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Soil erosion in East Africa: an interdisciplinary approach to realising pastoral land management change

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Abstract

Implementation of socially acceptable and environmentally desirable solutions to soil erosion challenges is often limited by (1) fundamental gaps between the evidence bases of different disciplines and (2) an implementation gap between science-based recommendations, policy makers and practitioners. We present an integrated, interdisciplinary approach to support co-design of land management policy tailored to the needs of specific communities and places in degraded pastoral land in the East African Rift System. In a northern Tanzanian case study site, hydrological and sedimentary evidence shows that, over the past two decades, severe drought and increased livestock have reduced grass cover, leading to surface crusting, loss of soil aggregate stability, and lower infiltration capacity. Infiltration excess overland flow has driven (a) sheet wash erosion, (b) incision along convergence pathways and livestock tracks, and (c) gully development, leading to increased hydrological connectivity. Stakeholder interviews in associated sedenterising Maasai communities identified significant barriers to adoption of soil conservation measures, despite local awareness of problems. Barriers were rooted in specific pathways of vulnerability, such as a strong cattle-based cultural identity, weak governance structures, and a lack of resources and motivation for community action to protect shared land. At the same time, opportunities for overcoming such barriers exist, through openness to change and appetite for education and participatory decision-making. Guided by specialist knowledge from natural and social sciences, we used a participatory approach that enabled practitioners to start co-designing potential solutions, increasing their sense of efficacy and willingness to change practice. This approach, tested in East Africa, provides a valuable conceptual model around which other soil erosion challenges in the Global South might be addressed.

1. Introduction

1.1. Rationale and aim

Every year 12 million hectares of productive land are lost to soil erosion [1] globally and 33% of soils are currently thought to be degraded [2]. The problem of soil erosion and land degradation has traditionally been investigated through a sectoral or disciplinary lens, rather than holistically. In addition, the formulation of policy solutions for achieving sustainable land management has often been detached from those responsible for implementing them on the ground. We argue that it is (1) the *interdisciplinary gap* left between specialist researcher groups, and (2) the *implementation gap* between policy makers and practitioners, that lie at the heart of a collective failure to achieve greater socio-ecological resilience in the face of this environmental challenge. Against this, we aim to outline and demonstrate a field-based approach designed *ab initio* to overcome these two key deficiencies. Interdisciplinary and transdisciplinary research targeting socio-ecological problems is not a new concept, but increasing demand for solutions via this pathway reveals inherent challenges in approaching and structuring interdisciplinary research processes [3]. The approach we offer here aims to address specifically the 'interdisciplinary' and 'implementation' gaps that are hampering soil erosion control in northern Tanzania and the wider East African Rift System (EARS) region, with relevance to challenges in the wider Global South.

1.2. Soil erosion and socio-ecological resilience

Soil erosion and associated land degradation is a widespread 'wicked problem' [4, 5] for rural communities undergoing transitions across the Global South, as climate change, population growth, political upheaval, land tenure change, and migration put unprecedented pressure on natural resources. Urgent intervention is required to prevent irreversible loss of ecosystem services as unsustainable land management leads to rates of erosion that exceed natural soil production. While on-site loss of soil and nutrients threatens food security [6], pollution of waterways by silt and nutrients impacts water security, and siltation threatens freshwater biodiversity, tourism and efficiency and lifespan of hydropower dams [7, 8]. Hence, soil erosion has far-reaching implications for the food, water, and energy security nexus [9] with impacts that span multiple UN sustainable development goals (e.g. SDG 1, 2, 3, 6, 13, 15).

Despite decades of research on soil erosion and land degradation [10] the problem has, in fact, worsened rather than improved, and more communities are being affected than ever before [2]. This is in part because successful implementation of mitigation measures is intrinsically linked to socio-cultural, governance and political complexities [11] and opportunities for livelihood transitions [12]. Often, when these are not taken into account, insufficient traction is gained to shift systems from unsustainable to sustainable pathways. While population growth can promote more 'intensive' sustainable agricultural practices through technological and organisational innovation [13–15] there are many circumstances where fragile land in combination with weak 'institutions' (e.g. local governance) and historically-inappropriate management policies have led to severe damage to soil resources following population growth [16, 17]. This is further compounded by socio-cultural lock-ins [18] where decision-making is constrained within often narrow bands of what is perceived as possible. Accelerating unsustainable land use change, such as conversion of forest to agricultural and grazing land [19], is likely to amplify the effect of hydro-climatic drivers of soil erosion by water with unknown consequences for community resilience and development [20]. Soil erosion and resulting land degradation are a consequence of both individual and community land management choices [21, 22] compounded by dynamic environmental factors which are evolving with climate change [23].

Land degradation directly affects community resilience wherein the direction and rate of response is complex [18]. On-site problems caused by soil erosion are compounded by downstream physical and socio-cultural impacts (e.g. water pollution, reservoir siltation, freshwater biodiversity loss), the solutions for which often lie outside the communities affected. Since socio-economic resilience is intrinsically linked to ecological resilience [24] through the coupled co-evolution of natural resource systems and dependent rural communities, soil erosion and downstream siltation problems [25] undermine the resilience of all communities that depend on soil and water resources.

Soil erosion shocks are often amplified by physical and socio-cultural positive feedback mechanisms [18]. In this context soil erosion and land degradation challenges can be considered 'intractable'. Complex physical and socio-cultural feedbacks are difficult to disentangle meaning discipline-specific solutions have, to date, proved inadequate in many areas affected by land degradation. In some cases, shocks can lead to a learning experience that propels a system to a qualitatively different pathway that supports greater-than-previous levels of resilience [18] based on capacity for renewal, re-organization and development [26]. Accordingly, reactions to disturbance shocks have been categorized, in a 'disaster resilience' context, as ranging from (i) 'collapse' through (ii) 'recover to worse than before' and (iii) 'bounce back to normal', to (iv) bounce back better [27]. Examples of 'bounce back better' tend to be cited in the context of natural hazard impacts e.g. the development of community coping mechanisms to drought and flood impacts, linked to climate change, that were both (a) community-led and (b) NGO/aid-sponsored livelihood adaptions [28]. In terms of responses to soil erosion, archaeological evidence has been interpreted to indicate marked episodes of soil erosion associated with development and then subsequent decline of civilizations [29]. While such evidence has been pitched as a 'collapse' response, recent analysis of contrasting archaeological cases [30] indicates a diversity of responses to severe erosion that in part relate to the nature of substrate and role of tillage in soil production but more importantly how erosion itself can engender sound ecological behaviours and socio-technical innovation in organised societies (see [15]). Indeed diversity of response might be expected given recently reported global variability in spatial and

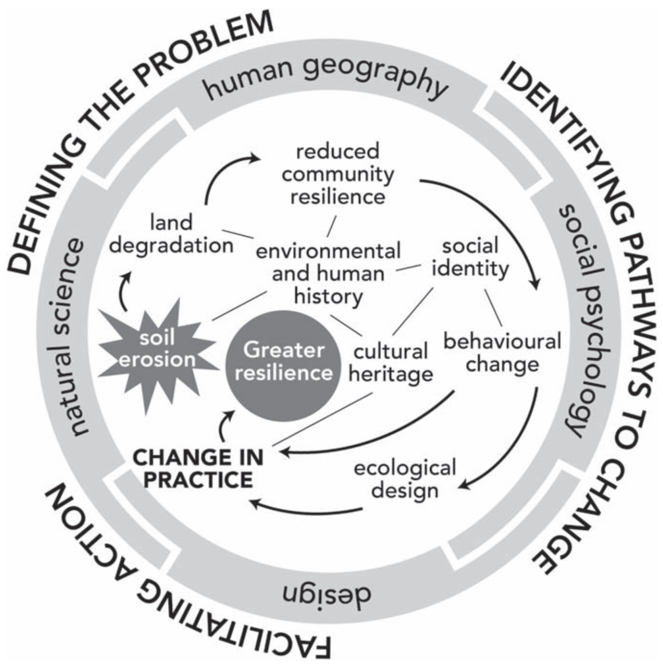

Figure 1. Disciplines involved in the present study, their interconnections and position in the soil erosion-land degradation-community resilience challenge.

temporal effects of land use change in different development contexts [31] and inevitable differences in socio-cultural approaches to soil conservation. Recent analysis has predicted that greatest increases in soil erosion rates into the 21st century will occur in Sub-Saharan Africa, South America and Southeast Asia [31]. In the context of above complexities, attention needs therefore to focus on co-production of sustainable land management practises in the Global South.

1.3. An interdisciplinary approach to realising land management change

The intractability of soil erosion and land degradation problems can only be addressed though interdisciplinary collaboration, rather than a narrowly sectoral approach.

In order to overcome the *interdisciplinary gap*, the project design (figure 1) included both natural and social scientists from the outset, working in the same region and communities at the same time. This ensured that there was spatial and temporal congruence between the results from different disciplines, with findings being as commensurable as possible and minimising the risk of a 'false diagnosis' based on one disciplinary view. Each discipline contributed specific knowledge: physical geography and agricultural science to evaluate erosion processes impacts of land management; human geography to evaluate community resilience response to degradation; social psychology to explore existing behaviour change approaches wherein social/group processes are likely to be a key to bringing change. This first stage drew on knowledge and expertize equally from researchers in the host country (Tanzania) and donor (UK). Secondly, the *implementation gap*, i.e. between policy makers and practitioners, was bridged by engaging local stakeholders in the co-design of land management policies. Here, the discipline of ecological design thinking was integral in integrating concepts and underpinning participatory action. Against this challenging context, our programme of interdisciplinary research in Northern Tanzania sought to (1) develop knowledge of complex interlinkages between soil degradation, climate change, and community processes in the past and present landscape, and (2) test a participatory approach [32] to underpin co-designed soil conservation and restoration strategies in the future. This was based around three key transferable steps: (a) defining the problem, (b) identifying pathways to change and (c) facilitating action (figure 1).

2. Methods

2.1. Study area: lake Manyara basin, northern Tanzania

The EARS region has the highest catchment sediment yields of sub-Saharan Africa [33] linked in part to topography and rainfall (semi-arid climate with bimodal rainfall pattern) but also to recent and historic land conversion to agriculture and, in particular, increasing livestock numbers on grasslands. Indeed recent analysis [31] has shown that the poorest tropical countries are most susceptible to high levels of soil erosion and this will be further challenged by growing populations, in the absence of soil conservation strategies. In the EARS, extreme drought and rainfall events, which are already a characteristic feature of tropical climatology

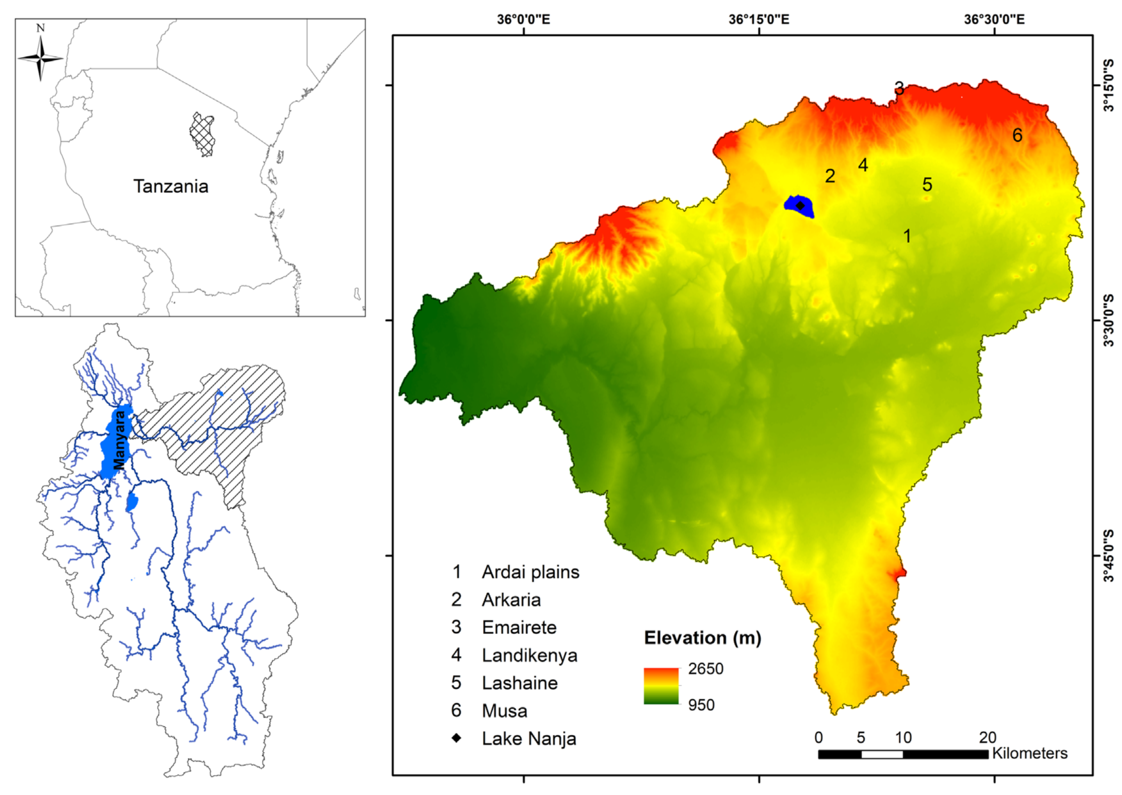

Figure 2. Study site location in Northern Tanzania.

e.g. linked to ENSO or IOD [34, 35], are widely believed to be changing in magnitude and/or frequency with global climate change [36]. In this context, we selected the Lake Manyara catchment system in Tanzania (figure 2) to represent a natural 'socio-ecological laboratory' typical of EARS catchments supporting vulnerable pastoral and agricultural communities in East Africa.

The study was undertaken principally in Maasailand of the Monduli District, near Arusha within the Lake Manyara catchment (figure 2, supplementary information 1 is available online at stacks.iop.org/ERL/13/124014/mmedia). Study areas were selected in collaboration with village leaders from upland (1814 m) Emaerete (EE), mid elevation (1430 m and 1470 m resp.) Landikinya (LA) and Arkaria (AA) and lowland (1304 m) Ardai Plains (AP). At all sites, sheetwash and consequent soil erosion was causing notable loss of topsoil and incision of flow convergence pathways and drainage lines. Local herders have reported that gully erosion has become more severe over the past ca 15 years. Control sites were based in upland areas of conservation agriculture in Musa Valley (MA) and lowland areas controlled and restricted by the military, Lashaine (LE).

2.2. Integrating disciplinary expertize to develop pathways to change

Jali Ardhi means Care for the Land in Swahili. The interdisciplinary 'Jali Ardhi' approach (figure 1) is grounded in an adapted 4-step PATH model drawn from applied social psychology [37]: (I) Problem (formulating a problem definition), (II) Analysis (finding explanations for the problem), (III) Test (developing and testing a conceptual process model), and (IV) Help (co-designing an intervention and testing its effectiveness). The work described below primarily addresses steps 1 and 2 of the PATH model and commenced with an evaluation of the spatial and temporal extent of soil erosion and its impacts on landscape and community resilience in the study area. Consequently, barriers and opportunities for sustainable behaviour change were explored within the framework of group processes with a focus on the concepts of community cohesion [38] social and cultural identity [39, 40], and social norms [41]. The evidence bases were integrated using a resilience approach which, in turn, supported participatory engagement [32, 42] within an applied design-thinking [43] framework to evaluate potential for co-designed solutions [44] and create a transferable framework for wider application.

2.3. Objectives and data collection

2.3.1. Defining the problem

A key natural science objective (figure 1) was to develop comparative datasets of soil erosion risk in different geomorphic zones of the study area, from lowland to upland pastoral land, and relate this to Google Earth-based analysis of rill and gully incision extent. This was integrated with a social science objective to gain understanding of stakeholder awareness of the problem, and existing socio-cultural barriers to its resolution. These contemporary insights were set in the context of a timeline of past landscape erosional response to anthropogenic land use change and climatic events over recent decades. This was achieved via analysis of local swamp/lake stratigraphic records, historic air photography and satellite imagery, and local anecdotal evidence.

For assessment of erosion extent, a representative 100 × 100 m plot within each study area was demarcated and surveyed (see [21]) to produce a geomorphological map of key landscape features. Within the plot, soil samples were collected in triplicate at nine random locations for (a) aggregate stability assessment [45], (b) total organic matter (OM), by loss on ignition, and (c) particle size, by laser granulometry. Alongside, the soil sampling regime, soil surface permeability measurements were made using a Decagon minidisc infiltrometer [46] with samples stratified to evaluate bare, crusted and non-crusted surfaces. Control sites were conservation agriculture underlain by the same soil type and a military zone with restricted livestock access. To evaluate natural archives of landscape change, sediment cores were recovered from exposed lake bed in catchments heavily impacted by erosion. The cores were sectioned into 1 cm slices which were freeze dried and homogenized for geochemical analysis. To derive a chronology for the sedimentary sequence, subsamples were analysed for fallout ^{210}Pb and ^{137}Cs by alpha and gamma spectrometry following standard procedures [47]. To support application of environmental diagnostics tools to evaluate sediment production processes and source dynamics [48], subsamples were analysed for a full suite of major and minor element geochemistry by Wave-length Dispersive-XRF.

2.3.2. Identifying pathways to change

Key objectives regarding pathways to change were to identify (a) suboptimal practices that need change to manage the problem successfully and (b) opportunities for practice change and processes to be targeted in an intervention. To evaluate interlinkage between the ecological problem and social drivers, a mixed-method inductive approach was used to identify stakeholder perceptions. A series of 17 semi-structured interviews (13 male participants, 4 female) were conducted with pastoralists and farmers living in the areas where the soil samples were collected ($n = 14$), as well as with other stakeholders (e.g., representatives of farmer organisations and local government). The interviews focussed on stakeholders' awareness of the soil erosion problem, its perceived reasons and impacts, understanding of problematic land management and cattle-keeping practices, and perceived barriers and opportunities for adopting new land management approaches. A selection of key land management practices to focus on was informed by natural science insights. Each interview lasted between 30 and 100 min. Interviews were transcribed verbatim, translated into English, and processed using NVivo for thematic analysis [49].

2.3.3. Facilitating action

Following the first stage of soil erodibility assessment, evaluation of sedimentary evidence and interview data analysis, a stakeholder workshop was held to (i) exchange knowledge between researchers and the study communities, (2) explore the opportunities for co-design of solutions and (3) lay the foundation for a co-designed framework within which to support future land management change [43]. The approach was closely aligned with Reed *et al*'s [44] 'bottom-up' participatory principles (see [42]) in that workshop participants included stakeholders from each of the study communities as well as District and Regional Council representatives and NGOs. It was important that local government stakeholders were present as cross-sector and participatory decision-making is more likely to be successfully implemented when co-designed to meet the specific local socio-economic and institutional culture as well as the environmental context [32]. Workshop impact was assessed by administering pre- and post- measures of problem awareness, efficacy, and behavioural change intentions (supplementary information 2).

3. Results and discussion

3.1. The present: soil erosion processes, dynamics and societal challenges.

Extensive visual evidence of sheet wash, rill and gully erosion (figure 3, supplementary information 3) across the study sites implied indicative hydrological process controls on overland flow and soil erosion. Extensive ponding of surface water was observed across the eroding study sites during rainfall events (figure 3(a)) leading to rapid overland flow generation. Soil infiltration data (supplementary information 4) demonstrated that soils in impacted areas had an unsaturated hydraulic conductivity less than 10 mm hr^{-1} with a notable influence of crusting [50]. These observations are in line with, albeit at the lower end of, other studies in the region [51, 52]. While soils under conservation agriculture showed greater infiltration rates with median values two to three times those of the degraded soils, infiltration capacity was still low in global terms indicating the generally high risk of infiltration excess overland flow during high intensity events.

Both interview and stakeholder workshop data with pastoralists and farmers demonstrated a high level of awareness of soil erosion issues and impacts (table 1) with contrasting perceptions of the scale of root causes. Interviewees highlighted the implications

Figure 3. Photographs of key erosion features and processes in the study area (a) surface ponding due to low soil infiltration capacity, (b) grass root pedestal indicative of sheet erosion, (c) cattle track along a topographic flow convergence line, (d) deep 'gully' incision along flow convergence lines (Images University of Plymouth/Carey Marks).

Table 1. Community perceptions of challenges and opportunity.

Community identified challenge	Barriers to change	Pathways to change
- Changing rainfall patterns (drought = loss of grass cover; extreme events damage and erode bare soil)	- Climate change impacts are outside of community control	- Recognition that environment may force change will catalyse adaptability - Learning from negative experiences (e.g. prior drought)
- Impact of livestock numbers and trackways on soil erodibility	- Cultural importance of cattle as a symbol of wealth and status - Economic role of herds as 'saving accounts' - Perception of high risk and challenges in growing crops - Lack of skills, opportunities and knowledge to switch to alternative livelihoods	- Learning from others within and between communities - Education and training - NGO and government micro-finance schemes - Support for development of alternative livelihoods (local government)
- Shifts in land ownership and lack of common land management strategy	- No individual incentive to take responsibility for common land - Inefficient governance, lack of natural resource protection enforcement	- Harnessing community cohesion and the power of group norms - Community ownership of problem through participatory action
	- Harmony in community sometimes valued over environmental protection	- Opportunities for discussion within and between communities - Collective decision-making
- Change of migration patterns focussing pressure on land		- Government and NGO support
	- Land designations (e.g. conservation areas, large scale commercial ownership) and social change outside of community control	- Community education/awareness
		- Development of alternative livelihoods

of erosion for their livelihoods (such as reduced availability of pasture and poorer soil quality), and concerns about the future (such as opportunities for the next generation to make a living). Participants reported a strong shared perception that action needs to be taken to address the problem. They spoke about a range of solutions they are practicing, directed both at the adaptation to the existing erosion (e.g. filling the gullies with branches or manure) and the mitigation of future damage (e.g. building barriers on farmland, using contour cultivation, hole planting, chemical weeding).

There was notable variability in soil erodibility in different environmental and land management settings. Soil aggregate stability data (supplementary information 4) showed marked variability in Relative Soil Stability Index (RSSI) (how easily aggregates break down) [45]. Values were notably low (<10) for soils from the mid elevation region (AA) and lowland plains (AP) which also had the lowest OM content (6%–7% loss on ignition). Soils in the upper mid elevation rangelands (LA) showed high variability (RSSI 15–70) which might be related to widespread evidence of sheet erosion that had removed up to 30 mm topsoil in places as indicated by grass root pedestals (figure 3(b)) although OM content at this site was surprisingly consistent and greater than the lowland sites (Inter Quartile Range 8%–9%). The greatest RSSI (ca 80) was observed at the upland site (EE) coinciding with highest OM content in rangeland sites (IQR 8%–10.5%). This can, in part, be linked to higher rainfall at this elevation reflected in notably richer grass cover compared to drier lowland sites. Eroded soils with depleted OM have reduced potential to sequester further carbon [53] leading to a positive feedback in erosion and erodibility. The complex erosion response in relation to land use impacts [54] and feedbacks, as well as topography and rainfall patterns (affecting both vegetation cover and erosivity), are a key part of the adaptation challenge.

In this regard, many participants expressed an understanding that current practices would need to be adapted to reduce further soil erosion, and some participants showed awareness that reducing cattle numbers would be an important step and/or diversification of land management approaches. However, the interviews also revealed a number of barriers that stand in the way of achieving this. In line with previous research [55], some of the most pertinent issues include the central place that cattle-keeping occupies in Maasai identity, the status-signalling value of large cattle herds, the function of cattle as a liquid asset (i.e., as the equivalent of a savings account), and the perceived risks associated with alternative livelihoods (such as mixed or predominantly cropland agriculture). These issues may act as a brake on effecting change on an individual level and lock pastoralists into pathways maintaining herd sizes at unsustainable levels, limiting land management change through diversification.

Evidence of sheet erosion at all sites requires some consideration against the extent of erosion due to incision by rills and gullies (figure 3(d)). Gully erosion represents a major sediment source despite occupying a relatively small proportion of the catchment area [56]. Emerging gully networks also represent efficient conveyance routes connecting sheet and rill erosion to downstream channel network, which is becoming incised by enhanced surface runoff linked to increased structural connectivity (see [57]). Other studies have implicated gully erosion as a key contributor to sediment delivery downstream [58]. Here we note that 'unseen' sheet erosion may be equally if not more important in terms of raising awareness to land degradation given (1) its key contribution to incision and gully formation through infiltration excess overland flow convergence, and (2) loss of topsoil horizons which contain most soil OM, nutrients and the seedbank.

Overall, the development of the present day dissected and gullied landscape requires consideration from both a natural and social science perspective. Taken together, multidisciplinary evidence demonstrates that the extent of physical erosion is significant, reflected in stakeholders' awareness of the scale of the problem and efforts to manage the erosion. At the same time, these efforts can be limited by the cultural and social meaning of cattle in Maasai communities, reducing grass cover and increasing the pressure on the land.

3.2. The past: dynamics of social change and landscape response

In addition to contemporary barriers to change related to cultural identity, available economic resources, and individual risk perceptions, interviews (table 1) also highlighted issues related to local governance, community cohesion and cooperation which are perceived to have been exacerbated in recent decades by population growth and urban expansion. Recent decades have brought increased large scale commercial land ownership to Tanzania and other East African countries, which has disrupted traditional migration routes. This, in turn, resulted in Maasai way of life becoming more sedentary, with the pressure on locally available pastures increasing. Reduction in population movement led to communities' transitioning to a private land ownership model and to a reduction in the (historically high) importance of communal land. As a consequence of this recent transition, some participants suggested that there is a lack of cooperation within communities in managing shared (as opposed to privately owned) land resources. While some communities appeared strongly cohesive, others found it difficult to secure cooperation in the face of a shared problem. The interviewees also mentioned that past devolution of responsibility for managing natural resources to communities may not always be effective. In particular, there seems to be a lack of robust governance structures that would be well placed to protect local natural resources (e.g., highland forests) from encroachment.

Within this framework, the development of the gullied landscape and changing balance of sheet to gully erosion during this process was a key question with respect to stratigraphic interrogation of downstream lake deposits. The 100 cm core recovered from

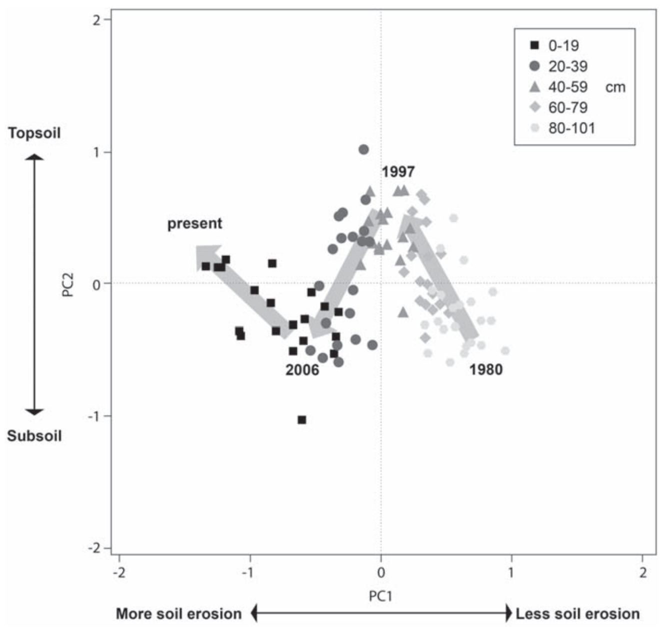

Figure 4. Principal Components Analysis plot distiling the major and minor element geochemistry evidence for shifts in dominant sediment sources to the lake sediment deposits over the past 30 years (elemental weightings provided in SI 5).

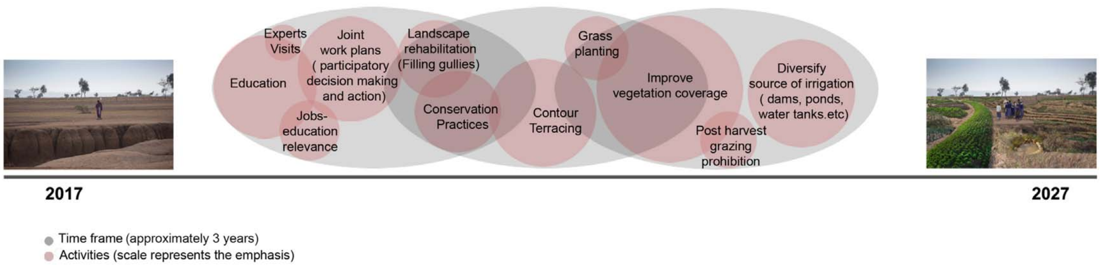

Figure 5. Outcome of a participatory visioning exercise to design a pathway via which local people can transform degraded landscapes through community action.

the exposed lake bed surface of Nanja lake (figure 1(d)) can be used to illustrate a representative catchment which drains the mid-slope Landikinya and Arkaria study areas that are heavily impacted by sheet wash, rill and gully erosion. Our initial ambition was to identify a longer-term baseline condition and permit lessons from past management change to be articulated but fallout radionuclide data demonstrated that the sequence collected was relatively young at ca 30 years (supplementary information 5). The full major and minor element geochemistry database (supplementary) was subject to Principal Components Analysis to draw out geochemical evidence for shifts in sediment source [48], and hence catchment erosion processes i.e. sheet-wash versus gully. The two emergent components (supplementary information 6) represent a shift from internal lake processes to external catchment inputs (*x*-axis, figure 4), based on geochemical indicators of authigenic precipitation versus detrital inputs, and a shift from subsoil (natural channel bank and gully erosion) to topsoil (sheetwash erosion) (*y*-axis, figure 4), based on geochemical markers of differential weathering. Within this factor space, it appears that the stratigraphy records marked shifts in erosion process over the past 30 years. From ca 1980, there is an increase in erosion initiated by a phase of sheetwash erosion followed by rill and gully incision in the late 1990s creating the present day landscape. The geochemical record of the past 10 years underpins observations of a heavily incised and well-connected drainage network fed and enhanced by infiltration excess overland flow which is efficiently conveyed, with eroded sediment, to downstream ecosystems.

Interpretations of environmental diagnostics were contextualized by historic remote sensing images, which showed, in accord with anecdotal evidence from village leaders, that gully erosion has become worse in this region over the past 15 years. Aerial photographs dating from ~1960 show only localized erosion scars, even though forest extent was almost unchanged from that at the present day. Overall, the evidence bases from environmental diagnostics and social science collectively tell a story of increased landscape vulnerability to soil erosion through loss of

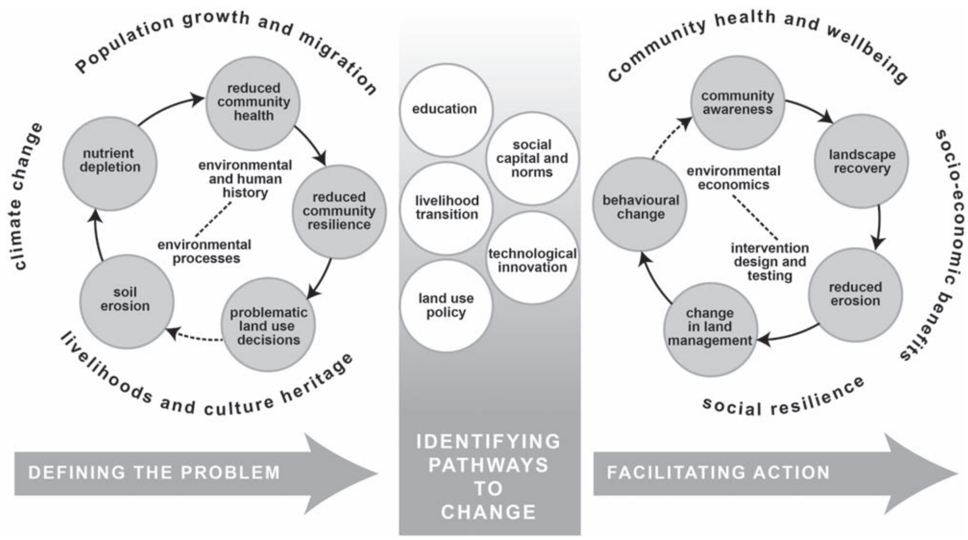

Figure 6. An interdisciplinary framework to tackle the 'intractable' challenge of soil erosion and land degradation in the Global South from identification of the environmental and social problems that emerge in response to distal pressures (left) to tangible pathways to change (middle) and anticipated societal benefits (right).

vegetation cover due to drought, grazing pressure and tree-cover thinning (all underpinned by lack of cooperation around shared natural resources) with development of a vicious circle of degradation as rill and gullies networks expand and connectivity increases.

3.3. The future: interdisciplinary integration to underpin behaviour change

As reflected by Allison *et al* [59], the strong desire for change and an openness for learning, education and participatory decision-making, when coupled with adoption of a 'post-normal science' viewpoint [60, 61] wherein human-environment systems are viewed and treated holistically, should enhance the likelihood of sustainable long-term change [59, 61] and a rebalancing between socio-economic and ecological resilience. Despite the constraints and barriers described above, participants demonstrated significant openness to change in the face of land degradation evidence. Many participants talked about the high value that they placed on education, and actively welcomed the opportunity to develop their knowledge. There was also a shared understanding of the need for change to enable land conservation. A number of pathways to change emerged from interview data (table 1), including learning from negative experiences (e.g., losing cattle during a drought), the importance of formal education (e.g., children learning new ideas about sustainable practice at school and transmitting these to their parents), inter-community exchange, and NGO-driven, as well as government-led, education and support.

Stakeholders openness to change was explored and developed further during participatory workshop exercises [62] that delivered a series of visions for change wherein priority steps and potential timelines within community control were identified (figure 5). This participatory approach is built on the belief that '*science can catalyse social learning processes especially where societal actors are integrated in research and knowledge production processes early on*' [63]. The resultant vision model encapsulated community views on achieving a stepwise shift from degraded land to a restored and productive landscape (figure 5). The impacts of interdisciplinary workshop participation on attitude and willingness to change were measured. The analysis (repeated measures ANOVA comparing pre and post scores) showed a statistically significant increase in participants' post-workshop awareness and understanding of the soil erosion problem ($F(25) = 11.21, p = 0.003, \eta_p^2 = 0.31$), perceived efficacy in dealing with it ($F(22) = 11.84$, $p = 0.002$, $\eta_p^2 = 0.35$), and willingness to change their practice ($F(24) = 8.51, p = 0.008, \eta_p^2 = 0.26$), as compared to the same measures taken before the workshop. Participants also reported that they learnt useful information during the workshop (*Mean* $= 4.91$ (where $5 =$ 'strongly agree' on Likert Scale), *Standard Deviation* $= 0.29$), received good advice ($M = 4.89$, $SD = 0.32$), and would use this to start to address soil erosion on their land ($M = 4.77, SD = 0.42$). A 1 year follow up demonstrated that in one severely degraded area, livestock are now permanently excluded from the damaged area until full recovery of vegetation cover is achieved. Elsewhere, a concerted effort is being made to implement rotational landscape recovery enforced by village leaders.There was a unanimous appetite amongst all community participants for land management change to be supported by new local bye-laws, co-designed by communities and the Local Authority, exemplifying the benefit of multi-stakeholder participation [32] in a non-hierarchical setting. The above shifts, in combination with the post-workshop evaluation, demonstrate that the proposed appoach has a strong potential for future impact on land management practices.

4. Conclusion

Integrated evidence bases collected through this research revealed a complex picture of path-dependent interlinked social, economic and environmental drivers of change, often with cross-scalar connections, which amplify and reinforce the speed and impacts of those changes. Historical data in the form of sedimentary archives and community anecdotal evidence reveal an increase in the rate and extent of erosion processes and increased landscape vulnerability through loss of vegetation cover (forest thinning and overgrazing) leading to increased soil surface fragility which, coupled with the onset of intense climate events, has resulted in decreasing ecological resilience. Stakeholder views imply that this is compounded by weak economic and institutional resilience through a lack of alternative livelihood opportunities and little enforcement of environmental protection legislation. Significant barriers to sustainable change are rooted in cultural identity content and lack of community cohesion and cooperation around shared resources (see [38]). Socio-economic processes operating at regional and higher spatial levels (population growth, urban expansion, and land tenure change) have constrained opportunities for change and locked Maasai communities in the study area into narrow decision-making pathways which have led to further exacerbation of environmental impacts, and further declining ecological resilience [64, 65]. At the same time, opportunities for potential 'bounce back' were identified through openness to new knowledge and awareness of the inevitability of change demonstrated by the target communities. These were enhanced through exposure to evidence of soil erosion process and causal factors on-the-ground and opportunities for developing cooperative solutions during stakeholder workshop events.

During major social transitions, the environment is at greater risk of degradation as socio-economic processes overlay and amplify environmental ones. The early stage of such transitions is the critical point at which to implement interventions, grounded in participatory engagement, for environmental protection and sustainable resource management, especially in the context of soil which is non-renewable in human timeframes. New concepts in transformative science thinking [63] emphasize the importance of deepening our understanding of on-going socio-ecological transformations and increasing societal capacity for reflexivity. Holistic, interdisciplinary systems thinking is required to deliver outcomes that empower local communities to break out of the vicious circle of land degradation. Consequently, we propose here a framework (figure 6) within which degradation problems associated with multi-scalar social transitions (e.g. pastoralism to mixed agri-pastoralism, rain-fed to irrigated agriculture, population expansion and response to climate variability) occurring across East Africa may be tackled.

In effect, guided by specialist knowledge, the approach enables practitioners to access new knowledge, develop problem understanding and new behavioural norms, and become local policy makers (see [66]). These processes can lead to sustainable change in land management practice, enabling landscape recovery and increased community well-being. This approach is grounded in a close interaction between natural and social science bases, closing the *interdisciplinary* gap. Environmental diagnostics evidence for a rapid onset of soil erosion supports local community narratives of recent landscape change and contributes to stakeholder understanding of the problem; quantifying baseline conditions beyond current social memory further evaluates the impact of historic societal transitions. It also actively involves stakeholders in the process of developing solutions, thus closing the *implementation* gap. Immediate impacts of this approach being implemented in the case study area are manifest in locally-enforced restriction and exclusion of cattle from severely damaged land around village meeting areas to allow recovery and stabilisation, spontaneous and strategic planting in gullies to create sediment traps, and establishment of firm stakeholder-policy maker channels for local byelaw co-design. Future research steps require quantitative evidence for natural and social processes identified as barriers to change, triangulating this knowledge through stakeholder engagement, and co-designing an intervention strategy targeting key barriers to sustainable land management practice. By doing this, we aspire to tackle successfully the soil erosion challenge and create change that is both environmentally sustainable and community-driven.

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