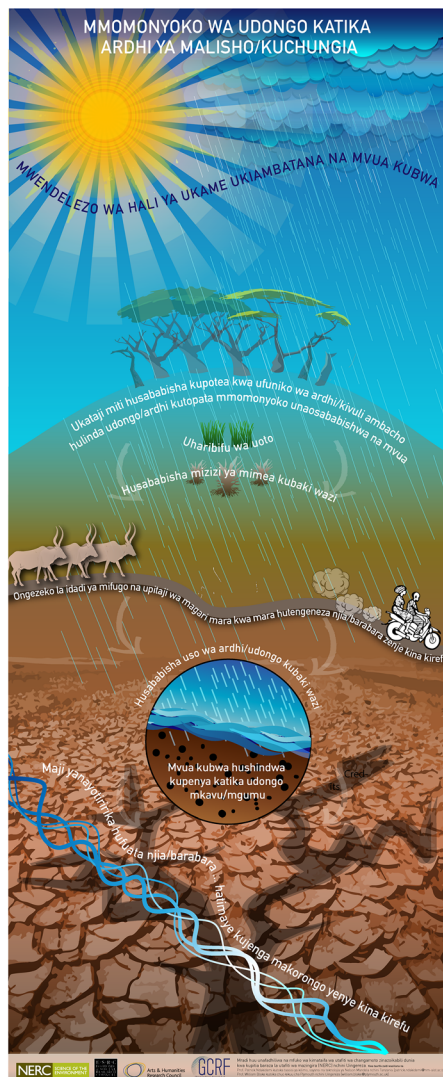


FIGURE 9 Infographic poster designed to explain structural and process connectivity concepts (see text for explanation) [Colour figure can be viewed at wileyonlinelibrary.com]

of that commitment, gullies in the excluded zones had begun to show significant vegetation growth, with the resulting reduction in hydrological flow across this lower-level topography, as this participant noted:

VLG2: "Another lesson, you might for example set aside an area for 3 years without livestock getting in. [...] For example, down there you can see we have set an area and prevent cattle from getting in and we have seen changes as gullies are now filling-up. The best practice, therefore, is to set an area and leave it for a while without allowing cattle in so as to allow grasses grow and reduce speed of water flow."

The community-led outcome of this workshop was a commitment to deliver a tree and shrub planting programme, with specific species and planting locations selected by community members. In order to facilitate this next step, a community tree committee was set up, led by the Village Leader, with externally-provided practical training and

support in planting techniques and ongoing maintenance. This programme was delivered during the short rainy season in December 2019 to allow the trees to use rain for survival.

4 | DISCUSSION

4.1 | Translating people-land-water connectivity evidence into targeted mitigation actions

The lack of relationship between slope, rill density and potential flow convergence across the whole study area underpins the need for a community-informed geospatial approach to tease out the driving factors of erosion risk in this complex human-physical landscape. The modelled potential flow convergence lines between different catchment areas map indicate a direct hydrological connection between severely eroded pastoral land in the mid and lower slope regions of the catchment (Figure 6e) with upslope runoff generation on cultivated plots. Connectivity is enhanced through the interconnection of major tracks with natural flow convergence lines, where downslope gully onset was often initiated directly below road channels entering the rangelands (exemplified again in Figure 6e). The whole-catchment view of this study is critical in underpinning community-led action. These observations also have important implications for track management and planning of runoff drains that can release water and eroded sediment and nutrients back into the fields.

Within plot improvements in soil infiltration capacity to reduce overland flow generation (Kuyah et al., 2019; Nishigaki, Sugihara, Kilasara, & Funakawa, 2017) is key as is the improvement of and aggregate stability, for example, with an amendment by organic matter, to reduce risk of soil capping/crusting (Laker & Nortjé, 2019; Smith, Strauss, & Hardie, 2019) and improve overall soil health (Belayneh, Yirgu, & Tsegaye, 2019; Mesfin et al., 2018). While such within-plot actions can be locally beneficial, analysis in this study has shown that different agricultural plot terraces on the same slope are chained to each other. At the edge of plots, implementation or augmentation of features that can attenuate or slow overland flow to retain soil within the plots are important but poor practice upslope can still generate significant overland flow that overwhelms the integrity of downslope plot terraces, even if the latter uses CA practices that promote infiltration and good soil health. Herein slope length is a key factor (Gourfi, Daoudi, & Shi, 2018). This is exemplified in zone B1 and B2 where slope length was high (< 800 m) and the relatively recent conversion of the land with under-developed boundaries meant that attenuation features could not cope with the amounts of overland flow generated. This allowed an extensive and well-connected rill network to develop and link all plots to each other and the main track (Figure 6b). This was augmented by a large proportion of plots cultivating crop rows in the direction of the slope even though the plots themselves, and their boundaries, were aligned across the slope. Off-contour cropping is widely known to enhance rill development (Ayele et al., 2018). In contrast, visual evidence of rilling was markedly lower in the longer-established plots (e.g., zone D)

where farmers have used contour ploughing and the plot boundaries themselves are more closely aligned with contours. While the upper slope angle is still high, the hilltop steep land has been left in natural vegetation both reducing run-on from the upslope contributing area and effectively reducing the overall length of the slope segment. With the longer-term establishment of plot boundaries, there is further resilience to development on connected rill networks due to edge-of-plot barriers that are not overwhelmed by any overland flow that does occur under extreme rainfall conditions. The strong influence of the direction of crop lines is further exemplified by a comparison of the two valley sides of Zone A (Figure 6a).

Comparison of the longer-established cultivated plots and recently converted land in this study highlights a problem in the initial phase of slow-forming terraces, as not enough time has passed for the buffers to become effective in stopping/slowing the flow and the slope gradients to decrease, giving almost free reign to erosive processes. The community picked up the key issue of plot boundary integrity and flow retardation by natural vegetation, wherein suggestions of planting trees and permanent grasses were made. The integration of people, land and water into one connectivity framework exposed a direct chain of cause and effect that can promote cooperative community-led mitigation to stop the downstream propagation of runoff. This is potentially facilitated by the agro-pastoral structure of the community, wherein farmers are both dependent on cropland and on the rangelands for livestock grazing, presenting an opportunity for integrated catchment management.

4.2 | Catalysing local governance decisions to increase landscape resilience to erosion

The DEM and orthomosaic aerial photograph provided a unique visualisation of the landscape connectivity for community members who have little formal scientific training and normally have no access to satellite or drone imagery. One of the central aspects underpinning the workshop discussion of hydrological connectivity on the ground was an implicit understanding of the need for effective governance mechanisms (including policy instruments) at both community and

District levels, to enable community-led actions to be implemented effectively and, more importantly, consistently. Herein a key incentive (German, 2018) is retention of soil and nutrients within the plot and reducing collective impact on downslope common land. Two specific governance elements were identified by participants: Committed leadership supported by the majority of the community; and effective sanctions for policy non-compliance. Previous co-designed community actions (Blake et al., 2018; Rabinovich et al., 2019) included setting aside (and fencing against livestock) an area of severely eroded and gullied communal grazing land as a demonstration plot to trial potential erosion mitigation and rehabilitation solutions. The demonstration exclusion plot had been established for 3 years and had been significantly expanded in area by the community without further external support or materials. The effectiveness of this area at slowing water and the speed of revegetation was frequently commented on during the workshop. Critically, the success of these plots (Figure 10) was recognised as being largely a reflection not of their physical design but of the quality of governance processes within this specific community. Despite severe pressure for grazing land, community members (including those who were not directly involved in the previous projects) were prepared to respect the Village Leader's decision to exclude grazing in this area notwithstanding the resulting personal economic costs (loss of grazing). Success rested on short term gain for a small number of community members being deferred for longer-term gain for the wider community. Land rights and land access present an ongoing dimension to this challenge (Wynants et al., 2019).

The connection between good governance mechanisms and mitigation measures to slow water in high-risk areas reflects the temporal and spatial challenges of taking proximal actions to achieve distal benefits (Wynants et al., 2019). Land management actions need to be taken upslope and regularly maintained, at cost to individual land owners and users, but the benefits are largely experienced downslope and across relatively longer time-frames. Despite these challenges, this research demonstrates that using images and other visual tools supports communities to visualise actions, and associated changes in three dimensions; and facilitates abstraction of impacts beyond individual costs, to reveal wider societal benefits.



FIGURE 10 Evidence of recovery following livestock exclusion (comparing March 2017 and November 2019) [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

5 | CONCLUSIONS

While soil erosion processes are complex and multifaceted, this study shows that co-design of land management policy tailored to the needs of specific communities can be achieved through participatory engagement where scientists and the community work together to identify evidence of the problem, evaluate the drivers and share knowledge to inform actions. We demonstrate how communication of land degradation process knowledge, through an established interdisciplinary participatory approach has supported a community-led change in land management in an East African agro-pastoral community. High-resolution aerial photography coupled with flow connectivity modelling and geospatial analysis demonstrated the importance of upslope overland flow generation and routing from recently converted cultivated land to downslope grazing land where severe erosion is observed and formerly believed to be wholly caused by overgrazing. Herein community adaptability that is needed to cope with the challenges brought by dynamic people-land-water connectivity can be undermined by a lack of ability to respond due to a lack of 'slack' in their systems caused by erosion of their resources and their options. Continued dialogue within and between communities is essential, as well as between community and policy makers, to ensure long-term sustainability and behaviour change. This study demonstrates that such barriers can be overcome wherein impact from research evidence bases was realised through a knowledge exchange workshop with community leaders, livestock owners, farmers and District Council officials. Key outcomes were (i) the formation of a tree-planting committee, (ii) implementation of a targeted planting programme of 200 trees and shrubs in hydrologically vulnerably hot spots, (iii) new grazing management regimes and (iv) commitment to a longer-term community land management plan. The findings demonstrate critical importance in integrated upstream/upslope and downstream/downslope thinking when tackling complex soil erosion challenges.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHORS' CONTRIBUTION

All authors are active contributors to the intellectual content. The manuscript concept was conceived by William H. Blake who led the drafting of the manuscript and analysis and interpretation of data. Claire Kelly led the acquisition and interpretation of the social science data and contributed to the structure and drafting of the manuscript. Maarten Wynants contributed analysis and interpretation of geospatial data and structure and drafting of the manuscript. Aloyce Patrick co-led the acquisition of social science data and contributed to socio-cultural interpretations and drafting of the manuscript. Shaun Lewin designed and undertook specialist geospatial data analysis, interpretation and visualisation and drafting of the manuscript. Joseph Lawson, Emmanuel Nasolwa, and Annabel Page made substantial contributions to the acquisition of data through drone survey design and implementation plus data interpretation within post-processing of DEM. Mona Nasserri contributed intellectual design of stakeholder engagement process to acquire social science data. Carey Marks conceived and delivered infographic design and intellectual integration with the science mission. David Gilvear, Kelvin Mtei, Linus Munishi, and Patrick Ndakidemi contributed to drafting through critical revision of manuscript intellectual content.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article and may be used with the permission of the corresponding author.

ORCID

William H. Blake  <https://orcid.org/0000-0001-9447-1361>

Claire Kelly  <https://orcid.org/0000-0002-3809-225X>

Maarten Wynants  <https://orcid.org/0000-0002-5367-7619>

Aloyce Patrick  <https://orcid.org/0000-0001-9434-9681>

Mona Nasserri  <https://orcid.org/0000-0002-7927-210X>

David Gilvear  <https://orcid.org/0000-0003-3859-8290>

Kelvin Mtei  <https://orcid.org/0000-0002-6792-3083>

Linus Munishi  <https://orcid.org/0000-0003-0188-8630>

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