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Natural regeneration of drylands and associated pathways to human health outcomes: Perspectives from rural households

Peninah Murage[1]*, Ayoub Asenga[2,3], Angelina Tarimo[2,3], Tabby Njunge[4], Thijs van der Zaan[3], Faraja Chiwanga[2]

1 Public Health Environment and Society Department, London School of Hygiene and Tropical Medicine, London, United Kingdom, **2** Leadership Formation, Environmental Conservation and Action for Development (LEAD) Foundation, Dodoma, Tanzania, **3** Justdiggit, Regional Office East Africa, Nairobi, Kenya, **4** Conservation International Country Office, Nairobi, Kenya

* Peninah.Murage@lshtm.ac.uk

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Abstract

Land degradation and climate change are intertwined global challenges, their implications on human health are driven by the unsustainable use of natural resources, resulting in the loss of vital ecosystem services that support human health. There are equity implications in that landscape degradation disproportionately affects vulnerable populations that live in the most fragile ecosystems. Solutions to reverse degradation are increasingly considered attractive because of their ability to meet multiple societal objectives, however, their implementation has outpaced research on impact; the research and evidence gaps are particularly acute in relation to quantifying the health and well-being impacts of nature-based solutions. This study documents the experiences of rural communities implementing Farmer Managed Natural Regeneration (FMNR) in Central Tanzanian drylands, which integrates trees in agricultural landscapes. FMNR technique has been hailed as the largest positive environmental transformation in African drylands due to its effectiveness in restoring landscapes at very low costs. Despite its success, the impact on human well-being is largely unquantified. We used in-depth group discussions across four villages to document how respondents perceive the health and well-being impacts of natural regeneration. We thereafter adapted the ecosystem services cascade model to conceptualise the pathways between natural regeneration and impact on health and well-being. Respondents across all study sites unanimously reported how FMNR implementation has reversed decades of land degradation, resulting in physical and mental health benefits that can be linked to food and nutritional security, improved air and water quality, income diversification, heat adaptation and gender equality. We demonstrate how the application of the cascade model can generate causal pathways that 1) map how changes in ecosystem structure, functions and services can result in measurable health outcomes, and, 2) support empirical investigation by defining concrete metrics for monitoring and evaluation of interventions.

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Introduction

Natural ecosystems provide numerous benefits that are indispensable to human health and well-being [1]. Degraded ecosystems are responsible for generating interrelated global challenges including climate change, loss of biodiversity, freshwater depletion and others [2]. Populations whose livelihoods are closely intertwined with the stable supply of ecosystem benefits experience the worst impacts of ecosystem degradation and face the greatest challenges in meeting key developmental goals [1–3]. This results in a cyclical loop where poverty further drives ecological destruction, for example, when natural habitats are converted for agricultural production. This is more apparent in drylands which are characterised by low and variable rainfall, low productivity and fragile ecosystems [4, 5].

Drylands cover approximately 41% of all land on Earth [6] and are home to 38% of the world's population [5]. An estimated 90% of this population is located in low and middle-income settings and includes some of the most deprived groups. Rural communities in drylands are the worst affected; they rely on fragile ecosystems for sustenance [5] which leads to high rates of food insecurity and poorer health outcomes such as high rates of infant mortality [4].

The recent joint declaration from UN bodies calling for the restoration of global ecosystems recognises that the 2030 Agenda for Sustainable Development, and its 17 Sustainable Development Goals (SDGs) are unlikely to be met unless ecosystem degradation is reversed [7]. The contribution of ecosystem restoration towards meeting both development and conservation objectives is well recognized [8]. As a result, solutions that work to enhance natural ecosystems whilst addressing multiple societal challenges are being implemented at a rate that has outpaced academic research on their impact [9, 10], with particularly acute evidence gaps on the impact on human health.

Farmer Managed Natural Regeneration (FMNR) is a low-cost nature-based solution with demonstrated effectiveness in reversing degraded arable drylands [11, 12], for example, FMNR has been shown to restore an average of 3 million native trees per year in Central Tanzania [13]. The practice involves training farmers to encourage the growth of native trees on agricultural land [14, 15], but unlike mainstream agroforestry, this does not require watering or tree planting which is expensive, labour-intensive and has low survival rates in drylands [16]. Rather, farmers are encouraged to manage tree stumps where the selected strongest shoots develop into full-sized trees, and the rest are periodically pruned away for firewood and timber [14]. A recent systematic review found the integration of trees in agricultural landscapes is widely promoted as a development tool to meet SDGs, despite major gaps in empirical evidence to demonstrate the impact of these interventions [17].

This has led to calls for interdisciplinary research to understand the environmental and societal implications of FMNR and other agroecology techniques [9, 15, 18]. FMNR incorporates strategies to diversify household income and to increase social cohesion and empowerment [15], these important social determinants of health can support FMNR's potential to improve human well-being. In this study, we conducted in-depth discussions with key informants implementing FMNR to a) report how local communities experience FMNR implementation, and how they perceive health and well-being impacts of natural regeneration b) to conceptualise causal pathways that can link FMNR, ecological and human-health outcomes as a foundation for future rigorous quantitative evaluation of impact.

Materials and methods

Ethics statement

Research clearance was obtained from the LSHTM University Ethics Committee (Reference 26323). Research permits and clearance were issued by the Tanzanian Commission for Science

and Technology (COSTECH), Permit No 2021-638-NA-2021. The study was conducted according to the guidelines of the Declaration of Helsinki. All participants provided written informed consent before participation, and the study adhered to all ethical regulations.

Study design

We undertook in-depth group discussions to explore the health and well-being impacts of landscape regeneration. The data was collected via 90-minute long audio-recorded focus group discussions led by the study team that comprised of an epidemiologist, a clinician, and monitoring and evaluation (M&E) experts. Both the clinician and M&E experts work with the implementing organisations [19, 20] and are well known in the community.

The group discussions were conducted in four rural villages (Village 1–4 in the Results section) around the Mpwapwa district of Dodoma region. The area is semi-arid characterised by warm to hot temperatures all year round and annual precipitation of around 650mm [21]. S1 Fig summarises Dodoma's climatology and seasonal cycle for mean, maximum and minimum surface temperature and precipitation for the latest climatology, 1991–2022 [21]. The majority of households rely on subsistence farming for income. Rain-fed crop production and livestock rearing are vital economic activities, but these are characterised by low productivity due to the harsh climatic conditions [22]. Compared to other areas in Tanzania, Mpwapwa district also has higher maternal and infant mortality rates [23] and lower levels of literacy [23, 24]. At the time of the study, FMNR had been operational for 36 months in villages 2 and 3, and for 18 months in villages 1 and 4.

A semi-structured discussion guide was used to draw out the participants' experience of practising FMNR, perceived short and long-term impact (positive and negative) on health and well-being, barriers and opportunities of implementation as well opinions on how to scale up the intervention across other settings. In order to capture the diversity of experience, participants were purposively sampled to ensure an equal distribution of men and women, income levels and occupation groups. The recruitment was conducted by word of mouth in November 2021 and was done by local program coordinators who worked closely with village leaders to identify 6–8 participants per village. Participants were provided with details on the scope and purpose of the study, and written informed consent to participate and record the discussions was sought during the recruitment. The discussions were conducted in Swahili and the recordings were transcribed and translated into English. More detail on the study design is provided in the S1 Text.

Analysis

The transcripts were coded on NVIVO software to identify the emerging dominant themes, which were thereafter categorised into four ecosystem services defined by the Millenium Ecosystem Assessment (MEA) framework [4]; this groups ecosystem services with known benefits to human well-being as; provisioning, regulating, cultural and supporting services (see S1 Text for a full definition).

We thereafter used the ecosystem services cascade model [25] to conceptualise how the respondents defined pathways from ecosystem restoration to health outcomes. The cascade model is considered an improvement to the MEA framework, the latter has been criticised for defining 'ecosystem benefits/ends' and 'ecosystem services/means' interchangeably, thereby, failing to distinguish the differences between 'benefits' accrued and the 'mechanisms' that give rise to given services [25, 26]. Services can be defined as the aspects of ecosystems utilized (actively or passively) to produce human well-being benefits; services are therefore ecological in nature and what are traditionally defined as cultural services such as recreation are simply benefits [26]. Another criticism of the MEA framework is that it omits intermediary

components along the pathway to well-being, whereas the cascade model assigns these components as ecosystem 'services' and 'functions' [25], although their distinctiveness has been debated [25].

Ecosystem services, functions and benefits

In this study, we have used 'functions' to indicate the capability of the ecosystem to do something that is potentially useful to people, for example, woodlands have the capacity (function) to slow the passage of surface water and modify the intensity of flooding—flood control being the 'service' in this scenario [25]. Whether a 'function' leads to a given 'service' is context-dependent and is determined by how beneficial the 'service' is perceived [25]. In this study, a service was considered to generate 'benefits' or 'disbenefits' if it contributed to self-perceived outcomes related to human well-being.

Understanding what constitutes ecosystem functions, services and benefits requires contextual understanding of societal values, as well as knowledge of the structure and dynamics of ecological systems [25]. The cascade model can adequately handle the multi-dimensional and context dependency of the underlying value and impacts [27], for example, a given ecosystem may generate provisioning services in one community and regulating services in another; provisioning-regulating services tension could arise if consumption exceeds the levels needed to regulate ecosystem processes. This level of detail is an important step towards informing decision making, detailed mapping of causal pathways can enable the definition of credible metrics and end-points that facilitate the evaluation of landscape management and policy interventions [25].

The Results section presents the emerging themes and outcomes in various ways, firstly, as a word cloud to show the frequency of occurrence of the most common 100 words, this highlights the most important themes from the respondents' perspectives. Secondly, the emerging themes and outcomes are mapped against four broad ecosystem services as per the MEA framework, this is to assess how local knowledge matches the existing literature, and the strength of the evidence i.e. how frequently the themes were discussed across the sites. Lastly, the cascade model is applied across four pathways to demonstrate how intermediary ecosystem functions and services translate to measurable impact on health and well-being. The pathways are supported by verbatim quotes from the group discussions to add depth in illustrating the lived experience. Similar emerging concepts across the different study sites are also reported to validate the findings. During the translation, some editing was required to remove redundant words and to capture the key points whilst retaining meaning and context.

Results

The health outcomes reported in this section are what emerged from the group discussions, and do not represent an inclusive list of all possible outcomes. The discussions generated rich accounts of cascading events where ecosystem transformation led to ecological changes that directly and indirectly affected health outcomes and socio-economic circumstances. Benefits linked to ecosystem provisioning services (see S1 Text for definition) were the most discussed outcomes (Figs 1 and 2) and included terms like 'crops', 'firewood', 'yield' and 'water' (Fig 1). Regulation of ecosystem processes was also frequently discussed as shown by terms like 'shade', 'erosion' 'air' and 'dust'. Soil fertility and increased biodiversity were the most frequently reported terms in relation to supporting services (Figs 1 and 2).

Pathways from regeneration to health outcomes

Emerging pathways linking FMNR, ecosystem and health outcomes are summarised in Fig 2, the arrows show the direction of flow from regeneration to health outcomes via intermediary

Fig 1. Frequency of occurrence of the top 100 words from the group discussions.

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components. The line thickness is a qualitative assessment of how frequently the pathway emerged from the group discussions; the thickest lines suggest emergence across all four study sites. Although provisioning services in relation to food security were frequently reported across all sites, regulating services were associated with the greatest number of health outcomes that included respiratory, water-borne and eye diseases, chronic back pain, dehydration, sanitation and mental health. Fig 2 shows complex interactions in how ecosystem services work to drive human health. This complexity renders the MEA framework inadequate for quantifying impact and for informing decision making on 'where to intervene' to deliver desired effects.

In Fig 3A–3D, we show how the cascade model can help determine causal pathways characterised by intermediary components and measurable health outcomes. Four pathways emerged from our content analysis of the group discussions (Fig 3A–3D), these do not describe all the possible pathways, but rather summarise dominant routes through which respondents perceived FMNR's impact on their health and well-being. Inevitably, there are overlaps in the intermediary functions and services shown in each pathway, but the end health-related outcomes are distinct. The pathway model enables the identification of end outcomes and key mediating factors which can inform the evaluation of impact by guiding decisions on 'what to measure' and 'where to intervene'.

Pathway (A) is the simplest and shows a direct impact from ecosystem changes to health without intermediary factors. Pathway (B) suggests a complex pathway with one clear intermediary ecosystem service to health. Pathway (C) is more complex and involves multiple intermediary ecosystem services and functions to achieve health and pathway (D) is marked by socioeconomic factors that act to mediate health outcomes.

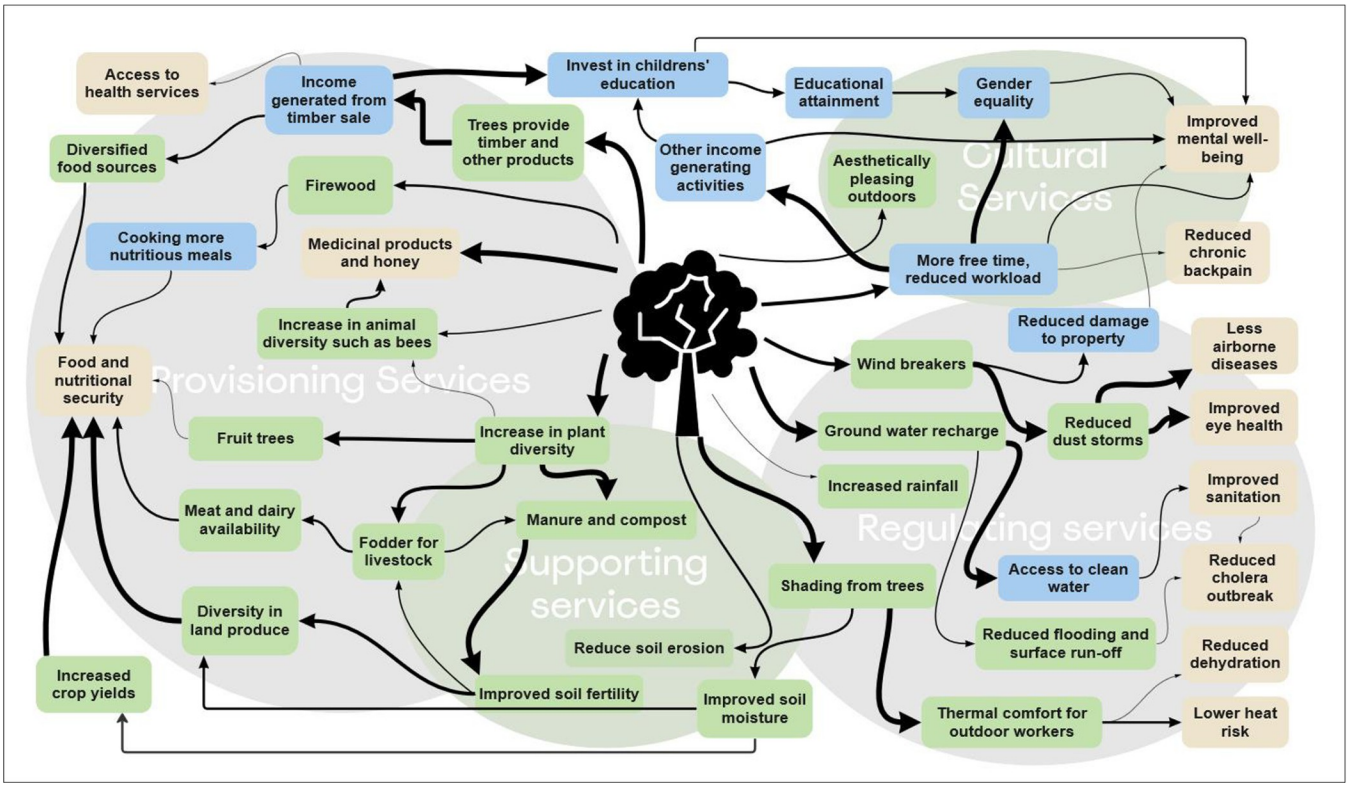

Fig 2. Pathways from FMNR to perceived intermediary and final outcomes. Green boxes depict ecological outcomes, blue boxes are socio-mediating factors and beige boxes show health outcomes. Provisioning, regulating, cultural and supporting services are highlighted using a shaded background. The emergence of the pathways from the group discussions is portrayed by line thickness; the thickest line means the pathway was discussed across all the four study sites, and the thinnest line means the discussion emerged from only one study site.

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A) Simple/direct pathway between ecosystem changes and health outcomes. An increase in the availability of wild fruits as a result of regeneration is an example of a direct pathway to health and well-being (Fig 3A). The respondents noted a return of native tree species that were previously thought extinct and commented on their role in alleviating hunger. Wild fruits were eaten directly or converted to juices which were added to porridge as a healthier alternative to sugar.

> *Village 4*: *'there is one specific tree called Mkwata (Strychnos innocua) which bears fruits that are locally known as wild mangoes. People eat them when they are hungry. You will often find people coming back from the hills [presumably from the community owned forests] with bags of mangoes*'
>
> Village 3: 'the native fruits are very nutritious when I eat Ukwata (Strychnos innocua) fruit I feel as though I have eaten an avocado.'
>
> *Village 3*: *'There are plenty of native fruits at the moment, children go and pick them when we have run out of fruits bought from the market. Mdawi tree (Cordia sinensis) produces fruits that the children like, the juice is added to porridge instead of sugar.'*

Some native trees were also used as traditional medicine, respondents from one village noted that the tree bark from the *Acacia nilotica* (locally known as Mfuku) is used to treat coughs, in another village, respondents added that the *Acacia nilotica* is mixed with the Baobab tree (Mbuyu) juice to treat chest pains.

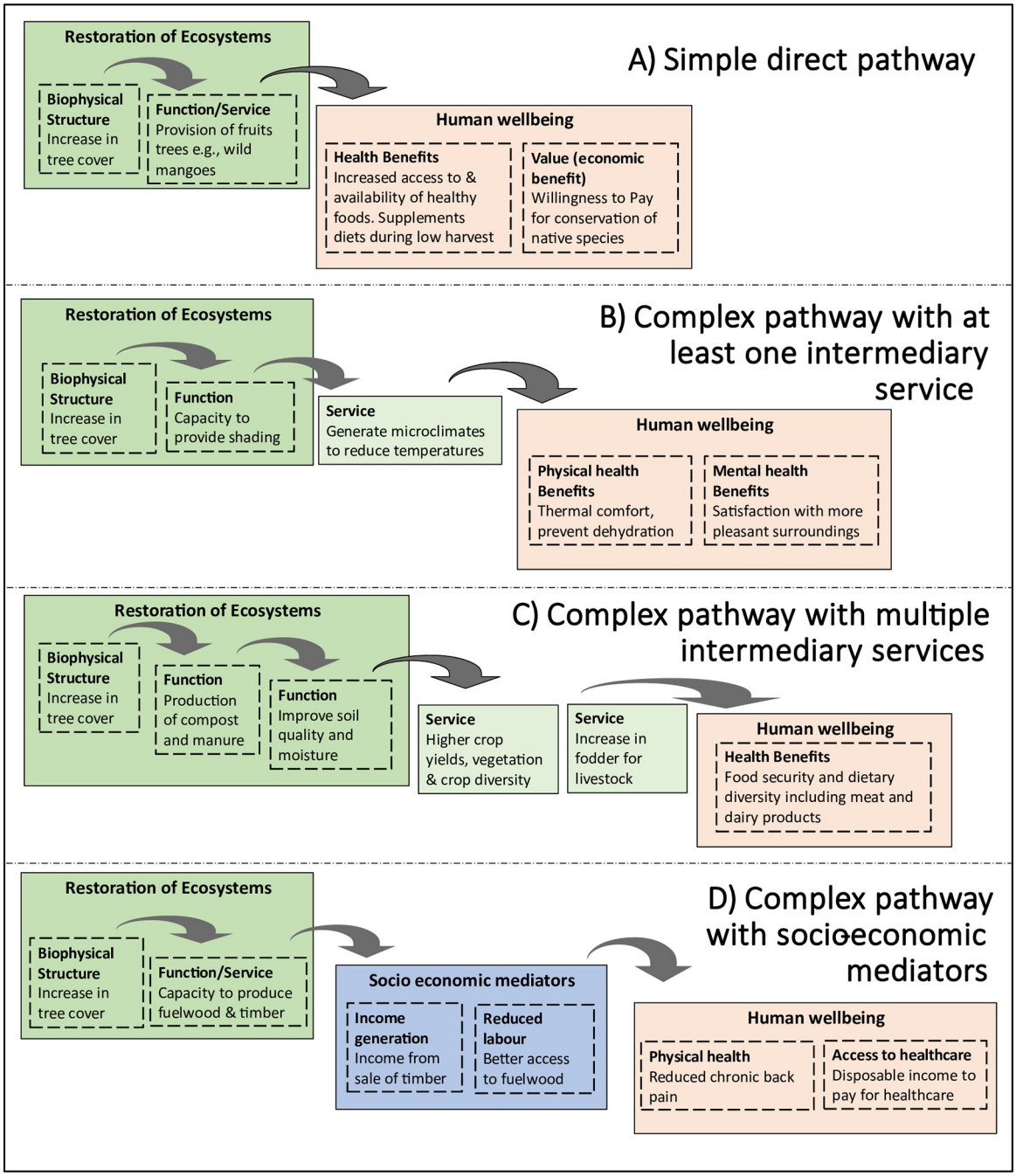

Fig 3. (A-D)–Use of the cascade model to show causal pathways from ecosystem regeneration to health outcomes, highlighting intermediary components and the final health outcomes.

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B) Complex pathways to health with one intermediary ecosystem service. This pathway can be highlighted by the benefits generated through regulation of ecosystem processes such as air and water quality, microclimate and natural hazard regulation. In Fig 3B, we show how tree shading was perceived to generate a cooling effect (service) which improved thermal comfort (benefit) and a reduction in adverse health effects such as dehydration (benefit). Previous work at the study sites found areas with a higher tree cover were markedly cooler [28].

Village 2: *'The air is a lot cleaner. I recall in the past during dry and hot seasons, around this time of the year, people used to be taken to hospital with cases of dehydration. . .there are fewer occurrences of this since FMNR'*

Village 3: *'During afternoon hours the weather is terrible due to the heat. . .at the time of year when we are preparing seeds for farming, you find people shaded under the trees preparing their seeds'*

This pathway can also be linked to health impacts resulting from changes in air and water quality, and flood mitigation. Regenerated trees reportedly acted as windbreakers, reducing the frequency and magnitude of dust storms and improving respiratory and eye health. Increased tree cover was also associated with improved accessibility to clean water and thereby a reduction in water-borne diseases.

Village 4: *'the dust used to give us sore eyes very often. . .nowadays we get some eye disease but less frequently. . . for a period of two years or so since the trees matured, the dust has reduced. . .'*

Village 1: 'In the past we would leave home at 4 am to fetch water. . .it was a very long journey and we would return at 8 am. It is amazing how much water we have now. . .children from schools in the neighbouring villages come to our village to fetch water. . .'

Village 1: *'because of the availability of water we have seen a decrease in cholera incidences which were previously caused by consuming unsafe water'*

Respondents associated tree cover with the prevention of natural hazards that were responsible for the destruction of property, flood mitigation and a reduction in severe winds were frequently mentioned, although known health benefits such as prevention of injuries [1] were not mentioned.

C) Complex pathways to health with several intermediary ecosystem services. This pathway links regeneration with complex interactions of multiple functions and services that work together to deliver health outcomes. This is demonstrated in Fig 3C using the example of soil quality and food security. Respondents associated higher crop yields to multiple intermediary steps that were linked to the regeneration, for example, an increase in plant biodiversity generated compost, which enhanced soil nutrients, and increased crop yields. Higher yields and greater diversity of crops was associated with improved food and nutritional security.

Village 2: *'. . .in a 2 to 3 acre farm you can have about 50 trees, once those trees have some vegetation and the rains come, the soil is very fertile underneath the trees as a result of the compost'*

Village 2: *'In the past, we used to clear our farmlands completely but now the trees help nourish our farms, when the leaves fall and decompose, soil nutrient improves resulting in quality yield'*.

Respondents noted differences between crops grown near the regenerated trees with those in the open fields without trees and gave vivid comparisons of differences in crop yields and quality.

Village 4: 'You will find there is a difference in crops between areas practising FMNR and the fields without trees. The crop yields are higher where farmers practise FMNR, because the soils

are more fertile, and during the sunny periods the levels of humidity are higher because these areas are never overwhelmed by the sun, the soil stays moist until the rains return'.

Village 1: *'I have noticed the crops that grow nearer the trees look very different from crops that grow on open fields. The crops growing nearer the trees are healthier. . .they grow differently*'

Village 3: ' in the past manure was minimal in the soil and the vegetables had a yellow colour and were bitter in taste. But now the vegetables are greener and tastier'

In other accounts, tree cover and improved soil quality also increased the provision of pastures which diversified diets, by supplementing plant-based diets with meat and dairy products.

Village 4: 'for sure if you go there now (the community forest), the grass is very tall, it is as if someone has added manure. . .FMNR has helped restore the grass and the livestock have benefited'

Village 1: '. . .where no other places have grass, our communal fields will still have grass. . .we feed these to cows and the milk production truly increases. . . a lot more than when the cattle are left to graze randomly on their own'

D) Complex pathways to health with socio-economic mediators. This pathway illustrates intermediary factors between the regeneration and health outcomes that are associated with changes in socio-economic circumstances (Fig 3D). Income generation was the most frequently mentioned socio-economic mediator. FMNR increased income diversification through timber sales or beekeeping. The additional income enabled access to previously inaccessible goods and services (education, healthcare, food), and helped reduce the psychological distress and stigma associated with poverty. This pathway overlaps with 3C where socio-economic factors are achieved through improved intermediary ecological outcomes, for example where the sale of surplus crops (as a result of increased soil fertility) generates extra income.

Village 2: *"We used to hide our children because we did not have money to send them to school, but now we have surplus crops that we can sell and get money for school fees. . .*'

Village 2: "things have improved. . .we have money to buy rice. . .the children used to have rice only during Christmas and Easter. My older children born before 2015 were accustomed to eating vegetables without peanut flour [highly nutritious and adds flavour to vegetables]. But the younger one who was born after 2015 was born in a time of plenty. . . we have enough groundnuts to make peanut flour, and enough sunflower to make sunflower oil"

Village 1: *"One advantage for us as group members [refers to members of a bee keeping group] is that we have a lot of honey, which is something that we did not have before. . .we did not have anywhere to put a beehive before [the restoration]*"

Gender equality was another important mediator. Female respondents who did most of the house chores benefited from improved access to firewood and water. This reportedly improved school attendance in younger girls, and in adult women, it was linked to reductions in chronic back pain, more resting time and opportunities to engage in other income generating activities.

Village 2: *'in the past we suffered from terrible back pains from carrying firewood over long distances, practising FMNR has reduced the journey'*

Health and well-being impacts and scaling-up FMNR. The respondents reported initial obstacles in implementation, however, witnessing health and socio-economic benefits was seen as a driver for wider adoption, and as a means of ensuring the sustainability of FMNR.

Village 4: 'initially, it was only a few of us working in a communal plot, but later even those who were mocking us and opposing the idea, began to realize the benefits and they wanted to learn about FMNR'

Village 3: 'we are determined to continue with this practice not because we have a project. . . because we now know the advantage will continue regenerating trees even if the project ends'

Discussion

Summary of key findings

Our study reports findings of in-depth group discussions with local participants who are actively restoring degraded landscapes in Central Tanzania using FMNR. The participants reported how the restoration has reversed decades of degradation, whilst delivering multiple health and well-being co-benefits in relation to food and nutritional security, improved respiratory health, access to clean water, poverty reduction, gender equality, heat adaptation and many more. These benefits were perceived across all the study sites, regardless of the length of implementation which ranged from 18–36 months.

Using the MEA categorisation of ecosystem services, we found provisioning services in relation to food security were more frequently reported across the study sites, but regulating services were associated with a greater number of health outcomes (Fig 2). We demonstrate how the application of the cascade model can be mainstreamed in health studies; despite the perceived impact of many nature-based solutions such as FMNR, there is limited empirical evidence quantifying the health co-benefits of these solutions. Our study makes an important contribution towards conceptualising some of the ways that the restoration of natural habitats contributes to human health outcomes. We demonstrate how a pathway approach within the cascade model can map out causal mechanisms between ecosystem structure, functions, services and well-being. Four pathways emerged from the group discussions, ranging from direct pathways between natural regeneration to health, to pathways where health outcomes are mediated by complex changes in ecological or socio-economic factors (Fig 3). This pathway approach can help identify the exact metrics for use in quantifying impact and should be a fundamental process in designing rigorous impact and process evaluations of nature-based solutions.

Experiencing health and socio-economic benefits was seen as a key driver for conservation as it boosted FMNR uptake and sustainability. This exemplifies nature-based solutions' ability to unite health and ecological objectives which have traditionally been implemented in isolation (at least until the recent emergence of Planetary and One Health paradigms [29]). The cascade model supports this unification in several ways; firstly, quantifying changes in the ecosystem alongside health and well-being outcomes can help with measuring attribution. Secondly, characterising socio-economic mediation (Fig 3D) is important for public health which places great interest in understanding variations in exposures and outcomes by population vulnerability.

Contextualising our findings in the existing literature

The exploitation of natural ecosystems has made positive contributions to human well-being and economic development but has resulted in the rapid degradation of many ecosystem services [4, 30]. This deterioration is a principal factor in exacerbating poverty in marginalised groups [4] many of whom reside in drylands. Reversing it using nature-based solutions such as FMNR can offer effective climate change solutions [3] and help meet Sustainable Development Goals.

Widespread and successful solutions require a collective change in priorities and practices, shared positive experiences and enabling contextual factors [31]. Adoption of FMNR is no different, the successful implementation of the practice can be credited to the successful training of local farmers and to a sincere desire by communities to combat desertification through landscape restoration. However, the widespread success of the FMNR and its large scale implementation is mostly attributed to the positive feedback loops from restoration to experiencing benefits (including health and socio-economic benefits) which are often passed on by word of mouth. This indicates the need for joint policy formulation between environmental and health actors and is particularly important during the UN Decade on Ecosystem Restoration 2021–2030 which aims to significantly scale up global protection and restoration of ecosystems, and support integrated approaches that engage all stakeholders, and in particular local communities [7].

Engaging local communities is profoundly valuable, our findings confirm how tapping into the vast reservoir of indigenous knowledge can set research directions and support the successful implementation of nature-based solutions [32, 33]. In this study, some of this indigenous knowledge included respondents' astute accounts of linking ecosystem functions and services to human health, identification of the functional use of various tree species, and great insights of plant biodiversity including an understanding of the role of biodiversity in maintaining fundamental ecosystem functioning.

Strengths and limitations

Focus groups can draw out rich perspectives in a way that is not possible with quantitative methods, they also generate new hypotheses to formulate further research. Nevertheless, limitations in reporting the subjective experience of participants include the likelihood of over-attributing benefits to project activities where respondents may be concerned about damaging relationships with implementing NGOs [10]. Another limitation is recall bias, where respondents fail to accurately remember experiences before the intervention. We addressed these limitations by conducting group discussions across four villages that differed by 'time since implementation' and 'geographical proximity', we also varied the facilitators by village. Reassuringly, we found consistency in the dominant themes across all the sites, which increased the validity of the findings.

Several outcomes reported during the group discussions are difficult to verify, the surest way of demonstrating impact is to triangulate these accounts with robust quantitative studies. Future studies should also examine the trade-offs associated with landscape regeneration. Although no trade-offs emerged during the group discussions, tree intercropping has previously been shown to reduce crop yields but this is dependent on crop type [17]. Increased vegetation can also allow pests, pathogens and wildlife to accumulate over time, which may increase vector borne diseases, pests attack on crops and can lead to human-wildlife conflict [34]. Some ecosystem-based mitigation solutions have also been criticized for compromising the cultural and ecological rights of indigenous communities [35]. Our study did not report these disbenefits, presumably because FMNR focuses on improving livelihood and increasing

climate resilience, rather than mitigation. Also, farmers implementing FMNR are trained on the optimal number of trees per farm to avoid compromising crop yields, furthermore, the implementation is at an early phase so the landscape may not yet support the proliferation of pathogens and wildlife.

Conclusions

The protection, restoration, and sustainable management of natural ecosystems will play a critical role in reversing global environmental changes, and in safeguarding livelihoods. Recognising the associated human health impacts can help accelerate this process, but will require working across disciplines to judiciously characterise and evaluate the multiple pathways and the range of possible outcomes. In-depth discussions with local participants implementing natural regeneration under FMNR confirm the capacity of nature-based solutions to help meet multiple objectives, we especially highlight the impacts linked to human health which are less addressed in the existing literature. The application of the cascade model to define causal pathways and identify metrics for measurement can be extended to other contexts implementing ecosystem-based restoration; although the exact outcomes will vary. Donor funded restoration projects often struggle to sustain restoration efforts over time, we argue that highlighting health and well-being outcomes, alongside benefits to the ecosystem, can improve project sustainability by increasing uptake and sustained adoption.

Supporting information

S1 Fig. Monthly climatology of average mean, minimum and maximum surface air temperature and precipitation for 1991–2022, Dodoma, Tanzania. Source: Climate Change Knowledge Portal, Tanzania country summary [21].
(DOCX)

S1 Text. Supplementary information, defining ecosystem services as per the Millenium Ecosystem Assessment (MEA) framework.
(DOCX)

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Author Contributions

Conceptualization: Peninah Murage, Angelina Tarimo, Tabby Njunge, Faraja Chiwanga.

Formal analysis: Peninah Murage, Tabby Njunge, Faraja Chiwanga.

Funding acquisition: Peninah Murage, Thijs van der Zaan.

Investigation: Peninah Murage, Ayoub Asenga, Angelina Tarimo, Faraja Chiwanga.

Methodology: Peninah Murage, Ayoub Asenga, Angelina Tarimo, Tabby Njunge, Faraja Chiwanga.

Project administration: Angelina Tarimo, Faraja Chiwanga.

Resources: Peninah Murage, Thijs van der Zaan, Faraja Chiwanga.

Supervision: Peninah Murage, Faraja Chiwanga.

Visualization: Peninah Murage.

Writing – original draft: Peninah Murage, Tabby Njunge, Faraja Chiwanga.

Writing – review & editing: Peninah Murage, Ayoub Asenga, Angelina Tarimo, Tabby Njunge, Thijs van der Zaan, Faraja Chiwanga.

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