Sinare, H., G. D. Peterson, L. Börjeson, and L. J. Gordon. 2022. Ecosystem services in Sahelian village landscapes 1952–2016: estimating change in a data scarce region. Ecology and Society 27(3):1. https://doi.org/10.5751/ES-13292-270301

Research

Ecosystem services in Sahelian village landscapes 1952–2016: estimating change in a data scarce region

Hanna Sinare [1], *Garry D. Peterson* [1], *Lowe Börjeson* [2] and *Line J. Gordon* [1]

ABSTRACT. Burkina Faso and the wider Sahel region have experienced substantial changes in rainfall, population, and landscape use. These changes have altered ecosystem services, the benefits that people receive from ecosystems, and rural livelihoods. However, it is difficult to assess the magnitude of these changes because of missing and fragmented social, agricultural, and ecological data. We estimated changes in 10 key provisioning ecosystem services in rural Burkina Faso between 1952 and 2016. We used a simple model of plausible social-ecological changes to make a historical extrapolation that bridges these data gaps, and assessed historical changes. Our approach combined the interpretation of historic aerial photographs and satellite images, with field observations and interviews. We applied the approach for six villages in two administrative regions for six points in time. We modeled the use of historic ecosystems by analyzing a range of estimates of changes in the generation of each service and its value to people. We found that cultivated ecosystem services have increased 1.5–23 times over the study period, while the non-cultivated ecosystem services firewood, construction material, and medicine have decreased to 66–20% of their previous values. Per capita production of cultivated ecosystem services has remained relatively stable, while the per capita production of all other ecosystem services has decreased, to 54–11% of their 1952 values. Although alternatives are available for some ecosystem services, such as medicine and construction material, there are currently limited alternatives available for other services, such as firewood. Decline in wild food availability and consumption is likely to reduce the nutritional value of rural people's food. Our analysis of changes demonstrates that shrubs and trees on fields generate many ecosystem services that are key to rural livelihoods, and that efforts to enhance crop yields should maintain shrubs and trees. Our approach for estimating historical ecosystem services may also be useful to apply in other data scarce regions.

Key Words: *agroforestry; Burkina Faso; ecosystem services; landscape change; livelihoods; smallholder agriculture; West Africa*

INTRODUCTION

Vegetation and land use in the Sahel region are strongly shaped by human activities and variation in rainfall. The relative importance of these two factors has sparked persistent debates over what drives change in the Sahel. Following a series of severe droughts and famines in the 1970s and 1980s, researchers and policy makers revived a narrative of continuous human induced degradation and desertification, which was linked to population growth (Swift 1996, Reenberg 2012). Tree monitoring was previously focused on areas defined as forest, ignoring most of the trees present in the Sahel (Brandt et al. 2020). In the mid-2000s, observations of increases in vegetation since the early 1980s lead to a narrative of "re-greening" of large parts of the Sahel (Fensholt et al. 2009, Herrmann et al. 2005, Olsson et al. 2005, Souverijns et al. 2020). Over the period 2000–2015, there was no significant trend in total vegetation in most parts of the Sahel, but an increase in 16% of the area (Leroux et al. 2017), whereas woody vegetation was in general increasing, primarily in areas with low anthropogenic pressure (Brandt et al. 2016). The spatial variability was high, but there was no decrease in woody vegetation in established croplands. In fact, woody cover in farmlands in semi-arid Sahel was higher than in surrounding savannas (Brandt et al. 2018). Increase in vegetation has generally been seen as beneficial for peoples' livelihoods (Reij et al. 2005, Tougiani et al. 2009, Sendzimir et al. 2011). However, some studies have revealed that along with increased tree and shrub cover, there has been a shift in species composition toward more drought tolerant and/or exotic species, as well as a loss of large trees (Herrmann and Tappan 2013, Hänke et al. 2016), which change the value of the vegetation increase to people.

In this context, estimating the dynamics of ecosystem services, the benefits people obtain from nature (Millennium Ecosystem Assessment 2005), can reveal how these multiple changes in vegetation have been connected to multiple aspects of people's livelihoods. However, there has been limited success in analyzing temporal changes in ecosystem services (Nicholson et al. 2009, Bürgi et al. 2015, Berbés-Blázquez et al. 2016). Existing approaches to analyzing dynamics of ecosystem services are based on biophysical features and secondary data (Renard et al. 2015, Tomscha and Gergel 2016) or historic documents (Wilkinson et al. 2013, Bürgi et al. 2015), but in the Sahel region, secondary data and historic documents for the same area over time are absent or difficult to locate or access. For example, there is no data on collected wild foods beyond one or a few villages at a single point in time. Yield data for dominant crops is available since the 1980s, but not on finer scale than administrative province. Livestock data is also available for provinces but extrapolated from one census. Land cover maps, particularly historical, are limited and often only available at very low spatial resolution (Souverijns et al. 2020).

In the Sahel, rural people are highly dependent on the direct benefits produced by their local landscapes. For example, in Burkina Faso 63% of the total population and 80% of the rural population are occupied in different forms of agriculture, predominantly small-scale (INSD 2014). Using the framework of ecosystem services allowed us to move beyond the focus on a single resource (e.g., crops) to study change in multiple provisioning services across the village landscapes. The provisioning ecosystem services that we studied co-exist with cultural ecosystem services and depend on regulating and supporting ecosystem services

[1]Stockholm Resilience Centre, Stockholm University, Sweden, [2]Department of Human Geography, Stockholm University, Sweden

across these landscapes. For example, water is essential to life in the Sahel, and while all the ecosystem services we assessed require water, the ecosystem services that ensure water (moisture recycling, storage, and purification) are exceedingly difficult to estimate as they emerge from a temporally and spatially variable combination of tree density, landscape topography, soil hardening, and infrastructure built to support percolation and storage, such as planting pits (*zaï*), stone bunds, and ponds. A fuller understanding on how people depend on landscapes is needed as livelihoods in the Sahel region still face enormous challenges, not the least from effects of climate change (Salack et al. 2016, Sultan and Gaetani 2016), widespread poverty (UNDP 2015), and a rapidly growing population (FAO 2017).

We estimated historical changes in ecosystem services using a simple model to estimate changes in key provisioning ecosystem services through a combination of analysis of historic imagery, and results from previous fieldwork. We view ecosystem services as being co-produced by ecosystems and people (see, e.g., Reyers et al. 2013, Palomo et al. 2016). This co-production includes both human input of different capitals to enhance desired services, and the needs, values, and aspirations that shape what is appreciated as an ecosystem service (Daw et al. 2011, 2016, Chan et al. 2012, Ernstson 2013, Bennett et al. 2015).

Our assessment of changes in ecosystem services is based on what we term social-ecological patches: landscape units that correspond with the words that local people use when describing their landscapes, characterized by a combination of land use, land cover, and topography (Sinare et al. 2016), and the provisioning ecosystem services associated with each of these patches today. We explore the range of plausible change using (1) the assumption that social-ecological patches produced similar sets of ecosystem services in the past to what they do today, and (2) high and low estimates for plausible change based on literature and field observations of changes in the combination of availability and use of ecosystem services over time. This allows us to estimate ecosystem services across time despite having only partial knowledge or data of past changes in relationships between villagers and their landscapes.

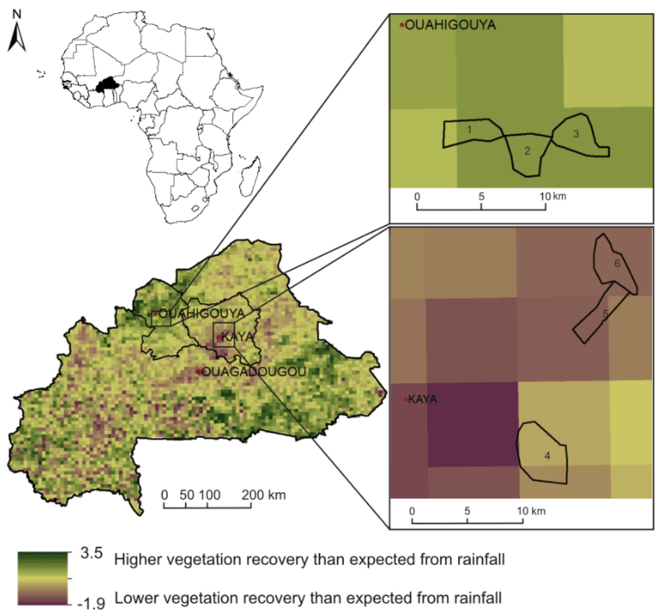
METHODS

This study was a part of a research project investigating ecosystem services and livelihoods in relation to the observed re-greening in Burkina Faso. It builds in particular on the assessment of current ecosystem services from different social-ecological patches made by Sinare et al. (2016), but is focused on how this information can be combined with interpretation of historical images to estimate change in ecosystem services over time.

Study sites

The study was conducted in six villages in Burkina Faso with similar biophysical and social characteristics, three in the administrative region Nord and three in the region Centre-Nord (Fig. 1). These regions have had, respectively, higher and lower vegetation recovery since the droughts that ended in the early 1980s than expected from increases in rainfall over the same period. This was shown in a large-scale study of residual trends in normalized difference vegetation index (NDVI) 1982–2008 that cannot be explained by change in 3-month cumulative rainfall (Herrmann et al. 2005). The villages are located around the 600 mm yearly rainfall isohyet 1968–2000 (OECD/SWAC 2014). The population in the villages range from 600 to 1500 inhabitants (Government of Burkina Faso 2005, see Sinare et al. 2016 for details), a size that is representative of villages in the region.

Fig. 1. Location of the studied villages in the administrative regions (black outline) Nord (including the town Ouahigouya) and Centre-Nord (including the town Kaya), in Burkina Faso. The villages are (1) Boursouma, (2) Oula, (3) Reko, (4) Lebda, (5) Koalma, and (6) Zarin. Background: The colors represent residual trends in normalized difference vegetation index (NDVI) 1982–2008, that cannot be explained by change in 3-month cumulative rainfall (Herrmann et al. 2005). Positive values show areas where vegetation greenness has increased more than expected from rainfall, and negative values represent areas where vegetation has increased less than expected from rainfall. NDVI data from S. Herrmann.



Mapping of past social-ecological patches

We mapped the change in spatial extent of social-ecological patches using visual interpretation of aerial photographs and satellite images from six times between 1952 and 2016: Aerial photographs from Institut Géographique du Burkina (IGB) and Institut National de l'Information Géographique et forestière (IGN) 1952/1955 (resolution - pixel size in meters at interpretation 0.9/0.7–0.8); Corona satellite images 1967/1968 (2.8/2.2–2.3); aerial photographs from IGB 1983/1984 (1.5–1.6/1.6); aerial photographs from IGB 1996 (1.5–1.8); satellite images CNES Astrium/Google Earth Pro 2006/2010 (0.9/0.6–0.7) and satellite images CNES Astrium/Google Earth Pro 2013/2016 (1.7/1.2–1.3). For more detail see Table 1. We imported all images to ArcGIS 10.3 software (ESRI 2013) and converted to UTM projection to allow for distance measurements. CNES Astrium/Google Earth Pro images from 2006/2010 were used as base layer for georeferencing all other images. We selected easily identifiable ground control points, for example sacred forest patches, for the georeferencing, resulting in 0.15–1 ground control point per

Table 1: Overview of image material used to identify change in social-ecological patches over time.

Decade	Image type	Region	Date	Mission	Resolution at interpretation (pixel size in meters)	Source
1950s	Aerial photograph	Nord	February 1952	A.O.F0171952_ND_30X	0.9	Institut Géographique du Burkina (IGB)
1950s	Aerial photograph	Centre-Nord	November 1955	A.O.F1955_56_ND_30_XII	0.7–0.8	IGB; Institut National de l'Information Géographique et forestière (IGN)
1960s	Corona	Nord	December 1967	1102-1	2.8	Data available from the U.S. Geological Survey
1960s	Corona	Centre-Nord	January 1968	1045-1	2.2–2.3	Data available from the U.S. Geological Survey.
1980s	Aerial photograph	Nord	December 1984	84066_B Ouahigouya	1.6	IGB
1980s	Aerial photograph	Centre-Nord	February 1983	83053_B Pissila	1.5–1.6	IGB
1990s	Aerial photograph	Nord	April 1996	96145_B Sourou/Passoré; 96145_B Ouahigouya	1.6–1.8	IGB
1990s	Aerial photograph	Centre-Nord	December 1996	96158_B Sanmatenga	1.5–1.6	IGB
2000s	Satellite image	Nord	March 2006	-	0.9	CNES Astrium through Google Earth Pro
2000s	Satellite image	Centre-Nord	October 2010 (Koalma, Zarin), November 2010 (Lebda)	-	0.6–0.7	CNES Astrium through Google Earth Pro
2010s	Satellite image	Nord	April 2013	-	1.7	CNES Astrium through Google Earth Pro
2010s	Satellite image	Centre-Nord	May 2016	-	1.2–1.3	CNES Astrium through Google Earth Pro

square kilometer. This is comparable or exceeding the density of ground control points used in a similar landscape (Ruelland et al. 2011). Each image was transformed with first order polynomial transformation.

The images were interpreted manually on-screen. Manual interpretation has previously been shown to give more reliable results than automated techniques in the Sahel context (Tappan et al. 2004, Tappan and McGahuey 2007) because of the possibility of combining different image sources including film-based aerial photographs, and integrating field knowledge in the interpretation. For this study, the detailed field knowledge from participatory research activities including walks across all villages with regular stops to document landscape use (methods described in Sinare et al. 2016), was important for the image interpretation.

We used the village borders identified in 2011 (Sinare et al. 2016) for all image analysis because there are no official maps of village borders available. We applied a grid on the time series of images for each village, and classified each cell as a type of social-ecological patch. We did this by looking at each 100 x 100 meters cell potentially covering multiple social-ecological patches, and classifying it by the social-ecological patch at its center (within a circle with 5 m radius around the cell center). The social-ecological patch class had to cover at least 0.25 hectares connected land for the cell to be classified to this patch class. We selected this method as compared to a method mapping polygons because it was faster and as accurate. The method was tested against polygons mapped for 2006 (Sinare et al. 2016) and yielded the same percentage cover of the different social-ecological patches.

We classified nine types of social-ecological patches (term in local language Mooré in parenthesis): Fields (*Pùtâ*), Shrubland (*Weoogo*), Homesteads (*Kamanse*), Depressions (*Baongho*), Forest (*Kaongo*), Bare soil (*Zipellé*), Woodland (*Kangré*), Irrigated land for vegetables (French term *Jardin maraîcher* used), and Public buildings (see Table 2 for definitions). As compared to the social-ecological patch types identified in the villages 2011 (Sinare et al. 2016), we added woodland, land around public buildings, and irrigated land for vegetables, and combined fallows into shrubland or fields. Fallows were not possible to detect, as young fallow looks like fields and old fallow resembles shrubland on the images, and therefore were classified into these categories. The attribution of values for ecosystem services to each social-ecological patch builds on modified scores from previous in-depth fieldwork (Sinare et al. 2016; see Appendix 1 for detailed description).

Woody vegetation has been documented to provide a wide range of ecosystem services such as food, fodder, firewood, and regulation of water, carbon nutrients, and micro climate in these landscapes (see, e.g., Bayala et al. 2014, Sinare and Gordon 2015). To examine the role of woody vegetation on cultivated land for the generation of ecosystem services, we removed the scores for leaf vegetables from trees, fruits, medicine, firewood, and construction material for the social-ecological patches, fields, homesteads (cultivated areas around houses), and depressions (cultivated lower lying areas) to create a "without trees" scenario.

Change in ecosystem services

We estimated the historical generation of ecosystem services in two ways. The first method assumed a constant relationship between ecosystem services and social-ecological patches, while the second estimated a range of ecosystem service values based on how relationships with social-ecological patches have changed over time. Comparing these methods allowed us to assess which historical estimates are likely robust or uncertain.

Table 2: Social-ecological patches and their definitions, presented in the order they were identified in the aerial photographs and satellite images.

Social-ecological patch (Name in Mooré)	Definition	Justification for inclusion
Homesteads (*Kamanse*)	Courtyards and the land surrounding them within 50 meters distance from buildings (following Sinare et al. 2016).	These areas are characterized by higher nutrient concentration due to human and animal excreta, and a different species composition based on what people cultivate to have close at hand.
Public buildings	Land within 50 meters from public buildings such as schools and municipality offices, which does not have homestead qualities, but are more similar to bare soil.	To not overestimate ecosystem services from homesteads, which the areas would otherwise be classified as.
Depressions (*Baongho*)	Depressions are to a large extent topographically defined, and were first mapped following the same extent as 2006/2010 where ground control points were available from Sinare et al. (2016). Adjustments were made for historical images where parts of a depression where formerly forest (had higher tree density).	These lower lying areas are to a large extent cultivated, and yields higher than other fields most years because of the higher soil moisture. It also has higher cover of large trees. Yields are decreased in these areas when rainfall is high.
Forest (*Kaongo*)	Patches with dense cover where individual crowns could not be detected. Forest patches are often sacred and therefore persistent over time.	Although only covering < 5% of the village landscapes, forest patches are distinct and of high cultural value. The extraction of provisioning ecosystem services is very limited.
Fields (*Pùtâ*)	Land with dispersed trees and shrubs, where features such as field borders and/or soil and water conservation methods indicate cultivation.	Cultivated land with different densities of dispersed trees and shrubs is dominant in the villages.
Woodland (*Kangré*)	Land with dispersed trees, relatively dense, without presence of field borders.	Present in historic images and not possible to classify into any of the other social-ecological patch classes.
Bare soil (*Zipellé*)	Land without vegetation cover, without presence of field borders.	Indicates land degradation.
Shrubland (*Weoogo*)	Land with sparse to relatively dense shrub cover.	Important for pasture.
Irrigated land for vegetables (*Jardin maraîcher*, French term used)	Land close to a reservoir or other water source and prepared for vegetable cultivation during the dry season.	Important new social-ecological patch with a distinct set of ecosystem services and benefits.

For the first method, we made the naïve assumption that each social-ecological patch type generated the same set and relative yield of ecosystem services over time. This assumption allowed us to extrapolate our field data on current ecosystem services produced by village landscapes into historical landscapes. We multiplied the production of ecosystem services in each patch type by the frequency of that patch type to estimate the total availability of each ecosystem service for each historical time period and village (Fig. 2). However, ecosystem service generation has changed over time because of changes in farming and land use practices, as well as in peoples' values and needs.

For the second method, we estimated a historic high and low production of each ecosystem service from each social-ecological patch type to establish a plausible interval for the generation of ecosystem services in 1952 relative to 2016. The co-produced nature of ecosystem services implies that change over time depends (a) on the generation of the potential ecosystem service, i.e., the material that can become an ecosystem service if valued, which is influenced, for example, by change in vegetation, or in technology and inputs used in agriculture; and (b) on people's demand for that material, which makes it a provisioning ecosystem service. The demand depends both on the population density (which we address below), and on the degree to which the population is dependent on the local landscape. To estimate a plausible interval for change in ecosystem services, we combined (a) and (b). The assumptions for historical high and low values for ecosystem services were based upon previous fieldwork (Sinare et al. 2016), further discussion with villagers about changes over time, and the previous studies from the region that we could find, which give an indication of changes (Table 3). We expected that most estimates of change would be between these values. We linearly extrapolated this range between 1952 and 2016 to estimate how the production of ecosystem services has changed over time. By combining this change in production with the change in the social-ecological patches in each village we were able to estimate the change in available ecosystem services in each village (Fig. 2). We used available population data for each village and time period (Table 4), to estimate how ecosystem service availability has change on a per person basis. We compared per person availability of each ecosystem service in the past to its current availability to identify whether this availability has changed over time. These calculations were done using R (R Core Team 2019), with the packages raster (Hijmans 2020), rasterVis (Perpinan Lamigueiro and Hijmans 2019), rgdal (Bivand et al. 2019), ggplot2 (Wickham 2016), and ggpubr (Kassambara 2020).

RESULTS

Change in social-ecological patches over time

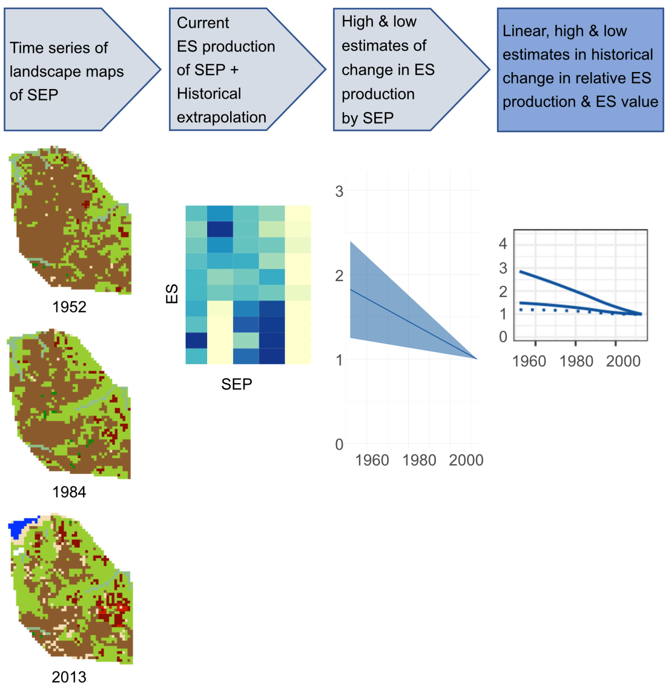
The dominant trend in all villages is a sharp increase in fields with trees (on average 60% increase between 1952 and 2016), and decrease in shrubland area (on average 64% decrease; Fig. 3). The villages have different rates of change, with less increase in villages that were predominantly cultivated already in the 1950s. For example, fields covered almost 70% of Boursouma in 1952, and that area increased by only 17% over the whole period, being relatively stable since the 1980s. Lebda, on the other extreme, was

Table 3: Justification for high and low estimates of changes in ecosystem service generation and the value of these ecosystem services to people 1952-2016, based on literature and field data. The number in parenthesis is used in the model to illustrate the justification. The estimates of change in ecosystem service generation and ecosystem services value to people are combined to estimate historical ecosystem services.

Ecosystem service (ES)	Estimate	ES generation plausible change	ES value to people plausible change
Cereals	Low	According to agricultural statistics, yield has increased from 500 kg per ha to 900 kg per ha over the period 1984–2013[†], but with high inter-annual variation. Extrapolating such changes backwards to the 1950s gives estimates of a quarter of current yields per ha (0.25).	Cereals were more important in the 1950s as people had less income to purchase alternatives (e.g., maize and rice). However, even today many households are at least partly dependent on their own cereals. Therefore, a low estimate is that previously cereals were 20% more important to people (1.2).
	High	Yields per ha could have been higher in the 1950s than in the 1980s, because higher land availability per capita may have enabled longer fallow periods. Similarly, manure application rates were higher before the 1970s, meaning that although lower than today, yields could have been up to 70% of current yields[‡] (0.7).	Informants have stated that cereals were more important in the past. Before all field area was dedicated to sorghum and millet, now cereals make up only 1/3 of the field area for some farmers, the rest is dedicated to cash crops. Therefore, a high estimate is cereals were 50% more important to people (1.5).
Legumes	Low	Yields per ha have slightly increased (0–30%) since the 1980s[†]. The area dedicated to cowpeas has increased over the past 15–20 years according to informants. This indicate that less legumes were produced in the past (0.8).	Legumes are more important as cash crops today. Informants dedicate up to 2/3 of their land to legumes. This suggests that legumes were much less in demand in the past. (0.3)
	High	Yields may have been higher in 1950s than early 1980s. Evidence for this view is that groundnuts were cultivated on less area in the 1970s than earlier, and on less fertile land[‡]. Cowpeas were also distributed by extension services and grown in the 1950s. Consequently, yields of legumes per ha may have been the same in the 1950s as today (1).	Groundnuts were as important for income in the 1950s as they are today because there were fewer alternative sources of income, suggesting that demand for groundnuts could have remained constant (1).
Vegetables	Low	Available agricultural statistics[†] indicate a substantial yield increase over the period 1996–2008. Dry season irrigation from small-scale dams has been behind much of this increase, therefore vegetable yield was much lower in the past when these dams were not present (0.1).	The importance of vegetables has increased over time. Currently, vegetables are in important income source, and because edible leaves are less available, they are a more important food source. Demand for vegetables may have been up to 30% lower in the past (0.7).
	High	Although vegetables have increased, there are no statistics that include the entire period. Rainfed vegetables might have yielded more in the past, so previous yields could have been as much as half current yield (0.5).	Although demand for vegetables has increased, this increase may have been quite small, perhaps only 20% lower than present (0.8).
Leaf vegetables herbs	Low	The conditions for herbs to sprout in and around fields and homesteads have not changed over time (1);	The importance of herbs has decreased somewhat as more alternatives are available. Therefore, demand may have been slightly higher in the past (1.2).
	High	More intensive cultivation may have decreased possibilities for herbs to sprout in and around fields. Therefore, productivity of herbs may have been slightly higher in the past (1.2).	Wild foods were more important in the past, especially during drought years, as fewer alternative foods were available. Therefore, demand was substantially higher (1.5).
Leaf vegetables trees	Low	Tree species valued for their leaves have decreased[§], but the impact has not been too large as people have preserved or enabled the regeneration of important species. Therefore, leaf production was minimally higher in the past (1.1).	The importance of leaf vegetables from trees has decreased somewhat because alternatives are available. However, because leaves are still culturally important then importance was only minimally higher in the past (1.1).
	High	Tree species valued for their leaves have substantially decreased[§]. Therefore, leaf production was substantially higher in the past (1.5).	Leaves from trees were substantially more important in the past when there were few alternatives available to buy, especially during times of crop failure. Therefore, demand was substantially higher (1.5)
Fruits	Low	Tree species valued for their fruits have decreased[§], but because people have preserved/regenerated important species this decline is minimal (1.1);	Fruits were as important in the past for income and food as now (1).
	High	Tree species valued for their fruits have decreased[§] resulting in a substantial decline in fruit production (1.5).	Fruits were more important in the past both as food and as source of income. Therefore, importance for fruits has substantially declined (1.5).
Medicine	Low	The diversity of medicinal species in shrublands have decreased slightly. Therefore, past production of medical plants in shrublands was slightly higher than today (1.2)	The demand has decreased over time with increased access to healthcare and pharmaceuticals, but traditional medicine is still culturally important and healthcare expensive. Therefore, demand for medicinal plants has only minimally declined (1.1);
	High	The diversity of medicinal species in shrublands have decreased a lot. Therefore, past production of medical plants in shrublands was twice as great previously as it is now (2).	The demand for medicinal plants has decreased a lot over time because of increased access to healthcare and pharmaceuticals. The demand in the past was much higher than today (1.8).
Firewood	Low	Firewood available to collect on fields and shrublands has decreased over time. Tree densities are recovering to levels of the 1960s[§]. However, tree densities could have been higher in the 1950s, leading to slightly higher availability than today (1.2)	About 96% of the rural population is still dependent on firewood for cooking[|]. With the assumption that 100% was dependent on it in the 1950s, we assume very small decline in importance (1.04)
	High	Before the 1960s, the availability of firewood was far higher than the demand[¶]. Informants report that they need to walk longer distances to collect firewood today. This could indicate that firewood production was substantially higher in the past (1.5).	A large part of the population still dependent on firewood for cooking but the need for wood may have decreased somewhat in recent years if more households use improved stoves with higher energy efficiency. We assume a small decline in importance (1.08)
Construction Materials	Low	Although other woody vegetation has decreased, people have increased the number of neem trees close to homesteads. These cultivated trees compensate for loss of wild construction materials meaning production of construction materials was likely similar in the past (1).	Currently, people use more purchased than local materials for construction. Assuming that purchased materials were used in the 1950s but to a lower degree then importance of construction was slightly higher in the past (1.25).
	High	Presence of a more diverse set of species meant that slightly more local construction materials were available in the past (1.2).	Assuming that only local materials were used in the 1950s. Importance of local construction materials was twice as great as it was now (2).
Resources for Livestock	Low	Pasture areas were larger and more connected in the past[#], meaning that more resources for livestock were available (1.3).	Livestock keeping has greatly increased. Fewer people kept livestock in the past because there was more specialization in either crops or livestock[††]. Therefore, the importance of resources for livestock was much lower in the past (0.6)
	High	The ability to move more freely across the landscape meant that much greater amount of resources for livestock were available because livestock could take advantage of spatial and temporal variation in the landscape (2).	Although fewer people kept livestock, resources for livestock were still important for most people because there was collaboration between herders and farmers. Therefore, production for livestock was important for farmers, because herders could keep animals on fields after harvest, and its importance was minimally lower in the past (0.9).

[†] Ministère de l'agriculture et de securité alimentaire 2013, [‡] Breusers 2001, [§] Hänke et al. 2016, [|] INSD 2014, [¶] Ozer 2004, [#] Malmborg et al. 2018, [††] Powell et al. 2004

Fig. 2. Historical ecosystem services (ES) are estimated by combining maps of social-ecological patches (SEP; Fig. 3a), with current relationships between ES and SEP (Appendix 1) and extrapolating for each time period and village landscape. A high and low estimate of historical generation of each ES for each time period is then produced by multiplying these extrapolations by how changes in use and production of each ES are estimated to have changed over time (Table 3). This process produces an estimated range of historical generation of each ES for each village landscape that combines changes in land use, and changes in the use and production of ES within each SEP.



covered with less than 30% fields in 1955, and the field area increased by 70% over the whole period. Zarin had the largest increase in fields, where it almost doubled. The percentage increase in fields is higher in all villages in region Centre-Nord (70–99%) as compared to region Nord (17–56%). Fields with trees covers on average 64% of the village area and shrubland covers on average 18%.

There were substantial changes in the extent of less common social-ecological patches (Fig. 3b). On average, homesteads have quadrupled. Bare soil has also increased with larger increase in the region Centre-Nord than in the region Nord. Lebda had the largest presence of bare soil with 8% of the landscape covered in 2010, and a nine-fold increase in bare soil surface versus its minimum extent (1983). All the villages shared a relatively recent peak in the area of bare soil, in 1996 or 2006/2010. The area of bare soil has been very limited in Boursouma and Oula over the whole period. Woodland was present in smaller areas in most villages in the past, but has now vanished. The existence of this social-ecological patch was confirmed by the villagers in the focus group discussions. The area of depressions has been relatively stable through time, as they are mainly topographically defined. Public land is mainly included in the maps to avoid overestimation of the homestead areas. In Lebda, a dam was constructed in 2009, transforming the northwest corner of the village into a small reservoir. In 2016, irrigated vegetables had emerged as a distinct social-ecological patch in Lebda, but this was not included in the assessment of change in ecosystem services because of its limited spatial extent.

Change in ecosystem services over time

The overall trends of change in social-ecological patches were surprisingly similar in all villages (Fig. 3b), therefore we present the results on change in ecosystem services over time as averages for all villages. We describe the results of our plausible interval model, and then contrast these results to those from the linear model.

Since 1952 cultivated ecosystem services from cereals, legumes, and vegetables have increased. Vegetables increased by a factor of 4–23 times, while cereals and legumes increased 1.5–7 times (Fig. 4a). For leaf vegetables from herbs and resources for livestock it is not possible to discern whether there has been an increase or decrease. Medicine, construction material, fruits, and leaf vegetables from trees decreased. Leaf vegetables from trees and fruit decreased less, maintaining 90–50% and 80–40% of their respective 1952 levels. Medicine, firewood, and construction material declined to 66–20% of their previous values. Only three estimates from the linear model, for legumes, cereals, and livestock, were within the intervals estimated by our plausible interval model. The linear model estimated less change in ecosystem services than the plausible interval model for all services except leaf vegetables from herbs, where the linear model estimated an increase and the plausible interval estimated a decrease.

Population density has almost doubled over the period 1960–2006 (Table 4). The generation of the cultivated ecosystem services cereals, legumes, and vegetables have almost kept up with this population increase, or increased slightly per capita (Fig. 4b). Leaf vegetables from herbs has kept up with population growth or declined somewhat per capita. All other ecosystem services have declined per capita. Firewood declined to about a third of its level in 1952 even in the linear estimate, and has, together with medicine, fruits, construction material, and leaf vegetables from trees decreased to 11–54% of their 1952 levels. Informants described how they nowadays need to walk long distances to collect the firewood they need.

By comparing our estimates of ecosystem services with a scenario in which there were no trees and shrubs in croplands, we demonstrate that cropland trees substantially contribute to availability of leaf vegetables from trees, fruits, medicine, firewood, and construction material (Fig. 5). Thus, the decline in ecosystem services generation over time would have been much higher if trees and shrubs were not conserved on fields in the farming system in the study area.

DISCUSSION

We first reflect on the accuracy of our mapping of social-ecological patches, estimates of population density, and simple model for historical extrapolation of ecosystem services. We discuss its value for studies of change in ecosystem services, and how the model could be improved and extended. Second, we discuss the challenges for landscape-based livelihoods in Burkina Faso that our historic analysis indicates, and their policy implications.

Table 4: Overview of population data used in the analysis of per capita change in ecosystem services.

Year	Type of data	Geographical unit	Population density (inhabitants per km²)
1960	national survey†	Coarser geographical units, the unit Yatenga is somewhat larger than the province Yatenga is today, and the unit Mossi Central includes what is Sanmatenga today, but is approximately five times larger.	46 (Nord); 32 (Centre-Nord)
1975	national census‡	Nord: Ouahigouya (not comparable to today's units); Centre-Nord: municipality Pissila	67 (Nord); 33 (Centre-Nord)
1985	national census§	Nord: municipality Oula; Centre-Nord: municipality Pissila	55 (Nord); 39 (Centre-Nord)
1996	national census|	Nord: municipality Oula; Centre-Nord: municipality Pissila	68 (Nord); 37 (Centre-Nord)
2006	national census¶	Nord: municipality Oula; Centre-Nord: municipality Pissila	80 (Nord); 63 (Centre-Nord)

† Republique de Haute-Volta 1962, ‡ Republique de Haute-Volta 1978, § Government of Burkina Faso 1988, | Government of Burkina Faso 2000, ¶ INSD 2009

Image interpretation and population data

Interpretation of aerial photographs and satellite images is affected by seasonal differences between photo dates. The elements that we used for the identification of social-ecological patches such as trees and shrubs, field borders, permanent soil and water conservation structures, and buildings are visible all seasons. We are therefore confident that seasonal differences between images taken in the beginning of the dry season (November) and in the end of the dry season (April) did not have a major impact on the results. The aim of our approach was to map trends in change in social-ecological patches and ecosystem services over time. We were therefore less interested in exact map accuracies for exact points. When working with historical images it is difficult to assess classification accuracy as other reference material is seldom complete (Manies and Mladenoff 2000, Schulte et al. 2002). For the study sites, neither ground truthing points nor historical land use maps are available. However, the interpretation of the images in this study was facilitated by the knowledge of the landscape from previous in-depth fieldwork. To study change in larger areas, some automation to identify social-ecological patches in images would be necessary. For recent remote sensing images, Malmborg et al. (2018) developed a hybrid classification approach to address this. Even though we were unable to map fallows, the set of provisioning ecosystem services from fallows can be represented by the combination of shrublands and fields that the actual fallows are classified as in our maps. However, excluding fallows as a separate social-ecological patch would be problematic in an assessment of regulating ecosystem services because fallows help restore soil fertility through accumulation of nutrients and organic material.

We used data on population densities for the smallest unit where reliable data were available. Data at village level were available for some years, but have been proven unreliable at least for some villages from fieldwork experience. However, this village level data suggest 2–3 times higher population densities in Boursouma, Oula, and Koalma, and 1.25–2 times higher population densities in Zarin, as compared to the regional densities used in our analysis (Marchal 1983, Government of Burkina Faso 1988, 2000, 2005). This indicates that the decrease in ecosystem services per capita might actually be larger than our results show (Fig. 4b). However, in Reko and Lebda, the population densities might be up to 30% lower than the regional densities used. Actual population in the villages varies within a year, which is not captured in the population data. Young men in particular migrate to cities or neighboring countries to work during the dry season and return for the harvest season. This means that there are seasonal differences in beneficiaries of ecosystem services, a lack of labor force for investment in the landscape, e.g., when fields with soil and water conservation structures are prepared, and an inflow of financial capital.

Landscape variability

Landscapes vary over both time and space in ways that are poorly known. Key issues within patches include variation in crop yield and composition of woody vegetation. Key issues within the landscape include configuration and interactions between patches, and the emergence of new types of social-ecological patches. Soil and water conservation techniques are widespread investments to increase water infiltration and storage and thereby yields in the study area, particularly in villages in region Nord. After the droughts in the 1970s and 1980s, village committees led the construction of stone bunds empowered by customary chiefs and elders and supported by development projects (Batterbury 2010). A farmer in the region frequently mentioned by informants, Yacouba Sawadogo, started to improve traditional planting pits, *zaï*, in the 1980s by making them larger and adding manure, a practice that spread over large areas through farmer-to-farmer study visits (Pasiecznik and Reij 2020). Sawadogo was a Right Livelihood Award laureate in 2018 and UNEP Champion of the Earth 2020. The construction of stone bunds and *zaï* is labor intensive, and it is more likely that these techniques are adopted by farmers who are trusted and can mobilize mutual assistance work, or head larger or wealthier households (Yaméogo et al. 2018). Yields have also been enhanced by increased use of manure and fertilizers, animal traction, and improved crop varieties adapted to a shorter rainy season. However, yield data is available at a relatively coarse scale while yields are highly variable, even within fields. In addition, there is seasonal variation in generation of ecosystem services, where crops are grown during one rainy season, and many wild foods harvested during a single period each year, as well as interannual variation in generation due to rainfall variability.

A second key source of variation among patches are differences in the density and species composition of woody vegetation. There is only partial data on these changes. In the villages in region Nord, woody vegetation decreased after the droughts in the 1970s

Fig. 3. (a) Maps of social-ecological patches in all villages at three different time points: 1952/1955, 1983/1984, and 2013/2016; (b) Change in percentage cover of social-ecological patches over time for each village. Differences are generally larger between villages than between regions.

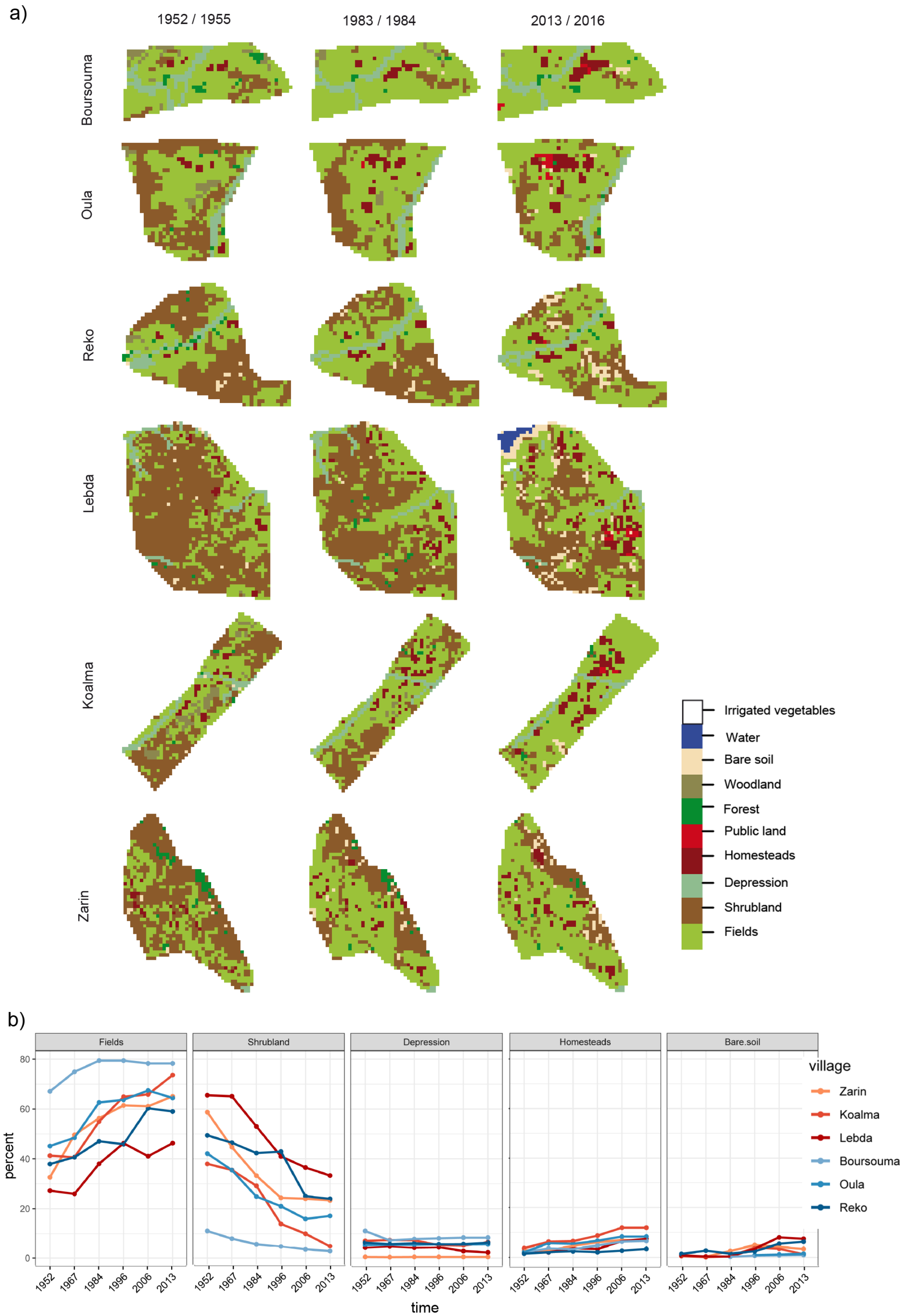
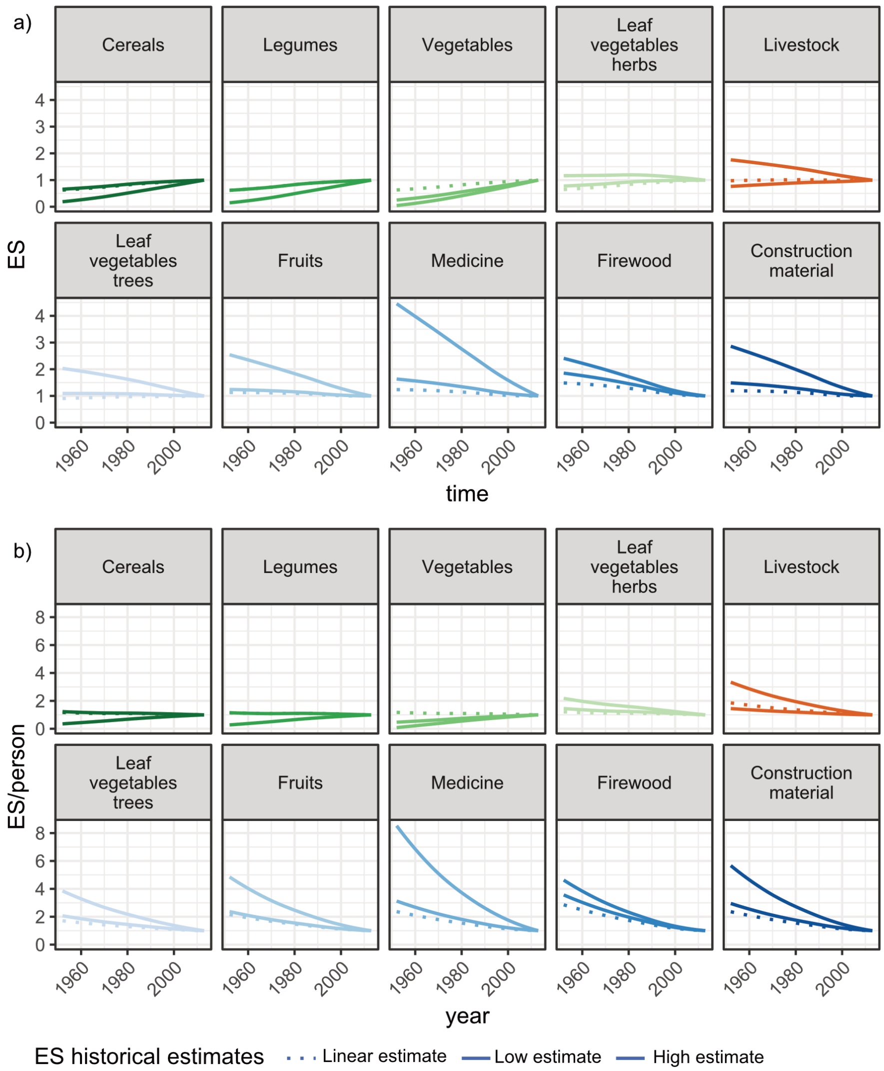


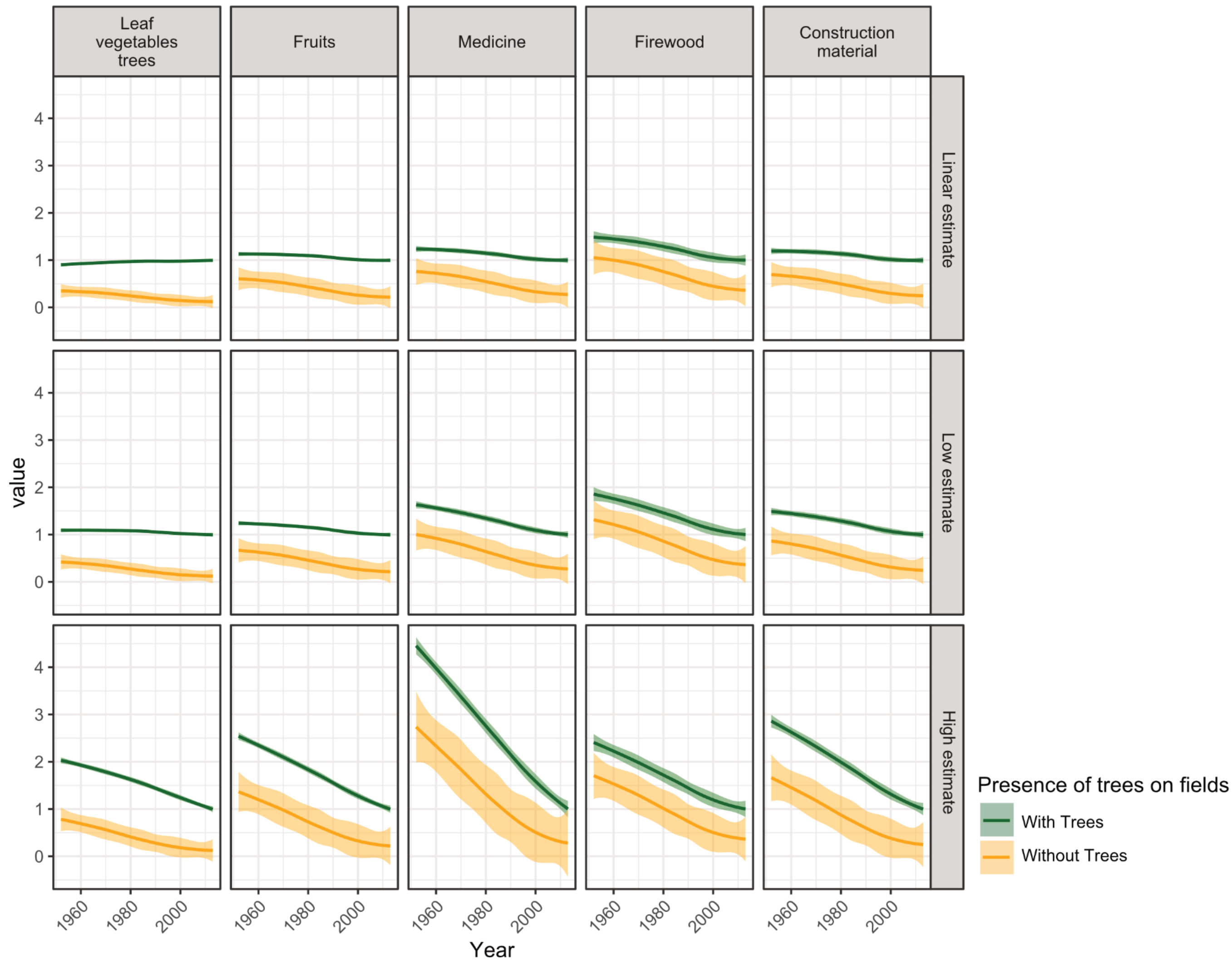
Fig. 4. (a) Linear, high, and low estimates of change in 10 different ecosystem services (ES) between 1952 and 2016. The time series is normalized to the potential generation of ecosystem services with the 2016 percentage cover of social-ecological patches, with relative values on the y-axis; (b) Linear, high, and low estimates of change in ecosystem services per capita, normalized to population density in 2006, with relative values on the y-axis.



and 1980s, but then recovered until 2006 (Hänke et al 2016). However, the species composition has shifted to more drought tolerant and introduced species, which do not generate the same set of ecosystem services. Informants in our study reported a decrease in species diversity in shrublands, which has made it more difficult to find fruits, leaves, and products for traditional medicinal use. On the contrary, the introduced fast-growing species may increase availability of construction material and firewood (Hänke et al. 2016). Regional differences in the quality of woody vegetation in social-ecological patches is a potential explanation of the lack of difference between the two study regions, despite their different NDVI trends that motivated the site selection (Fig. 1). Vegetation greenness measured as NDVI is potentially more affected by differences in vegetation density and species composition within social-ecological patches, than by changes between social-ecological patch classes. Studies from Senegal have shown that it is difficult to relate differences in vegetation greenness between pixels to changes in landscape composition and livelihoods that are measured and perceived on the ground (Herrmann and Tappan 2013, Herrmann et al. 2014). Including better assessment of woody resources quality in patches (see, e.g., Hänke et al. 2016 for methods) would improve estimates of ecosystem services, but is difficult to apply to this long-time series of historical images because of the lack of data of historical species composition.

Along with changes within patches, changes in the landscape composition and configuration can also alter the supply of

Fig. 5. Linear, high, and low estimates for change in ecosystem services from trees across village landscapes comparing the simple model with a scenario of no trees on cultivated land (fields, homesteads, and depression). The time series is normalized to the potential generation of ecosystem services with the 2016 percentage cover of social-ecological patches and trees, with relative values on the y-axis.



ecosystem services. This study used total patch area, but not relationships among patches or patch configuration to estimate the supply of ecosystem services. Better understanding of how people use different patches during different seasons would potentially allow configuration of patches to be used to better estimate changes in ecosystem services. For example, if shrubland patches decrease below a certain size, they become too small to keep livestock and to maintain diversity of medicinal plants and fruits (Malmborg et al. 2018).

Despite these aspects, we argue that this approach is valuable for the literature on change in ecosystem services over time because of its simplicity and transparency, which allows estimates to be easily refined when additional observations of changes in availability or value to people at different points in time become available for these landscapes. The linear extrapolation, the high estimate of change, and the low estimate of change all have a consistent direction of change for almost all ecosystem services. This indicates a robust estimation of change in ecosystem services. For some services, the plausible range of change is large, indicating that the underlying assumptions are important, and that a more precise understanding of how relationships between people and nature have changed is needed to reduce uncertainty. The approach of analyzing a range of plausible change in ecosystem services over time can also be used in other settings, particularly where data availability is low.

Challenges for future livelihoods in rural Burkina Faso

In interviews, villagers stressed that while they diversify their activities to earn cash income, they depend on the local landscape for their livelihoods. This is consistent with occupation and income data from a national survey (INSD 2014), showing that despite the general importance of migrant remittances (Batterbury 2010), more than half of the households do not report remittances. Our results indicate that field expansion in the studied village landscapes in northern Burkina Faso is approaching limits, both because of lack of additional land that can be meaningfully cultivated, and because of lack and fragmentation of shrubland for livestock grazing. Farmers in Boursouma and Oula, for example, set aside fields for livestock to prevent their livestock from grazing on other farmers' land, because shrubland is too scarce. Farmers do not have enough crop residues or other fodder sources to replace grazing with fodder during the cropping season. Specialized pastoralists with larger herds are present in the area, and field expansion can exacerbate already occurring conflicts between crop producers and livestock producers (Sanfo et al. 2015). Land is no longer sufficient to leave fields fallow according to informants, and if they do leave fields uncultivated, the high pressure of livestock grazing is expected to degrade rather than increase soil fertility. The decline of the fallow practice increases the need for external input of nutrients on fields to maintain or increase yields. Manure from farmers' own cattle is insufficient, which means that access to manure depends on social capital to maintain or establish good relationships with livestock herders. Mineral fertilizers can be purchased, but farmers can often afford only limited quantities.

Concern that conversion of shrubland to fields is approaching saturation has been raised in other parts of Burkina Faso (Hansen and Reenberg 1998, Knauer et al. 2017, Jahel et al. 2018). In parts of the Sahel, where cropland area has been stable, this stability has been explained by access to improved agricultural practices (Reij et al. 2005, Tappan and McGahuey 2007) and national or international markets (van Vliet et al. 2013). If that is true in our study area, it means that not enough farmers have had access to improved agricultural practices and/or local, national, or international markets. Our study shows that although changed agricultural practices such as soil and water conservation methods have improved yields, the increase has neither been enough to hinder expansion of cultivated land, nor to lift people out of poverty. In the regions Centre-Nord and Nord, 47% and 70% of the population, respectively, lives in poverty, according to nationally defined income levels (corresponding to approximately US$0.75 per day). These poverty rates are higher than the national average of 40% (Government of Burkina Faso 2016).

Avoiding trade-offs in agricultural landscapes with trees

To further intensify crop production, multiple challenges must be navigated. Farmers' capacity to apply manure and/or mineral fertilizer has become central to gain a good or even acceptable yield. Farmers do apply compost or manure, but the availability of manure is generally insufficient for the area cultivated (Kambire 2016), and mineral fertilizers are often too expensive for farmers to apply to the whole field area. Increased temperatures and more irregular rains are expected in the area (Salack et al. 2016, Sultan and Gaetani 2016). These changes would make it more difficult for farmers to increase yields of rainfed crops and increase the need for water management, which can reduce insecurity and increase incomes for farmers. In this context, access to and management of small-scale reservoirs is important. The construction of a dam in Lebda in 2009 was a major change for the population and informants stressed the much higher income per hectare from vegetable cultivation as compared to millet production. Because of the rapid increase in dams in Burkina Faso in general (Cecchi et al. 2009, Ofosu et al. 2010), irrigated land for dry season vegetable production that we identified as a new patch type, should be considered in regional analyses or projections of future changes. This patch type may be limited in surface area, but has the potential to contribute substantially to the diversification of production and increase of farmers' income. Life in the study area, particularly the region Centre-Nord, is today challenged by numerous terrorist attacks targeting civilians. This has resulted in more than 1 million internally displaced persons since the beginning of 2019 (UNHCR 2021). This violence is an immediate threat to people, and hinders investments in land and livestock.

All non-cultivated ecosystem services have decreased per capita over the study period (Fig. 4b). Population is rapidly growing in Burkina Faso; in 1960 the population was under 5 million people, whereas in 2019 it was over 20 million (World Bank 2019). Currently population growth rates remain high, at 3.1% per year (Government of Burkina Faso 2016). These high rates of population growth are likely to persist, as the population is forecast to increase for the rest of the century (FAO 2017). This rapid population growth presents opportunities and risks for Burkina Faso, and means per capita availability of ecosystem services is likely to continue to decline without unprecedented changes to land management. The vast majority of people depend on firewood for cooking (more than 95% according to Government of Burkina Faso 2006a, 2006b), and there is already a deficit in firewood and charcoal in relation to the demand in the regions Nord and Centre-Nord (Kambire et al. 2015). This decline in fuel availability highlights the urgent need to develop rural access to more sustainable energy sources. Decline in wild foods is likely to have negative effects on nutrition, as many have much higher nutritional values than cultivated vegetables, and may not be available or affordable for people to purchase. For example, frequently cited food items from trees such as leaves of *Adansonia digitata*, nuts of *Sclerocarya birrea*, and calyx of *Bombax costatum*, have high concentrations of different minerals (Smith et al. 1996), and food leaves from herbs such as *Corchorus tridens* and *Amaranthus hybridus* have high values of proteins and mineral nutrients (Humphry et al. 1993). Decreased availability of firewood in particular, but also wild foods affect the time available for women, because mainly women are responsible for their collection (see, e.g., Reij et al. 2005, Perez et al. 2015) and need to spend more time collecting when resources are scarce.

Improved productivity in agriculture is a main goal of Burkina Faso's government (Government of Burkina Faso 2016) and international development donors, who also focus on increasing yields in African smallholder agriculture, including in Burkina Faso (see Moseley 2017 and Gengenbach et al. 2018 for critical perspectives). Our analysis shows that non-crop provisioning ecosystem services from croplands are essential to people's livelihoods in these multifunctional village landscapes. If the croplands in this study (fields with trees, depressions, and homesteads) had only been assigned values for crops, we would have seen much lower levels of leaf vegetables from trees, fruits, medicine, firewood, and construction material across all time steps and estimates (Fig. 5). The importance of trees and shrubs for generation of provisioning as well as regulating ecosystem services in the Sahel has also been previously documented (see, e.g., Bayala et al. 2014, Sinare and Gordon 2015). Maintenance of trees and shrubs on fields is closely linked to development of social capital in a context where colonial agricultural extension services focused on removal of trees from fields, a practice that persisted for decades (Reij and Garrity 2016). Building of trust between farmers and extension services, transfer of authority to village committees for land and vegetation management, and capacity development are examples of this development of social capital (Hilhorst 2008, Batterbury 2010, Pasiecznik and Reij 2020). Our study illustrates the importance to consider the multiple ecosystem services generated from trees and shrubs in any landscape intervention to avoid trade-offs, for example, when designing strategies to improve crop productivity, or in the establishment of mining activities, which is an important income source in the regions and for Burkina Faso. We hope that the findings and methods developed in this research can help guide future landscape management decisions.

CONCLUSION

We estimated historical ecosystem services in village landscapes in Burkina Faso, using a simple model that estimates the range over which the social-ecological production and use of ecosystem services has changed. These estimates are based on a combination of image interpretation, field data, and literature data. The approach has the strengths of being simple, transparent, and easy to refine if additional data on change in generation or value to people become available. We believe that this approach will be useful to estimate historical ecosystem services in other regions in which there is limited historical data.

Our analysis revealed that although the generation of cultivated ecosystem services has almost kept up with population growth or increased somewhat per capita, the potential to generate other provisioning ecosystem services has substantially declined. Fields cover between 46% and 78% of village area and grazing areas are increasingly scarce. Historical analysis indicates that there is little potential for further expansion of cultivated area or grazed area. Although yields have increased, future intensification is limited by lack of access to reliable and sustained access to water from percolation and storage of surface water through natural or artificial structures, lack of access to manure and fertilizers, and yield reductions due to climate change. Alternatives for some non-cultivated ecosystem services like medicine and construction material are becoming increasingly available. However, there are currently limited alternatives for other ecosystem services. Today, the majority of Burkina Faso's population depends on wood for cooking. Furthermore, there are no alternatives to compensate for the declining availability of nutritious wild foods. The ecosystem services provided by trees and shrubs on fields do not have accessible alternatives, therefore trees and shrubs should be preserved in landscape interventions.

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/13292

Acknowledgments:

This work was conducted within the project "Adapting to changing climate in drylands: The re-greening in Sahel as a potential success case" funded by research grants from Sida (SWE-2008-148) and Vetenskapsrådet (SWE-2012-115), and with core funding to the Stockholm Resilience Centre from Mistra (The Swedish Foundation For Strategic Environmental Research). The work of the fourth author was funded by Ebba och Sven Schwartz Stiftelse. We would like to thank the population of the villages for welcoming us and for participating in the research, as well as the field assistant Desiré R. Kaboré. Thanks to Korodjouma Ouattara and Issa Ouedraogo at INERA in Burkina Faso for support during the fieldwork.

Data Availability:

The data/code that support the findings of this study are openly available in figshare at https://doi.org/10.17045/sthlmuni.19144616.v1; https://doi.org/10.17045/sthlmuni.17032511.v1; https://doi.org/10.17045/sthlmuni.17032724.v1.

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Appendix 1 Attribution of values for ecosystem services to each social-ecological patch

Social-ecological patches generate distinct but overlapping sets of provisioning ecosystem services used directly by the local population for multiple benefits (Fig. A1.1). The attribution of values for ecosystem services to each social-ecological patch builds on previous in-depth fieldwork (Sinare et al., 2016) that captured local knowledge on distribution of key ecosystem services using a diverse set of participatory research methods. The relative importance of each social-ecological patch for each provisioning ecosystem service was assessed using matrix scoring in 36 focus groups. Scores represented the relative contribution per unit area of each social-ecological patch to each of the provisioning ecosystem services and were normalized to 100, so that for each ecosystem service, the contribution of all social-ecological patches sum up to 100.

In this paper we used the scores to develop the simple model for backwards extrapolation (Fig. A1.2), and for that purpose we modified the matrix of ecosystem service production by social-ecological patches created by Sinare et al. (2016), in three major ways. First, because fallow cannot be distinguished from other patches on aerial photographs, the category of fallow was removed. The scores for the remaining social-ecological patch categories were adjusted so that their relative importance for each ecosystem service stayed the same, while still normalizing to 100. Second, in response to feedback in focus groups in January 2016, we adjusted the scores for relative productivity of annual crops so that homesteads generated double the production of fields, and depression 1.66 times the productivity of fields. Villagers argued that homesteads have in general more intensive management (including more nutrient inputs). Depressions have better soils and higher water availability, also maintaining a higher yield in drier years. Finally, since there are no woodlands among the current social-ecological patches, but these were identified in the past, we had to estimate what ecosystem services woodlands produce. We assumed that woodlands produce the same amount of ecosystem services as fields for ecosystem services from woody vegetation, but provide no contribution to cultivated ecosystem services, as woodland has similar cover of woody vegetation as fields, but are not cultivated. As forest only covers < 5% of the village surface and was pooled with shrubland in Sinare et al. (2016), forest has no scores in the analysis. Most forest patches are sacred and do not contribute provisioning ecosystem services, while non-sacred forest is similar to dense shrubland. Forests have strong cultural meaning, and would have had values if cultural and regulating ecosystem services were included in the analysis.

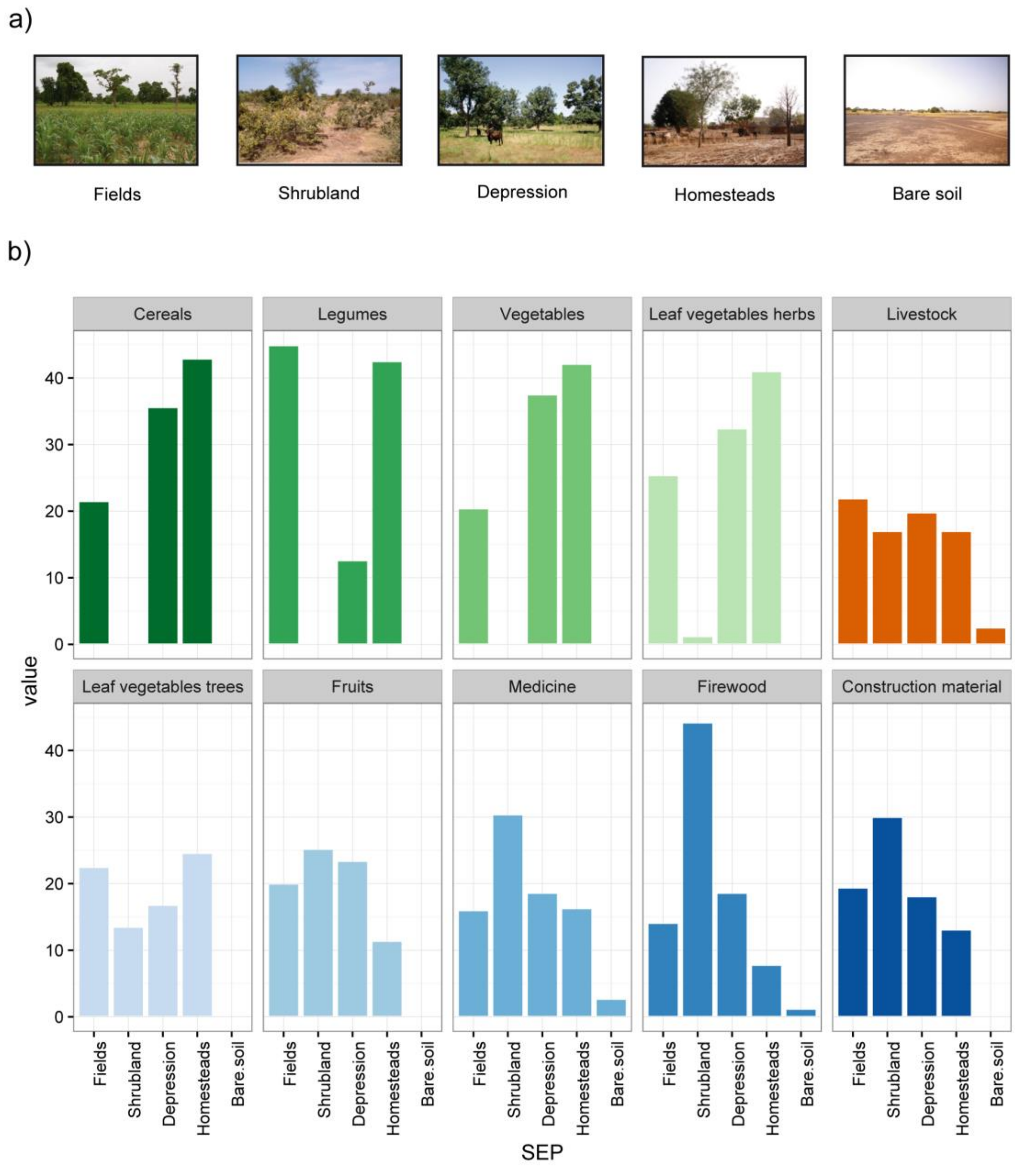

Fig. A1.1 a) Photographs of social-ecological patches today, and b) their related sets of ecosystem services adjusted from Sinare et al. (2016). Values indicate the relative contribution per unit area of each social-ecological patch to that ecosystem service, and is normalized to 100 for each ecosystem service

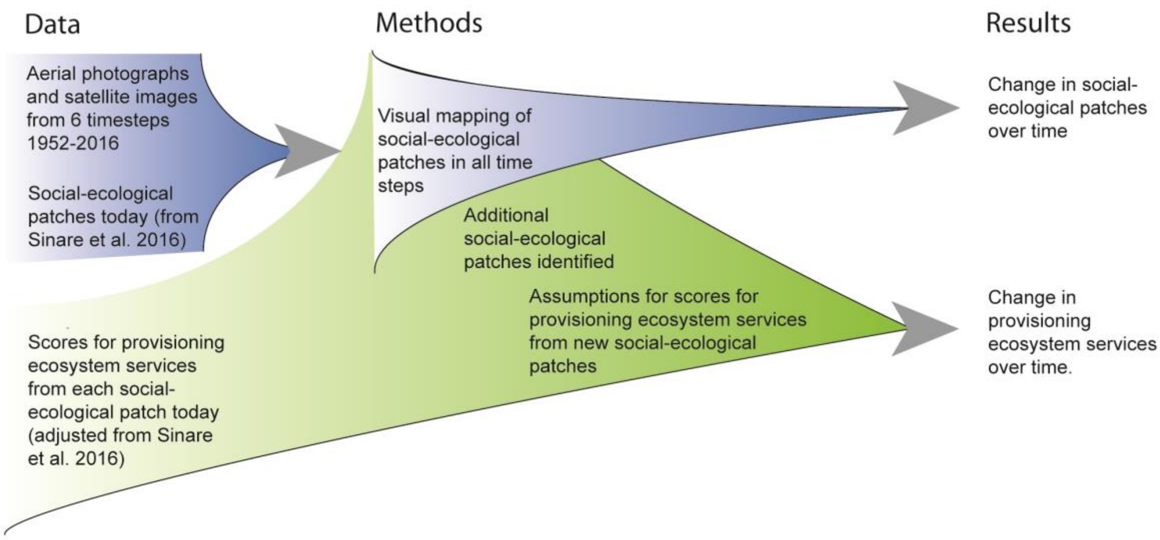

Fig. A1.2 Schematic illustration of data and methods used to identify change in social-ecological patches and change in provisioning ecosystem services over time