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Empirical assessments of small-scale ecosystem service flows in rural mosaic landscapes in the Ethiopian highlands

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ABSTRACT

Human activities have rapidly altered natural ecosystems worldwide, resulting in fragmented ecosystems that are either culturally or formally protected. These ecosystem patches can be critical for ecosystem services (ES) that support human well-being. In the Ethiopian highlands, the remaining church forests and wetlands have a unique conservation status and are part of the global priority areas for biodiversity conservation. ES flows from these ecosystems to surrounding benefiting areas lack local-scale field evidence data and are not well-understood. Here, we empirically quantify the distance-dependent flows for four ES: grass biomass, microclimate regulation, crop pollination, and soil erosion retention since they exhibit considerable variation in spatial scales and processes of ES flows. The effect of spatial distance on each ES benefit flow was analysed using spatially explicit empirical models. The key findings are as follows: (1) The benefit of ES varies significantly with distance to the source ecosystems. (2) ES supply is determined by the extent (fragmentation) and condition of ecosystems, together with ecosystem type. (3) The quantity and number of ES provided decreases with distance from the source, and beneficiaries up to 3 km of the source only receive one type of ES (grass biomass). Approximately 80 % of the benefiting areas are within a radius of 200 m from forests and wetlands. Bundles of multiple ES types are received at the frontiers of service-providing ecosystems, where number of benefits are compared at particular locations from the source point. The investigated ecosystems (440 km^2) provided benefits to 8,770 km^2 for the four types of ES. Our findings imply that non-linear effects of key ecosystem variables need to be considered when mapping the distance-dependent ES flows. This study helps to understand the spatial connectivity between ecosystems and beneficiaries in the human-nature interdependency, which is useful for developing different strategies for ES conservation.

1. Introduction

Ecosystems provide a wide range of ecosystem services that support human well-being (MEA, 2005; TEEB, 2010). In recent decades, the science of ecosystem services (ES), or nature's contributions to people (NCP), has become increasingly important for decision-making and environmental management (Díaz et al., 2018; IPBES, 2019). Globally, natural ecosystems have been declining at unprecedented rates due to human activities directly or through climate change, resulting in a significant loss of biodiversity and a reduction in nature's benefits to people (IPBES, 2019). Various conservation practices, such as legal protection, cultural conservation, and incentive-based instruments (e.g., payment for ES), are being applied to prevent further loss. The success of these conservation efforts will mainly depend on how they consider the benefits, including the spatial ES flow that connects natural ecosystems and humans at benefiting locations. The spatial variations in the supply and flow of ES in linked human-natural systems can significantly impact the perceived local benefits and the success and failure of conservation policies (Barbier, 2009; Yamaguchi and Shah, 2020).

Forests and wetlands are ecosystems increasingly acknowledged for their multiple ES supporting livelihoods and the well-being of nearby communities (Aerts et al., 2016; Alohou et al., 2017; Stave et al., 2017). Almost all dry Afromontane forests and wetlands in Northern Ethiopia have been converted to human-modified landscapes. Continued

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deterioration of these forest and wetland ecosystems leads to fragmentation, which reduces size, increases edge effects, and isolates them, jeopardising their capacity to provide vital services to people who rely on them. Fragments of church forests and wetlands are found throughout the heavily degraded and fragmented landscapes of Ethiopian highlands. Here, unique sacred church forests surrounding churches have long been preserved by local communities due to their religious value (Cardelús et al., 2012; Wilson, 2016). Church forests are the only refuge for old-aged trees and biodiversity, including many endangered species. Wetlands located at the fringes of Lake Tana (Heide, 2012) provide erosion control, biodiversity maintenance, carbon sequestration, climate change mitigation, and recreational possibilities. Church forests and wetlands, which appear as small green 'islands' in the dry Ethiopian highlands, are vital for global biodiversity conservation efforts (Ermilov et al., 2012; Wilson, 2016). Besides the historical, spiritual, and ecological conservation, these ecosystems provide benefits that can flow to the surrounding areas (Sitotaw et al., 2022). Most ES assessments do not incorporate the direction and distance of ES flows to the corresponding benefiting areas (Anley et al., 2022). As a result, local communities and policymakers often fail to recognise the contributions of ES provided by natural systems to the larger landscape and underemphasise them in decision-making and for further development of policy instruments.

Understanding ES flows can reveal their spatial distribution and highlight societal inequities between people living within supplying ecosystems and distant beneficiaries (Felipe-Lucia et al., 2015). When assessing the relationship between nature and people over time and space, it is important to consider service-specific flows and linkages between the service-providing areas (SPAs) and service-benefiting areas (SBAs). Benefits move passively through biophysical processes (e.g., local cooling effect), dispersal (pollinator), or actively through human mobility to supply areas (e.g., free-grazing systems) (Ala-Hulkko et al., 2019). Currently, the quantification of ES flows from SPAs to SBAs that support the livelihood and well-being of local people across spatial distances is not well explored and cannot be easily recognised and acknowledged.

Numerous studies have developed conceptual frameworks for assessing ES flows, emphasizing conceptual and theoretical approaches (Chalkiadakis et al., 2022; Schirpke et al., 2019; Wang et al., 2022). Additionally, spatially explicit tools exist like InVEST, ARIES, and participatory mapping that facilitate the mapping of a wide range of ES across various scales (Bagstad et al., 2013; Sharp et al., 2020; Villa et al., 2014). However, empirical studies examining the spatial relationships between SPAs and SBAs, which account for complex interactions, are scarce. To explore if spatial dependencies can be measured and monitored, empirical studies are needed to map ES flow as a function of the distance between SPAs and the location of beneficiaries. In this study, we aimed to empirically assess the flows of ES in spatially explicit ways, incorporating distance-dependent effects and non-linear effects of ecosystem properties on benefits delivery as patterns of distance-dependent ES flow vary. In our study, we used the concepts of transportation mechanisms, flow directions, and spatial/ distance decay to map the actual ES flow outside the church forest and wetland ecosystems in the Lake Tana basin, Ethiopia. This study focuses on four ES flows: grass biomass for livestock feed, local climate regulation (cooling effect), crop pollination, and soil erosion retention.

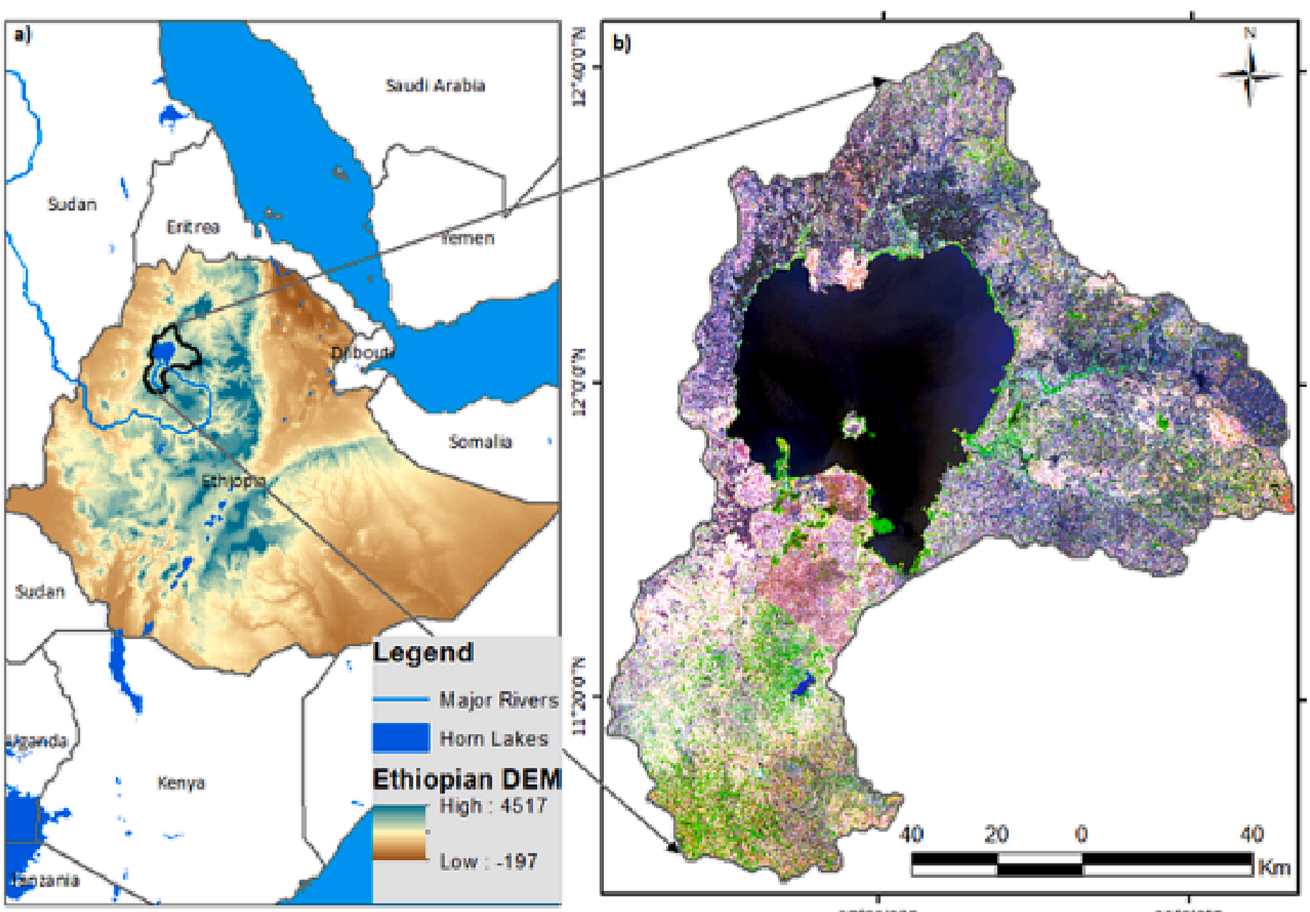

Fig. 1. Map of the Tana Basin study area (right), located in the north-western Ethiopian highlands (left). The Lake Tana basin study area is illustrated with a Sentinel-1 false colour composite image for November 2020 to May 2021 (Red – B11 (short wave-infrared, SWIR): Green – B8 (near-infrared, NIR); Blue – B4 (red)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Materials and methods

2.1. Description of the study area

This study was conducted on Ethiopian Afromontane church forests (12,200 ha) and wetlands (32,000 ha) in the Lake Tana basin of the Blue Nile, located in the Ethiopian highlands (36°44′ to 38°13′ N and 10°56′ to 12°44′ E) with a drainage area of about 15,000 km^2 (Fig. 1). The basin is a semi-mountainous, heterogeneous, and fragmented landscape, with elevations between 1,790 and 4,084 m a.s.l (Setegn et al., 2010). The area has a tropical highland monsoon climate with an annual average rainfall of about 1,280 mm, with 90 % of the total rainfall occurring between June and September (Conway and Schipper, 2011). The average air temperature of the Lake Tana basin is 24 °C (Dargahi and Setegn, 2011). The primary sources of income and basis for livelihoods are crop production, livestock farming, forest products, and tourism (religious and recreational). Lake Tana basin was chosen because it contains many church forests, wetland areas, and several urbanised areas and rural settlements that may benefit from these ecosystems. With a primary focus on the ecological conservation and sustainable use of forest and wetland systems and their services, the Lake Tana Biosphere Reserve was established in 2015, covering an area of 696,000 ha (including core area, buffer zone, and transition zone) around Lake Tana (Heide, 2012). The Biosphere Reserve is part of the Eastern Afromontane Biodiversity Hotspot. It is characterised by considerable land use/cover heterogeneity. The contrasts in land use/cover make this an ideal study area, i.e., the existence of forest and wetland 'islands' in the 'sea' agricultural and residential areas makes the Lake Tana basin a perfect landscape for modelling ES flow.

2.2. Choice of ecosystem services

This study covers four ES, including one provisioning service (grass biomass) and three regulating services (local climate regulation, crop pollination, and soil erosion retention). Aside from the cultural values of church forests and wetlands, our study focused on the ES that were considered as essential to food security, rural livelihoods, and providing benefits for various local community groups in the study area (Reynolds et al., 2017; Wondie, 2018). We used The Economics of Ecosystems and Biodiversity (TEEB) (TEEB, 2010) and the Common International Classification of Ecosystem Services (CICES) classification frameworks (Haines-Young and Potschin-Young, 2018) to classify the contributions of natural ecosystems to human well-being through ecological processes. A comprehensive list of ES provided by natural ecosystems in the study was developed by discussions with four natural resource experts from the Amhara Region Bureau of Agriculture and two from a non-governmental organisation. Four ES were selected from a list based on their contribution to local livelihoods and their feasibility for empirical measurement and modelling. Based on the commonly used criteria of credibility, salience, legitimacy, and feasibility (Ouchi et al., 1982; van Oudenhoven et al., 2018), we selected indicators to describe the selected ES that are easily quantifiable, replicable, and hence suitable for informing decision-making (supplementary material, appendix B). A list of the indicators for the chosen ES, the criteria and justifications for the selection of each indicator, and the information on the data and methodologies are presented in Table 2.

2.3. Methods

2.3.1. Conceptual framework

ES flows are described as the temporal and spatial connections between service-supplying and service-benefiting areas made possible by a service-connecting area (Syrbe and Walz, 2012). The spatial interaction between natural ecosystems that provide the benefits and the areas where these benefits are received can vary in scale—from local to global—depending on the type of ES (Chalkiadakis et al., 2022; Lindborg et al., 2017). In our study, we focus on local-scale ES, where the flow is mostly located in proximity to or within natural ecosystems, and the local communities are highly dependent on the services. We considered the church forests and wetlands as service-providing areas, and rural/urban settlement areas, agricultural fields, and habitats were considered SBAs for ES flow mapping (Fig. 2). We adapted existing conceptual frameworks to analyse the local scale ES flow in terms of direction and distances (Felipe-Lucia et al., 2015). Assuming that the ES flows occur only when the following conditions are met: (i) there is a service-generating ecosystem, the SPAs; (ii) there are beneficiaries for the service located within a threshold distance from SPAs; and (iii) there is a spatial connection between SPAs and the SBAs interlinked through the flow of nature's benefits to people (Bagstad et al., 2014; Fisher et al., 2009; Syrbe and Walz, 2012; Verhagen et al., 2015). Ecosystem functions and processes generate ES that directionally flows from the ecosystems to the beneficiaries (Bagstad et al., 2014; Villamagna et al., 2013). The level of service supply from ecosystems is influenced by different landscape properties (Willemen et al., 2012).

We used four key characteristics to analyse the ES flow based on the spatial relationships between SPAs and SBAs: transportation mechanism, distance decay, flow direction, and barriers. First, we employed four distinct types of ES flow transportation mechanisms: (a) movement of people to specific SPAs, e.g., wetland grass biomass for livestock grazing, which depends on accessibility (Bagstad et al., 2013); (b) passive biophysical flow through ecological processes, e.g., local temperature cooling effect and soil erosion retention are mediated by the biotic components (Schröter et al., 2018; Syrbe and Grunewald, 2017); (c) biophysical flows mediated by species migration and dispersal, e.g., crop pollination, which links ecological contribution and human benefits, estimates how much nature contributes to each cropland parcel in the landscape (Ricketts and Lonsdorf, 2013); and (d) active movement of people, e.g., nature-based tourism provided by natural and cultural landscapes and explained by geotagged data retrieved from social media platforms (Willemen et al., 2015; Wood et al., 2013). Second, ecosystems provide ES to the surrounding area in a distance-dependent manner. This distance decay relies on the type of ES and ecosystem properties. We applied calibrated and service-specific distance decay models to estimate the distance-related decline in ES flow, such as the cooling effect of the natural ecosystems and pollinator access from habitat to crop fields (Bagstad et al., 2014; Nelson et al., 2009). Third, we described the direction of ES flow such as in-situ (SPAs and SBAs are in the same location, e.g., erosion retention) (Costanza, 2008; Fisher et al., 2009), and omni-directional (SBAs are the surrounding landscapes of SPAs without directional bias, e.g., pollination, local climate regulation). Fourth, biophysical features can deplete service flows (sinks). We defined and described the ES flow in terms of transportation mechanisms, spatial scale, and flow directions (Table 1).

2.3.2. Mapping of land cover classes

In our study area, land cover types were mapped using high spatial resolution satellite images, and cropland cover was further differentiated into different crop types. The land cover map of the Lake Tana basin, which corresponds to the field collection period, was created using PlanetScope satellite images downloaded from Planet Labs Inc. (https://www.planet.com), acquired in March and May 2021. Eight land cover classes were identified: cultivated land, natural forests, woodland, shrubland, wetland, grassland, water, and built-up. Further classification and accuracy assessment details are presented in the supplementary materials, appendix A.

Service-providing ecosystems, including church forests and wetlands, were identified from the land cover classes. Church forest patches were separated from other forest types through visual interpretation using church building shapefiles and high-resolution images derived from Google Earth. Wetlands already existed as a class in the land cover map. Green patch area (ha), perimeter (m), and inter-patch distance (m) attributes were computed for each forest patch and wetland fragment

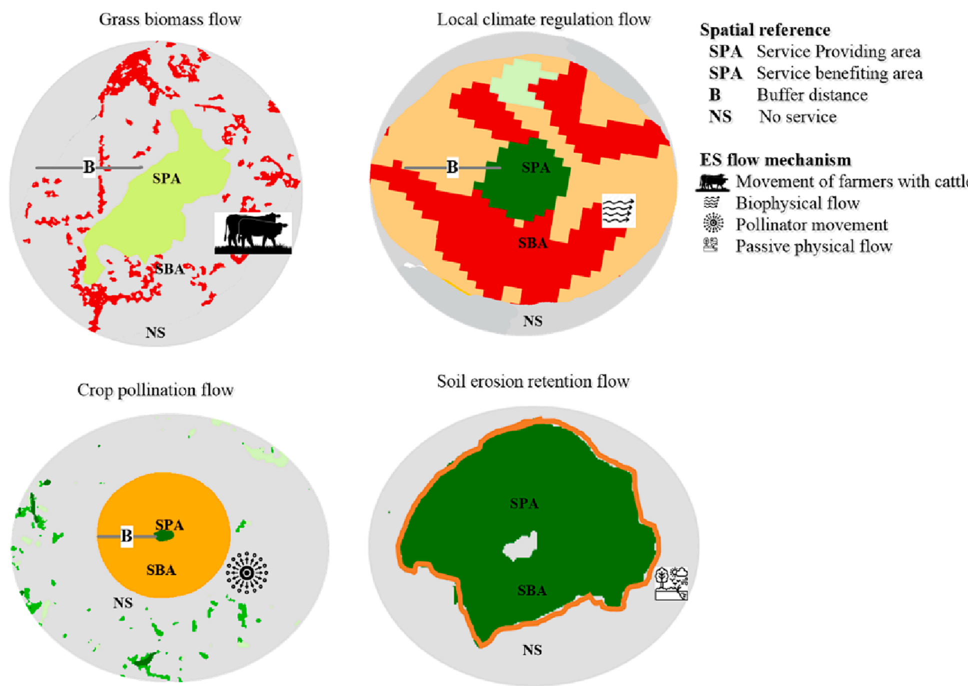

Fig. 2. Schematic diagram of ES flow. The flow radius varies per each ES. The green zones are SPAs, and the red zones are SBAs. The symbols represent different types of ES flow mechanisms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Explanation of the transportation mechanisms and directions of the four ES flows (Costanza, 2008; Fisher et al., 2009; Schröter et al., 2018; Serna-Chavez et al., 2014).

Component of ES Flow	Transportation mechanism	Spatial scale of ES flow	Flow direction
Grass biomass flow	Movement of cattle and transport of cut grass	Local = cattle/ human/ horse walking distance	Omni-directional, user movement-related
Local climate regulation flow	Biophysical flow	Local proximal	Omni-directional cooling
Crop pollination flow	Wild pollinator-movement based	Local proximal (flight range restricted) on crop fields	Omni-directional
Soil erosion retention flow	Passive physical flow	Local directional (watershed-based)	Directional with slope dependence

using FRAGSTAT version 4.2 (McGarigal et al., 2012).

2.3.3. Mapping the supply, flow and benefiting areas of ES

We quantified and mapped the distance-based ES-specific benefiting areas based on the supply and flow of the four ES. As shown in Fig. 3, a three-step method was used: (1) remote sensing-based mapping of land cover and identification of nature areas, including church forests and wetlands; (2) mapping of ES supply from church forests and wetlands; (3) mapping of benefiting areas using participatory mapping and measuring/modelling biophysical service movement. The following sections provide detailed descriptions of participatory mapping and biophysical modelling for mapping benefiting areas.

To map the supply for each ES, various data were collected from different sources between July 2019 and May 2022. We mapped the supply of ES based on current land cover and biophysical and ecological variables. We used two techniques to map the SBA: biophysical was used for regulating ES where the transportation mechanism is dependent on the biophysical flow (e.g., cooling effect, crop pollination, and erosion retention), and a participatory mapping approach was used to map the provisioning ES where the transportation mechanism is dependent on active movement of people or domestic animals (grass biomass). In our study, we used biophysical modeling to quantify the flow of regulating services in biophysical units, which do not rely directly on human intervention for service flow from ecosystems to surrounding areas. In contrast, we used participatory mapping to assess the spatial distribution of provisioning services, where human needs and access determine the use. The SBAs for each ES were mapped within the maximum or threshold distance of the ES flow extent from the outer boundary of the service-providing locations where services can be provided to beneficiaries. The threshold (maximum) distances for the spatial flow decay of regulating services were determined based on field measurements of their biophysical variables. The maximum distance for grass biomass use was determined by beneficiaries based on their estimated walking distance to grazing lands. In this study, only the locations of direct beneficiaries (i.e., first users of services) of the selected ES flows were considered. To map the SBAs, the spatial flow of each ES was modelled using service-specific distance gradients from SPAs and ecosystem variables.

Table 2 summarises the approaches used to map the supply, benefiting areas, and flow of the selected ES. ES indicators were mapped with a resolution of 100 m. We identified and mapped the areas where grass biomass was received using participatory mapping, and we mapped the areas where the other three ES were delivered using biophysical modelling based on field-recorded data. We used maximum/threshold distances to model the spatial flow decay for each ES. This study used a mix of spatial and regression models to empirically map the four ES flows to benefiting areas (Table 2). The data sources, models, and underlying assumptions for assessing and mapping supply, benefiting area, and flow of each ES are explained in more detail in the following sections.

2.3.3.1. Wetland grass biomass. In the Lake Tana basin, grazing wetlands are a critical resource that provides farmers with extensive livestock grazing services. This is a local ES supply where the grass is

Table 2
Indicators of selected ES, spatially explicit local data, and empirical methods for ES quantification. Data .

ES	Component of ES delivery	Indicator	Input data	Quantification method
Grass biomass from wetlands	Supply	Grass biomass (kg/ha/year) of meadows and pastures	Grass aboveground biomass field data, Sentinel-2 normalised difference vegetation index	Empirical linear regression model
	Flow	Flows of grass biomass (ton/ha/yr) to nearby villages across a distance	Grass biomass supply, distances (livestock travel time), and demand (biomass needed in kg)	Overlay analysis based on travel distance
	Benefiting area	Farmer with livestock farming in the nearby villages (3 km radius)	Participatory mapping of benefiting area and livestock data	Livestock population in the nearby villages
Local climate regulation from natural ecosystems	Supply	Cooling capacity index (°C) up to a maximum cooling distance	Local air temperature and humidity field records, habitat area, and canopy cover	GAMMs for distance-dependent cooling effect decay
	Flow	Cooling effect ΔT (°C) within cooling distances	SPAs and SBAs	Overlay analysis based on cooling distance
	Benefiting area	Settlement areas, crop fields, and natural habitats	Distance of the cooling effect, ecosystem type map	Extraction of benefiting areas
Crop pollination from church forest habitats	Supply	Crop flower visitation rate (# of visits/m^2/15′)	Visitation rates, church forest habitats, floral resources, forest age, and functional index	GAMMs for distance-dependent pollinator visit decay
	Flow	Actual crop flower visitation rates (# of visits/m^2/15′)	SPAs and SBAs	Overlay analysis
	Benefiting area	Area of pollinator-dependent crops within a buffer of 1,500 *m*	Land cover and pollinator-dependent crop types	Extraction of crop fields that require pollination
Soil erosion retention from natural forests	Supply	Soil retained (ton/ha/yr)	Land cover, vegetation index, soils, climate, DEM, site-specific model parameters, soil loss field data.	RUSLE InVEST
	Flow	Amount of soil retained (tons/ha/yr)	SPAs and SBAs	Overlay of lands prone to erosion and vegetation cover
	Benefiting area	Everywhere with slopes susceptible to erosion	Land cover map	Extraction of intersection areas with natural vegetation

Sources are specified in the section text

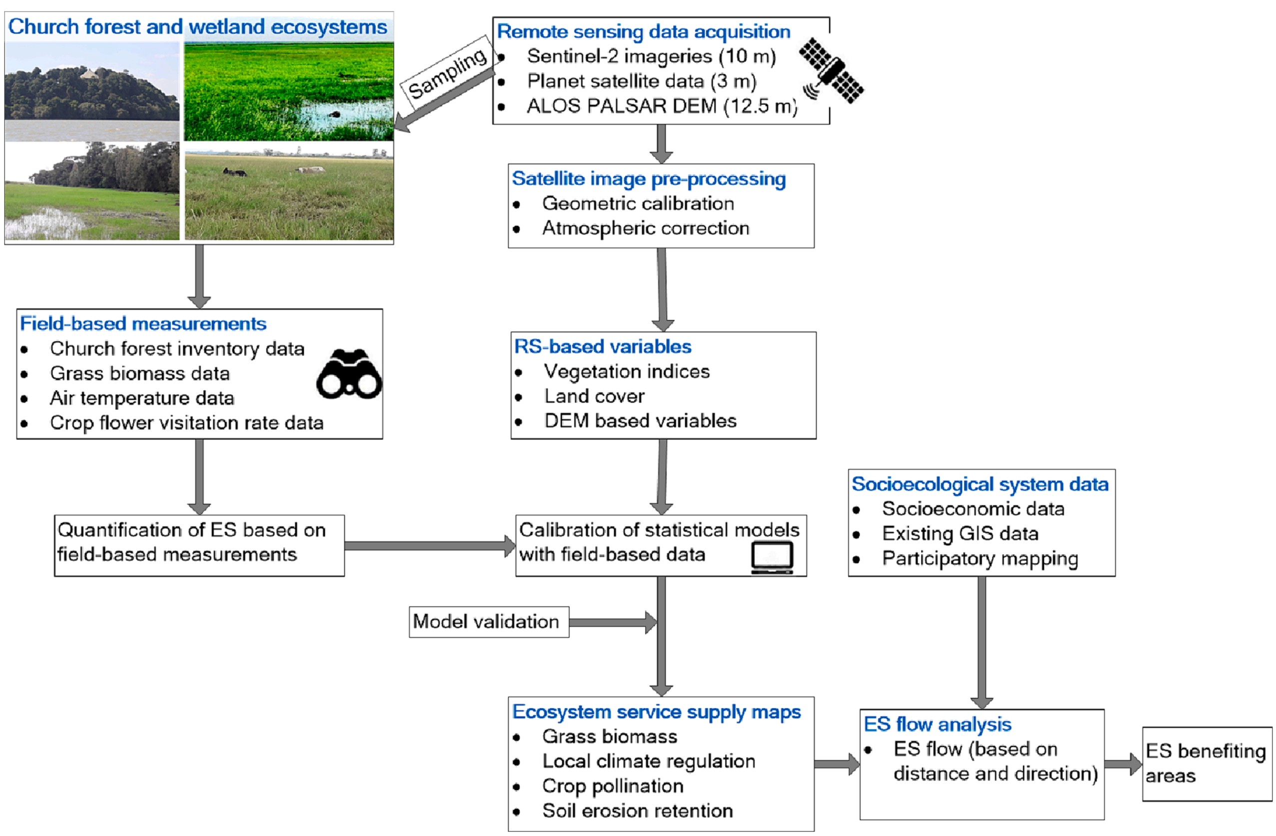

Fig. 3. The conceptual framework for mapping the SBAs based on the supply and flow of ES.

typically consumed in villages near the wetlands. Rural people often travel to wetlands to feed their livestock with a free-grazing system, and the grass is sometimes transported to settlement areas via human or horse transport. The total wetland grass biomass produced in the total wetland area used for grazing was used as an indicator for the biomass supply. Grass biomass was measured on 88 sample plots of 0.5 × 0.5 m from five wetland sites during peak growing seasons from October to November 2020. Fresh-cut vegetation was dried and weighed to obtain the dried grass biomass supply. The details of grass biomass data collection, testing of the vegetation indices, and upscaling plot-level biomass to the wetland area are available in supplementary material, appendix C. The Sentinel-2 satellite image dates and counts of livestock population dates correspond with the field grass biomass data collection period.

Information on the benefiting areas for grass biomass was collected between May 27 and June 20, 2022. Participants for participatory mapping of the benefiting areas were selected in the rural community living within a 3 km radius of each wetland. In order to include participants who have livestock and are located at varying distances from the wetland, the selection was carried out in cooperation with local contacts. The kebele (smallest administrative unit synonymous with the village) agricultural experts facilitated the selection of livestock farmers from different locations. We conducted two focus group discussions (FGDs); 23 people participated, including female-headed households, on benefit area mapping of grass biomass during the days when rural communities had fewer agriculture activities. FGD participants produced one agreed final map of SBAs (see example Fig. 4). The amount of grass biomass reaching the benefiting villages was quantified by considering the livestock population in each village (grid cell) within the 3 km distance travel distance to nearby wetland meadows. In the study area, the grazing season for livestock on wetland pastures usually lasts 6 to 7 months in the dry period following the summer rainy season. The biomass needed for grazing livestock for each village was calculated using livestock census data (CSA, 2021) and considering livestock composition and age-class energy requirements (tropical livestock unit − TLU) (Meshesha et al., 2019) for the seven months of dry season grazing period.

Finally, we employed yield reduction factors (17 % feeding losses (Stockdale, 2010) and 6 % storage losses (Bonesmo et al., 2013) to estimate summed grass biomass flow per village. The assessment of grass biomass flow was carried out through spatial data about the location of livestock populations in the surrounding villages. In our study area, where farmers travel to wetlands to obtain benefits, the flow is assumed to be a user movement-related omni-directional pattern. The benefits were calculated using livestock population in terms of tropical livestock unit (TLU) and grass biomass supply estimates within a 3 km radius of the supply locations.

2.3.3.2. Local climate regulation service (cooling effect). We investigated the local cooling service both on-site and beyond the church forests and wetlands boundaries. Church forests are expected to provide cooling benefits within the forest understory (homes of church nuns and monks, pollinators and natural enemies, shade crops, insect breeding sites, and regenerative seedlings) and beyond their boundaries (for nearby urban/rural settlements and crop fields). Wetland patches can also provide cooling benefits that reduce heat stress inside wetlands (e.g., for wetland birds, people, and grazing animals) and beyond their boundaries. The quantity of cooling provided by these natural ecosystems and the distance over which cooling extends is determined by the characteristics of the ecosystems (Table 3).

We selected natural ecosystems in the mosaic rural landscapes that constitute Bahir Dar city and its surroundings. We collected air temperature data in and around 34 sites (24 forests and 10 wetland patches) larger than 2 ha that represent a range of different sizes (small < 5 ha, medium < 10 ha, and large > 10 ha). Air temperature was recorded by the Kestrel 5400 Heat Stress Tracker from 5th to 28th May 2022. At each of the selected natural ecosystem sites, transect temperature monitoring was conducted from 1:00 to 3:00 pm in the afternoon when daytime temperatures were high. Temperature records were made in each transect, up to a maximum distance of 50 up to 300 m from each natural ecosystem (Fig. 5). For instance, based on the field air temperature measurements, the maximum distance for cooling intensity was 300 m. Refer for more details in the supplementary materials, Appendix D.

The temperature cooling intensity (air temperature change, ΔTa) was calculated as a weighted function of biophysical variables such as natural ecosystem area (ha), type, distances (m) from cooling islands, patch perimeter (m), inter-patch distance (km), tree canopy cover (%) of forests, fractional vegetation cover (%) of wetlands, and impervious soil cover (%). For the locations of each air temperature record, distances from the target ecosystems were recorded. Tree canopy cover was estimated using hemispherical photographs captured in the field with a fisheye lens, and fractional vegetation cover of wetlands was calculated from digital photographs taken with handheld cameras.

We used the cooling intensity (ΔTa) as the dependent variable and the ecosystem properties as predictor variables to spatially predict the cooling effect of natural ecosystems. The spatial pattern of cooling

Table 3
Summary information for the 34 vegetation patches (area and perimeter were extracted from the land cover map).

Explanatory variables	Mean	STD	Range
Cooling intensity, ΔTa (°C)	4.5	0.55	0.5–6.5
Patch area (ha)	7.13	0.64	2.1–26
Patch perimeter (km)	1.43	0. 2	1.02–2.29
Inter-patch distance (km)	0.75	0.37	
Tree canopy cover (%) of forests	0.54	0.30	0.31–0.99
Fractional vegetation cover (%) of wetlands	0.35	0.21	0.12–0.65
Impervious cover (%)	0.45	0.21	0.12–0.60
Distance (m)			50–300

Fig. 4. Example of FGD with local community members (left) and participatory mapping activity of the benefiting area for grass biomass in public wetlands (right).

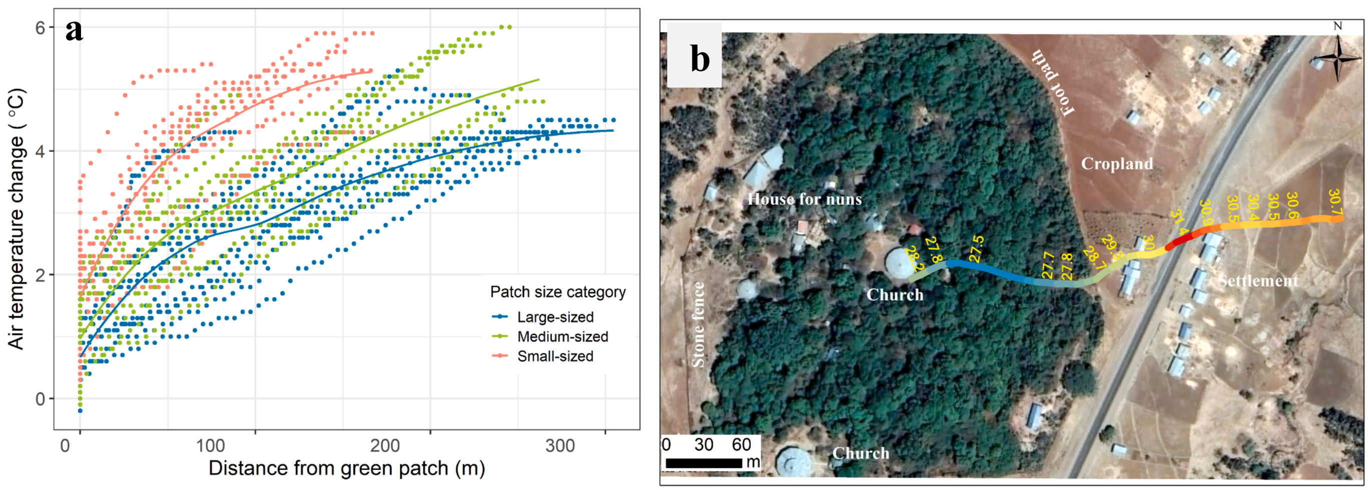

Fig. 5. (a) The air temperature delta from centres outwards over distances from different-sized natural ecosystems up to a turning point; (b) Example of the temperature transect showing how air temperature varies with distance.

intensity was modelled using generalised additive mixed models (GAMMs) with a logit link function. GAMMs, by considering distance gradients and ecosystem characteristics, can effectively estimate ES that exhibit decay with distance. The flexibility of GAMMs allows the incorporation of transect distances for each temperature record, along with other relevant predictors, as smooth terms into the model using the R package "mgcv" (Wood, 2017). Based on the field-recorded data, transect distances range from 50 to 300 m from different-sized forests and wetland patches. Therefore, the cooling distance, or the distance beyond which the local temperature is no longer influenced (became flatten), was calculated from the result of the field transects (Fig. 5). We used the generalised cross-validation (GCV) score (estimate of the mean square prediction error), which is estimated using the leave-one-out cross-validation technique for all data, to select the best model with GCV value. Finally, using the resulting fitted model, the cooling service was predicted on stacked raster datasets of all variables for the study area. The cooling benefits coverage (m^2) was estimated using the maximum transect distance from the centre of the ecosystem. More details of data collection and calculation methods are available in supplementary material, appendix D.

2.3.3.3. Crop pollination service. The church forest patches, potential wild pollinator habitat, and the visitation rate, based on the distance from nesting habitats, were used as indicators of ES supply (Lonsdorf et al., 2009; Schulp et al., 2014). This regulating service is a local-scale flow provided by wild pollinators in church forest habitats in degraded agricultural landscapes. The church forest patches are the natural habitats for wild pollinators in fragmented agricultural landscapes of the Lake Tana basin. The current information on pollinator habitat requirements, foraging ranges (Kremen et al., 2007), and the geographical location of crops benefiting from this service (Klein et al., 2007; Lautenbach et al., 2012) allows for a detailed depiction of their spatial flows. Visitation rate was calculated as an exponential decay function with increasing distance to the forest habitats.

This analysis is based on GAMMs analysis of the relationship between forest habitat characteristics and pollination visitation rate. Here, we consider pollinator-dependent croplands within a 1,500 m radius of church forests, about the maximum foraging distance of central place pollinators (Klein et al., 2007; Marzinzig et al., 2018; Osborne et al., 2008). We recorded pollinator visitation rates on 72 crop fields within 200, 500, 1,000, and 1,500 m buffers around church forest habitats. Our GAMMs model considered the additive effect of six explanatory variables (distance, forest patch area, proximity, forest age, and forest functional index) to estimate the visitation rate distance decay. Crop flower visitation rates were modelled as an exponential decay function with increasing distance to the church forest habitats. This model predicted the capacity of forest habitats to provide pollination services by estimating the likelihood that pollinators will travel from habitat to croplands that require pollination.

The benefiting area for crop pollination was mapped by selecting farmland that relies totally or partially on biotic pollination within a 1,500 m buffer from church forest habitats. The location and extent of pollinator-dependent crop fields that depend (at least partially) on wild insect pollination adjacent to church forest habitats were determined using a combination of local crop data (CSA, 2021). The land cover map was produced from Sentinel-2 images. We grouped crop field demand for pollination into four classes based on crop dependency values on pollinators (Gallai et al., 2009). A report on the area and production of major crops (2020/2021) obtained from the central statistical authority of Ethiopia was used (CSA, 2021).

We assessed crop pollination ES flow for crop production using the methodology of Gallai et al. (2009). Crops that benefit from wild pollination were identified, and pollinator dependency values were assigned (Gallai et al., 2009; Klein et al., 2007). To map the crop pollination service flow, we used data on crop type maps, pollinator visitation counts, and crop dependency values on pollinators (Gallai et al., 2009). We established four forest habitat interaction zones for each forest habitat patch, reflecting high pollinator visitation rates at 0 – 200 m and low visitation rates between 1,000 and 1,500 m distance gradients. Again, we used the generalised cross-validation score to select the best model based on its lowest value. Details of assessing pollination service about data collection, crop types, and calculation are available in supplementary material in Appendix E.

2.3.3.4. Soil erosion retention. Soil erosion retention (prevention) by vegetative cover encompasses on-site (avoided soil erosion – where SPAs is the same as the SBAs) and off-site (directional, such as sediment control) effects. Our primary focus is the on-site erosion control, which reduces topsoil loss and can improve crop production, contributing to human well-being. In our conceptualisation, we focused on the capacity of natural ecosystems to prevent soil erosion and preferred the term "soil erosion retention." Other case studies, such as the System of Environmental Economic Accounting (SEEA) and Guerra et al. (2014), support this study. The supply of soil erosion retention was estimated by combining the structural impact of soil erosion and social-ecological processes that allow for its retention. Ethiopian churches have traditionally been built on hilltops where the mountains are prone to erosion. We used the locally parametrised version of the Revised Universal Soil

Loss Equation (RUSLE), a common empirical model for soil loss estimation (Renard et al., 1997; Wischmeier and Smith, 1978) to calculate soil erosion retention between 2010 and 2021 (Guerra et al., 2014; Syrbe et al., 2018). We used locally calibrated/validated RUSLE-based soil retention estimations by comparing them to actual soil loss measurements from Lemma et al. (2019). This study used the parameters adapted and validated to the Ethiopian Highlands using 6 to 14 years of measurement in the Soil Conservation Research Programme (SCRP) stations (Betrie et al., 2011; SCRP, 2000). The spatial long-term average annual erosion rate was estimated by applying the following RUSLE equation:

$$A = R \times K \times LS \times C \times P$$

where A is the amount of soil loss (t ha^{-1} yr^{-1}). R is the rainfall erosivity factor (MJ mm ha^{-1}h^{-1} yr^{-1}) computed using long-term mean annual rainfall data from the National Meteorological Agency of Ethiopia for 49 stations from 2000 to 2021. K is the soil erodibility factor (t ha h MJ^{-1} mm^{-1}) determined from soil data obtained from the Ethiopian Ministry of Water, Irrigation and Electricity (MoWIE). LS is the slope length factor computed from a 12.5 m resolution digital elevation model (DEM) from ALOS PALSAR imagery. C is the dimensionless vegetation cover factor derived from average NDVI from Sentinel-2 images from 2020 to 2021, and P refers to the dimensionless soil conservation and management practices factor assigned from the land cover map of the study area. The RUSLE factors were computed using high-resolution data related to different biophysical phenomena. The details of the required data and calculation methods for each factor are available in the supplementary material in Appendix E.

Benefiting areas of soil retention are in-situ relations (where SPAs is the same as the SBAs for erosion). We consider all terrestrial landscapes (mostly fragmented croplands). The erosion retention flow was estimated as soil loss for bare soil (i.e., potential soil loss) minus the actual soil loss under the current land use and cover pattern. Soil erosion retention was mapped as an in-situ service where the actual erosion control by ecosystems contributes to limiting negative impacts on sensitive areas.

2.4. Mapping ES bundles along distance gradients

We computed the quantity of ES benefits received and how many ES are bundled at specific locations along distances from the sources. Since we modelled ES in distinct units, we normalised the maps of each ES by using minimum and maximum values on a scale between 0 and 1 (low to high service levels), enabling us to perform bundling and correlation analysis (Mouchet et al., 2014; Raudsepp-Hearne et al., 2010). All four input ES maps were given an equal influence since the mapping is not intended to prioritise the importance of each ES. We used a summed, weighted overlay analysis to identify hotspots of ES across spatial distances from the centre of the patches to surrounding benefiting areas.

Mapping ES bundles, which are sets of ES that appear together, visually represent the number of ES provided by ecosystems (Raudsepp-Hearne et al., 2010). In this study, bundles of ES were explored at four spatial buffer distances (0, 300, 1,500, and 3,000 m) from the centre of the SPAs to surrounding benefiting areas to identify spatial associations.

Subsequently, the spatial interactions of the selected ES were examined using Spearman correlation analysis over distances from SPAs in the study area. We analysed synergies by visualising the spatial pairwise correlations among the four ES flows and revealing their synergetic relationships and interactions at benefiting locations of the four distance gradients from SPAs. We randomly selected overlapping grid cell values for each normalised ES map at 50,000 random locations at least 100 m apart, representing 5 % of the total ES flow coverage (Anderson et al., 2009; Turner et al., 2014). All analyses were performed in ArcGIS 10.8 and R statistical software 4.3.0 (R Development Core Team, 2020).

3. Results

3.1. Spatial characteristics of church forest and wetland ecosystems

Fig. 6 depicts eight land cover classes derived from high-resolution PlanetScope imagery for 2021, with detailed maps for selected ecosystems relating to local spatial detail within various landscapes in the Lake Tana basin. The overall accuracy of the land cover classification was 85.6 % ± 1.4 %, with a kappa statistic of 0.83. The two most important land cover classes in our analysis, church forest, and wetland ecosystems, had high user's and producer's accuracies. Specifically, the accuracy for the target church forest and wetland classes was 91.5 % and 89.6 %, respectively. For the Lake Tana Basin, cultivated land is the most common land cover (64 %), followed by Lake Tana (18.3 %) and shrubland (5.2 %). Conversely, church forests (~1%) and wetlands (2.8 %) are small-sized land cover classes that feature throughout the landscape.

About 1,058 church forest patches were extracted from the land cover map. The total church forest area in the Lake Tana basin is about 12,200 ha. Church forests ranging from 0.5 to 234.5 ha in size are separated from one another by a mean distance = 1.75 km ± 0.97 SD. There were fewer and smaller remaining forest patches in the north-western part of the study area. In general, small forest patches are more isolated than larger patches. Based on the land cover map generated from Sentinel-2 images, about 83 wetland fragments covering an estimated 32,000 ha were identified in the Lake Tana basin. The size of wetland fragments ranges from 100 to 8,600 ha. There were more and larger wetland fragments in the southern part of Lake Tana. While wetlands are formally protected by legislation, wetland fragments exist on the fringes of Lake Tana.

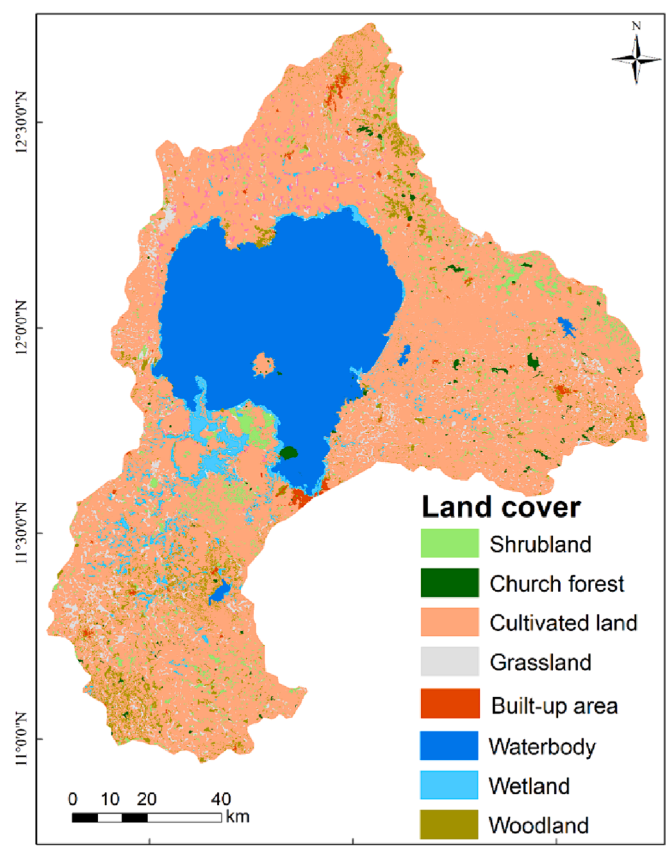

Fig. 6. Land cover classification map of Lake Tana basin for 2021 produced from PlanetScope satellite imagery during the dry season.

3.2. Spatial patterns of ES flow at basin level

Fig. 7 shows the spatial distributions of the four ES flows. All maps were normalised into values between 0 and 1, where 1 denotes a maximum value and 0 denotes no ES flow (ES maps with original units are found in the supplementary material appendix F). The spatial pattern of ES flow showed significant spatial variation because of the location proximity, characteristics, natural ecosystem functions, and season, but in different ways for each ES. The aggregated map of the four ES flows is presented in Fig. 7e.

ES varies per ecosystem site. In Table 4, we provide details on ES supply across the different locations. The specifics of the empirical analyses are further elaborated below per ES. For soil erosion retention, the crown and root zones of forest patches reduce soil erosion in the surrounding matrix, resulting in edge effects. As a result, the coverage of the benefiting area surpasses the actual extent of the vegetative ecosystems that prevent erosion.

3.2.1. Wetland grass biomass ES

The field measurements showed a mean dry matter grass biomass supply of 7.29 t DM ha^{-1} yr^{-1} (SD = ±3.6, range = 1.82–21.75 t DM ha^{-1} yr^{-1}) (Table 4). The relationship between field biomass data and Sentiniel-2 NDVI shows high predictive performance with an R^2 of 0.79 and normalised RMSE of 0.19 (n = 88, $p < 0.001$, more details are available in supplementary material in Appendix C). This fitted model was used to extrapolate to the entire study area using the Sentinel-2 NDVI image. Overall, the annual average grass biomass production from 32,000 ha of wetlands is estimated to support 354,700 ha of benefiting areas (Table 4). The spatial distribution of the grass biomass-benefiting areas follows the supply pattern. Based on our FGD results, individual rural farmers may travel from 3 min to 1 h (3 km) to reach public wetlands, depending on their location. This is in line with our SBAs threshold distance of 3 km. As a result, grass biomass flow to benefiting areas decreases with distance from wetland meadows (See inset Fig. 7a). There is a significant difference between supply and demand from the benefiting areas. The results indicate that only 43 % of the feed energy used in the Lake Tana basin can be obtained from natural wetland grasses. In many cases, demand exceeds supply in traditional livestock production locations, and local farmers are expected to consume all grass biomass.

Table 4
Summary of the ES provided by church forests and wetlands at the basin scale modelled based on field-measured ES data. The SBAs (ha) were calculated for each ecosystem patch based on ES supply data, patch variables, and transect distances.

ES	Ecosystem type	Amount of ES supply	ES benefiting area in ha
Grass biomass	Wetlands (32,000 ha)	7.29 t ha^{-1} yr^{-1} (range = 1.82 – 21.75, SD = ±3.6)	354,700
Local climate regulation	Church forests and wetlands (44,200 ha)	4.5 °C (ranges = 0.5–6.5, SD = ±2.5 °C)	220,400
Crop pollination	Church forests (12,200 ha)	0.38 visits per crop flower (range = 0.29–0.68, SD = ±0.11)	242,000
Soil erosion retention	Church forests and wetlands (44,200 ha)	62.5 ton ha^{-1} yr^{-1} (range = 0 – 2,280, SD = ±7.5)	60,100

3.2.2. Local climate regulation

The cooling intensity of the natural ecosystems ranged from 0.5 to 6.5 °C in April and May, with an average cooling intensity of 4.5 ± 2.5 °C (Table 4). Based on air temperature data collected in and around 34 natural ecosystems, we modelled the cooling effect provided by each natural ecosystem across distances and defined the relationships between cooling intensity and natural ecosystem attributes (Table 5). On hot days, cooling intensity increases with increasing natural ecosystem area and canopy. On hot days, the average air temperature in church forests was 4.4 °C lower than in wetlands. Fig. 8 shows a simplified map that was fitted using GAMMs with smoothers on six biophysical predictors (Table 5) and a random effect (bs = "re") for the study area. The GAMMs result in Table 5 reveals non-linearity and nearly linear relationships between the cooling intensity and biophysical predictors. The prediction performance was adequate, with a lower generalised

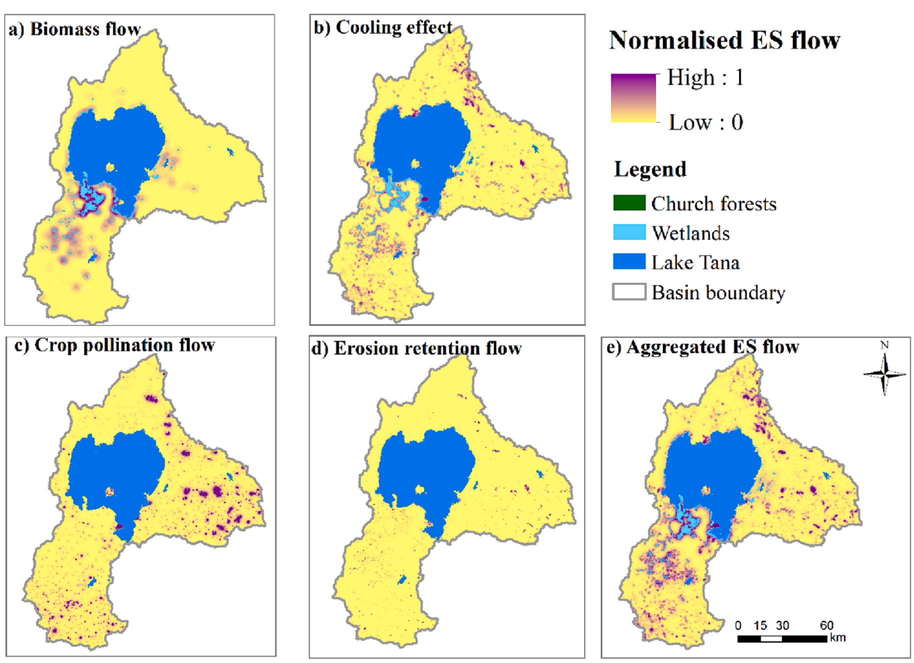

Fig. 7. Map of the spatial distribution of the four ES flows, showing their normalised values: (a) grass biomass flow from wetlands, (b) local cooling effects provided by church forests and wetlands, (c) crop pollination flow from forest habitats, (d) soil erosion retention offered by church forests and wetlands, and (e) the aggregated map of the four ES.

Table 5
Approximate significance of explanatory variables of the cooling effect (ΔTa) of wetland and church forests. Effective degrees of freedom (edf) refers to the additive curve's complexity (1.00 corresponds to a straight-line equivalent to a linear relationship, and edf > 1 indicates a non-linear relationship). Tree canopy cover (TCC) (%) for church forests and fractional vegetation cover (FVC) (%) for wetlands were determined separately and then combined. Total number of temperature logger points is n = 2154.

Explanatory variables	edf	F-value	*p*-value
s(Distances from target patches)	1.00	53242.8	<2e-16
s(Patch area)	1.00	80.61	<2e-16
s(Perimeter)	0.99	392.92	<2e-16
s(Inter-patch distance)	1.25	232.50	< 2e-16
s(TCC and FVC)	1.98	3233.08	<2e-16
s(Impervious soil cover)	1.00	1896	<2e-16
te(longitude, latitude)	14.51	27.1	<2e-16
R-sq.(adj) = 0.882 Deviance explained = 88.4 %			
GCV = 0.25994 Scale est. = 0.25747n = 2154			

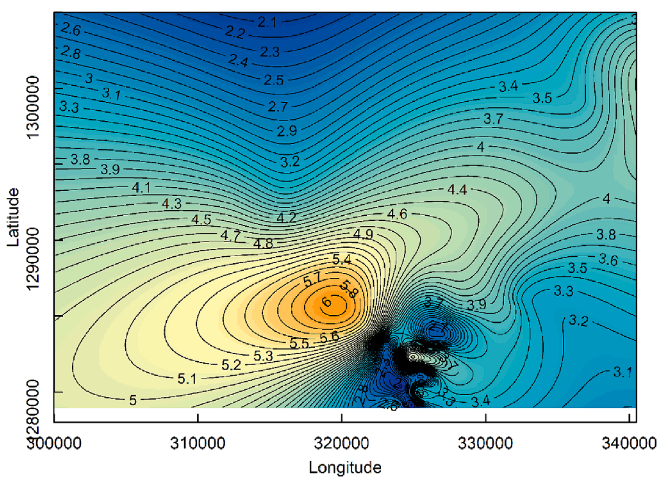

Fig. 8. The relationship between fitted cooling intensity (°C) and explanatory variables along longitudinal and latitudinal distances from natural ecosystems. The blue colours represent the highest cooling intensity predictions, and the light red colours lower ones. The capacity of cooling (contours) varies across contour distances. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cross-validation score of 0.26 and adjusted R^2 remaining stable at 0.88, respectively, along transect distances from ecosystem patches. The cooling service is influenced by the properties of the natural areas and the location distance where the cooling benefit occurs.

3.2.3. Crop pollination service

The mean crop pollination visitation rate was 0.38 visits per crop flower within a pollinator flight range of 1,500 m (SD 0.11, range 0.29–0.68) (Table 4). In general, crop pollination supply is predominant in the eastern part of the study area (Fig. 7c). The results show that crop fields adjacent to forest habitats have a higher pollinator visitation rate. Crop pollination service generally decays beyond 1,500 m from forest habitats. The benefiting area of crop pollination services on smallholder pollinator-dependent crop fields covers an area of 242,000 ha (28 % of croplands) with a threshold buffer distance of 1,500 m from forest habitats. For pollination services, for example, we determined that a total area of 4,400 ha within a radius of 200 m benefited from a mean visitation rate of 0.68 per plot. 58,000 ha of crop fields within a 1,000 to 1,500 m radius benefited from a mean visitation rate of 0.29 per plot. This implies that visitation rates decline rapidly with increasing distance to habitats (Fig. 9). The pollination capacity of church forest habitats is modulated by distance, forest patch size, proximity, tree functional index, and age (Table 6).

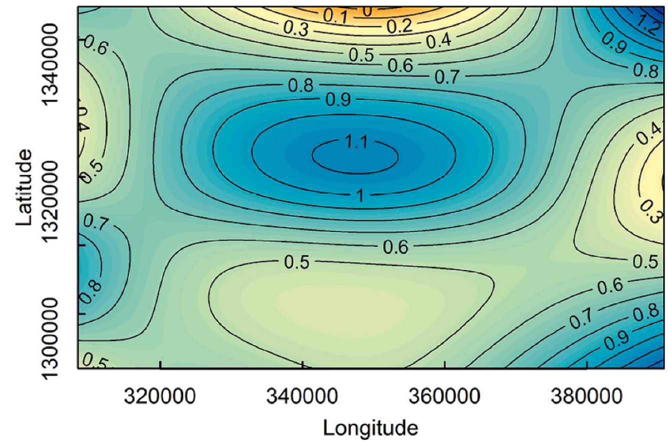

Fig. 9. The predicated visitation rates (contours) based on the explanatory variables across longitudinal and latitudinal distances. The numbers represent pollinator visitation rates that decline along transects from habitat patches to crop fields.

Table 6
Approximate significance of explanatory variables of the pollinator visitation rates. Effective degrees of freedom (edf) refers to the additive curve's complexity. Total number of visitation rate records is n = 72.

Explanatory variables	edf	F-value	*p*-value
s(Distances from habitats)	1.62	31.84	< 2e-16
s(Habitat area)	2.63	31.87	2.44e-07
s(Forest age)	1.00	1.94	0.168719
s(log.habitat functional index)	2.52	9.97	0.000266
s(log.proximity index)	2.77	11.63	1.29e-05
te(longitude, latitude)	2.01	6.42	0.002909
R-sq.(adj) = 0.879 Deviance explained = 90.5 %			
GCV = 0.0067167 Scale est. = 0.0052224n = 72			

3.2.4. Soil erosion retention

In the Lake Tana basin, church forests and wetlands retained an estimated average amount of 62.5 tons ha^{-1} yr^{-1} (0 – 2,280, SD = ±8.4) of soil in 2021 (Table 4). In the study area, almost all of the Afromontane forests are found on erosion-prone sites of Ethiopian highland mountains, and wetlands are also confined within the borders of agricultural fields and rivers. Terrestrial ecosystems in sloping landforms (>3% slope) provide significant levels of soil erosion control service by protecting soil from water erosion (Fig. 10d). The soil retention service varies significantly across the heterogeneous landscape of the study area, from high (>2,280 ton ha^{-1} yr^{-1}) to low (<1 ton ha^{-1} yr^{-1}) levels of erosion retention.

Thus, Fig. 10 provides an overview of the different spatial gradients for the investigated ES decay across distances. For an in-depth understanding of ES flow over distances, we focused on a smaller area and mapped the specific details of ES flow. As shown in Fig. 10, ES flow decays with increasing spatial distance, and the degree of influence varies with the characteristics of the source ecosystems.

3.3. Bundles of ES flow across distances

To describe the spatial distribution of ES flows in the landscape, we explore the SBAs of each service at four distinct distances: 0 (in-situ), 300, 1,500, and 3,000 m from the natural areas. The rate and number of ES decay delivered to specific locations of benefiting areas across distances from SPAs are illustrated in Fig. 11a.

We depicted the aggregated bundles of the four ES flows received at specific benefiting locations along distance gradients from the SPAs (Fig. 11a). Four distinctive local-scale ES bundles with varying dominant services were identified. Bundle 1 occurred at in-situ locations, where

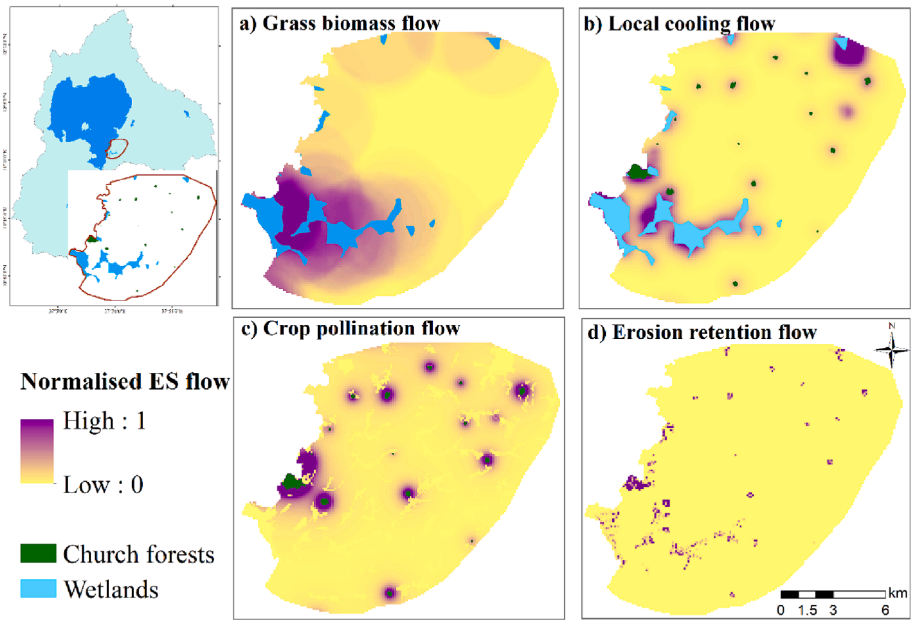

Fig. 10. Zooming in to a smaller area in the Tana Basin to showcase the detailed spatial patterns of the four ES flow (how far do ES flow?) at the patch level: (a) grass biomass flow from wetlands to surrounding settlement areas within a radius of 3,000 m walking distance, (b) local climate regulation (cooling) of church forest patches and wetlands within a radius of 300 m spatial cooling distance, (c) pollination flow with a buffer distance of 1,500 m over crop fields, and (d) soil erosion retention at in-situ locations of church forest and wetland ecosystems.

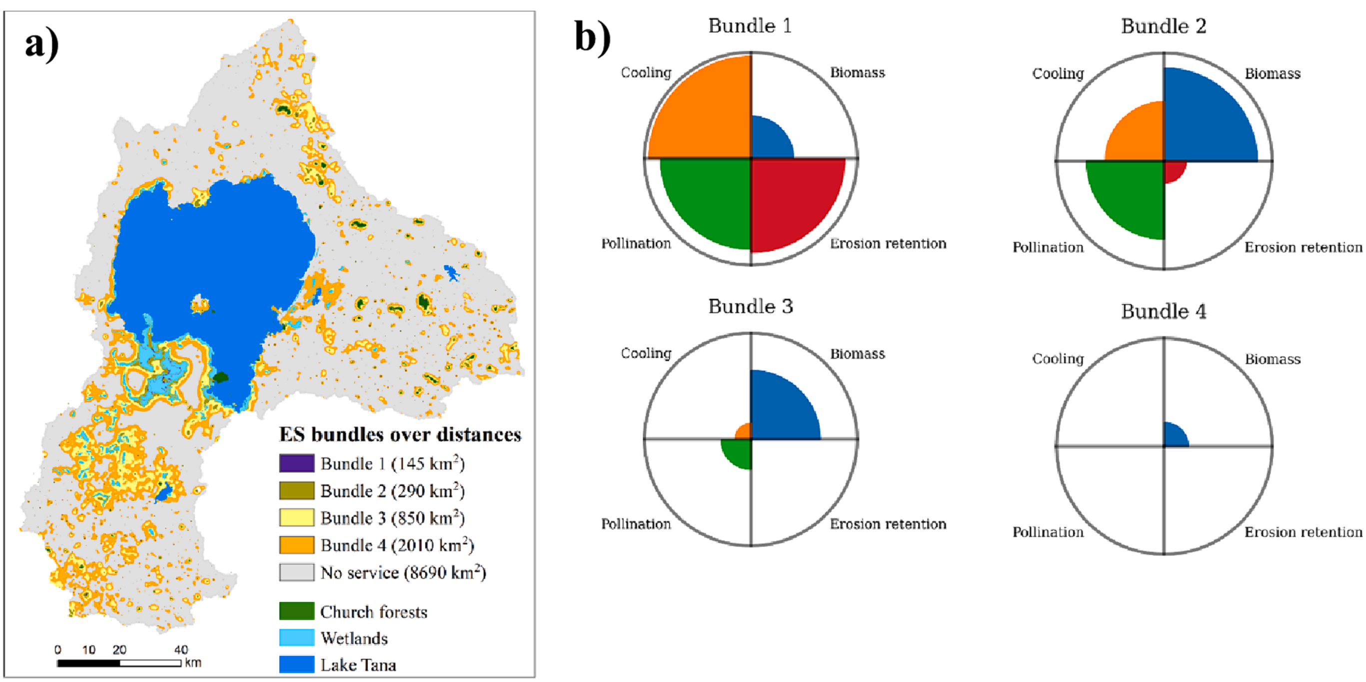

Fig. 11. (a) Bundles of ES flow map shown at four spatial distances (0, 300, 1,500, and 3,000) from the church forests and wetland ecosystems. The number indicates the spatial coverage of the benefiting area for each ES bundle. (b) Flower diagrams illustrating ES bundles and the number of ES provided in each bundle across four distance gradients (0, 300, 1,500, and 3,000). The length of each petal corresponds to the mean normalised value of ES within each bundle and is comparable across bundles.

the SPAs and SBAs are the same, and includes all four studied ES. In this bundle, the grass biomass flow is minimal due to the limited number of farmers residing within the wetlands. Perennial crops that grow inside forest ecosystems, such as forest coffee and mango, benefit from crop pollination services. Beneficiaries situated in the SPAs can receive a large number of services that these ecosystems provide. Bundle 2 is located within a 300 m buffer distance from SPAs and includes grass biomass, local cooling, and crop pollination with higher flow rates. In this bundle, grass biomass flow is high because all villages adjacent to the wetlands are located at optimum travel distances. Thus, bundle 2 covers an area of 290 km^2 of the study area landscape. Three ES are evident in this benefiting area, and the quantities are greater due to the proximity to SPAs. Bundle 3 covers benefiting areas of 850 km^2 between 300 and 1,500 m away from SPAs. This bundle comprises two ES with moderate ES flow rates, including grass biomass and crop pollination. Finally, bundle 4 consists of one ES with a low grass biomass flow and is located in benefiting areas between 1,500 and 3,000 m from SPAs. Bundle 4 covers a benefiting area of 2010 km^2. In this bundle, the grass biomass flow is minimal as the high travel cost (>= 1 hr) hinders most livestock farmers, and only a few with limited land might travel to wetland meadows. Benefiting areas beyond 3,000 m from ecosystems are estimated not to benefit from the selected ES flows.

The flower diagram in Fig. 11b shows that local cooling, pollination, and erosion retention show similar synergetic spatial patterns since church forests primarily provide them. Another synergy exists between grass biomass and erosion retention, primarily provided by wetlands. These results highlight that the natural ecosystems provide multiple services over distances.

4. Discussion

Our study reveals new evidence of distant dependent ES flows to surrounding benefitting areas in terms of quantity and bundles in the rural mosaic landscapes of the Ethiopian highlands. As a result, our study adds to how ES flows from terrestrial ecosystems to beneficiaries are depicted, where arrows have been commonly used to illustrate flows (Bagstad et al., 2019; Palomo et al., 2013). We achieved this by assessing multiple ES across space using field evidence data, participatory GIS, and biophysical modelling. We also incorporated the non-linear effects of distance and ecosystem properties at scales relevant to land management decisions (Aerts et al., 2016; Lowman, 2011; Sitotaw et al., 2022). Our study illustrates ES flows outside of natural ecosystems to understand better how spatial distance and ecosystem characteristics influence service flows to beneficiaries (Bagstad et al., 2013; Mitchell et al., 2015b; Schröter et al., 2014). In this section, we discuss our study findings, including the importance of scale for ES studies, the influence of ecosystem fragmentation on ES delivery, the choice of methods for modelling ES flow, and the teleconnections of ES benefits.

The success of ecosystem conservation in fragmented landscape conservation can be influenced by its perceived value at ecologically relevant spatial scales. In many cases, the benefits received by people depend on their proximity to ecosystems (Fremier et al., 2013). When the ES is to be received at local scales, availability depends on a specific distance from the source, and the quantity or intensity of supply varies over distance (Goldenberg et al., 2017; Roces-Díaz et al., 2015). These fine-scale benefits might be masked at larger-scale ES assessments (Raudsepp-Hearne and Peterson, 2016). Our research provides empirical evidence of local benefits that provide relevant information to planners and decision-makers at appropriate scales.

Several anthropogenic factors transform natural ecosystems into fragments (Daye and Healey, 2015; Fahrig, 2003). In the fragmented Ethiopian highlands, agricultural and settlement expansions immediately surrounding the church forests and wetlands led to reduced patch size and increased isolation of patches. Studies show fragmentation may positively influence ES flow by bringing people and ecosystems closer together (Bagstad et al., 2013; Mitchell et al., 2015a). On the contrary, fragmentation negatively influences ES flow for small ecosystem patches in degraded landscapes. Consistently, reduced patch area, increased isolation, and reduced ecosystem quality have detrimental effects on ecosystem functions and services (Haddad et al., 2015). In this study, we observed that fragmentation has an adverse effect on pollination services. Reduced habitat size resulted in a decline in pollinator population, and increased habitat isolation led to limited wild pollinator mobility and a decay in visitation rate. In another example, based on our findings from field recordings of air temperature over cooling distances along transects, we noticed the larger the vegetated patches, the greater the cooling extent. Our findings also reveal that the ES flow decline rate is less steep in larger patches than in small patches (Fig. 5). Our findings imply that future fragmentation or loss of diverse natural forests and wetlands elsewhere may result in a loss of associated ES.

Regardless of the size of ecosystem patches, the species present, or the matrix surrounding the patches, beneficiaries at different distances from the source receive benefits that decline linearly or non-linearly, and areas beyond the maximum flow distance of each service do not receive natures benefits. We addressed how multiple fragments in a landscape interacted to form an ecological network where the total benefit of ES within the maximum flow distance can exceed the summed services provided by individual fragments. For example, a particular crop field adjacent to multiple habitats with a radius of less than 1,500 m can benefit from the distance-based weighted visiting rates provided by those habitats. Similarly, areas within 300 m of numerous patches showed increased cooling effects, which accounted for the distance-based weighting. Therefore, maintaining and enhancing ES flows may be achieved by reducing the distance between patches by establishing additional vegetative patches and buffer zones and connecting them with vegetation corridors (Bennett and Mulongoy, 2006).

In our study, GAMMs addressed the complex non-linear relationship between the response variables (field records of temperature delta and pollinator visitation rates) and multiple explanatory variables (such as geographic locations, distances, and ecosystem properties) (Wood et al., 2015). The fitted GAMM models show the extent to which ES flows are determined by a sum of smooth functions of multiple factors that influence the benefits. Similarly, ES, like biological control (Mitchell et al., 2014) and species abundance (Gray et al., 2016), also exhibit similar spatial patterns to our analysis of the pollination service across space, which makes it easier to assess these types of ES using GAMMs. Studies exploring the spatial variation of ES flows by considering the non-linear effects of habitat fragmentation are vital to developing spatial policies that maximise the capacity of ecosystems to generate services (de Groot et al., 2010; Willemen et al., 2012) and develop strategies for restoring degraded ecosystems.

In this study, we did not consider the seasonality of ES delivery, but we observed that the examined ES flows have noticeable seasonal variations (del Río-Mena et al., 2020). Environmental factors and human demand determine ES flows. For example, wetland meadows are flooded by water and are regularly used for grazing from December to June after the rainy season. The seasonal flows of the other three ES are determined by human needs, such as temperature cooling during the warmer months, crop pollination during the summer flowering season, and erosion retention during the rainy season. Cooling effect, crop pollination, and erosion retention showed a synergistic relationship (positive correlation) but in different seasons and distance gradients. Earlier work shows that cooling intensity and pollination services have a complementary relationship when the cooling effect of forest habitats enhances pollinator activity (Proesmans et al., 2019). Grass biomass flow, however, has a detrimental influence on the flow of other regulating ES, and their flows from wetland ecosystems rapidly decline over distances. Grass biomass flow, however, can have detrimental influence on the flow of other regulating ES and their flows from wetland ecosystems rapidly decline over distances. This trade-off can be mitigated by implementing sustainable grazing management strategies, creating buffer zones of native vegetation and access control. Natural ecosystems are becoming islands within human-dominated landscapes due to human activity and climate change, and ecological studies do not sufficiently address the modelling of ES flow to benefiting areas in distance and time.

In the Lake Tana basin, isolated patches of SPAs (sacred church forests and wetlands) and SBAs (settlements and agricultural fields) are connected over distances through the flow of ES. The spatial ES flows over distances from isolated natural ecosystems and produces teleconnections with beneficiaries. The findings of our study can be combined with future studies on spatial economic discounting (e.g., payments for ES) to guide the sustainable use of ES. Our analysis can also inform conservation planning by identifying scenarios that consider distant beneficiaries, beneficiaries in the vicinity of natural ecosystems, and government activities for ES conservation. Our findings provide spatially explicit information on ES flows over distances that planners and conservation practitioners can understand and use as scientific evidence for ecosystem restoration and conservation efforts (Chalkiadakis et al., 2022; Liquete et al., 2016). ES flows are essential for quantifying the dependencies of traded agricultural products on nature, promoting sustainable management, serving as input to sustainable natural resource governance, and enhancing equity in the supply chain and accountability (Marques et al., 2024). Advancements in policy measures, specifically in ecological restoration and conservation, play a crucial role in addressing the rapid decline of biodiversity and ES flows (Burt et al., 2023; Mulya et al., 2023). Understanding ES flows can reveal their spatial distribution and highlight societal inequities between people living within supplying ecosystems and distant beneficiaries. To understand the link between ecosystems and their benefits, studies considering different types of ES beneficiaries that receive varying degrees of ES flows from natural areas in space and time contribute to better conserving the ES supporting economies and livelihoods. This study focuses mainly on the first beneficiaries and a specific geographical scale; however, combining global ES flow studies can allow to explore the wider implications across diverse regions and stakeholder groups (Marques et al., 2024). To acquire a comprehensive understanding of ES flow beyond SPAs, future studies might incorporate the economic valuation of ES flows in space and time, and payment for ES.

5. Conclusions

This study demonstrates the critical role of natural ecosystems, even degraded ones, in providing multiple ES through distant-dependent flows that benefit surrounding communities. Empirical studies are required to map ecosystem flow and measure and monitor spatial dependencies for informed decision-making. In our study, we mapped the proportion of benefiting areas supported by spatial ES flows from service-providing areas. Our research sheds light on a previously understudied aspect: the ability of ecosystems to provide essential services even at significant distances from their source. We found that both the flow quantity and bundles of ES decline at varying distances from sources to surrounding benefiting areas. The flows of these ES depend on the type, characteristics, and spatial distribution of ecosystem fragments and beneficiaries. Understanding the distant-dependent flows of multiple ES to beneficiaries can help support ecosystem restoration and ecosystem connectivity by vegetation corridors for sustainable ES supply.

CRediT authorship contribution statement

Tegegne Molla Sitotaw: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Louise Willemen:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Derege Tsegaye Meshesha:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Andrew Nelson:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

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