Landscape management strategies for multifunctionality and social equity

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Abstract

Increasing pressure on land resources necessitates landscape management strategies that simultaneously deliver multiple benefits to numerous stakeholder groups with competing interests. Accordingly, we developed an approach that combines ecological data on all types of ecosystem services with information describing the ecosystem service priorities of multiple stakeholder groups. We identified landscape scenarios that maximise overall ecosystem service supply relative to demand (multifunctionality) for the whole stakeholder community, while maintaining equitable distribution of ecosystem benefits across groups. For rural Germany, we show that the current landscape composition is close to optimal, and that most scenarios which maximise one or a few services increase inequities. This indicates that most major land use changes proposed for Europe (e.g. large-scale tree planting or agricultural intensification) could lead to social conflicts and reduced multifunctionality. However, moderate gains in multifunctionality (4%) and equity (1%) can be achieved by expanding and diversifying forests and de-intensifying grasslands. More broadly, our approach provides a tool for quantifying the social impact of land-use changes, and could be applied widely to identify sustainable land-use transformations.

Main text

Introduction

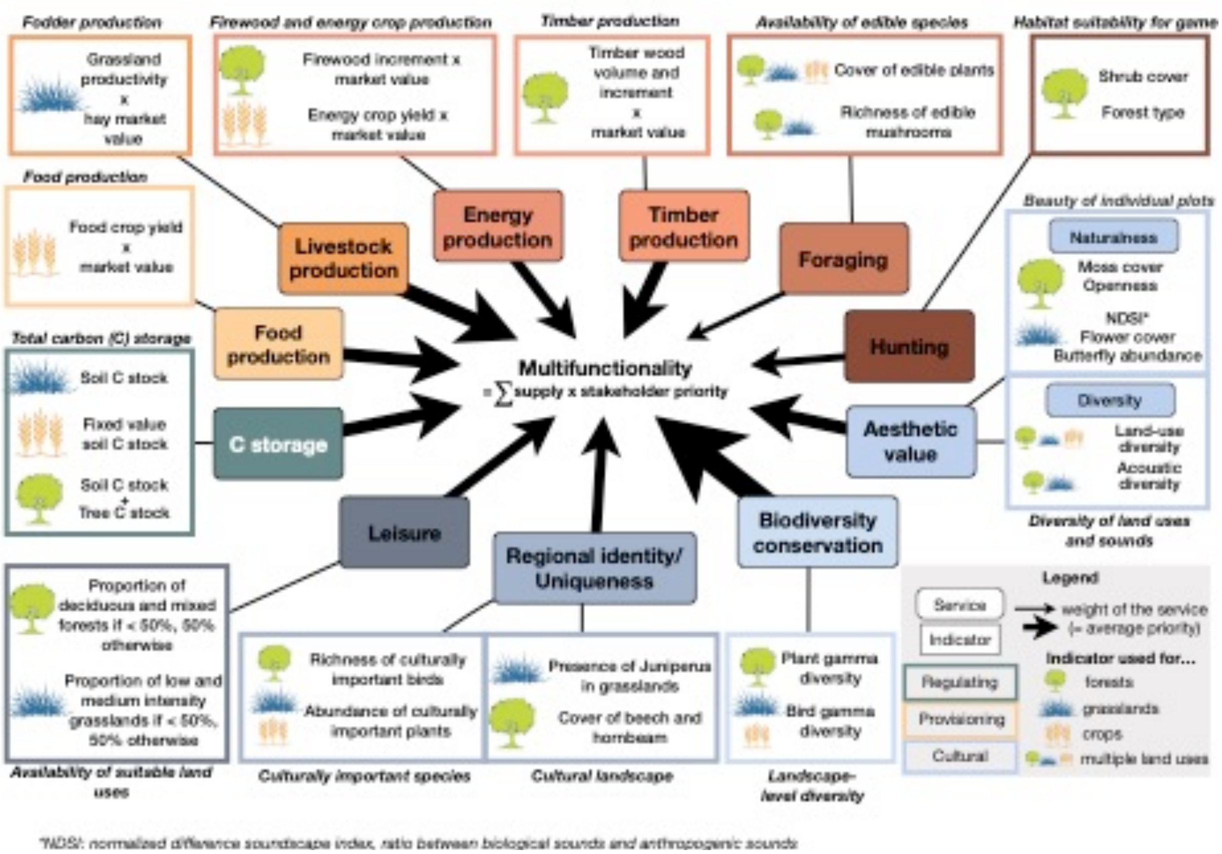
Growing demand for ecosystem goods and services throughout the globe is placing increased pressure on land resources to provide multiple benefits, simultaneously and at high levels[1,2]. These changing demands have also resulted in major shifts in land use which, by altering the balance of ecosystem services provided, can lead to conflicts between stakeholder groups. Conflicts often emerge because land-use changes typically promote only a few ecosystem services[3], often provisioning services. However, due to biophysical trade-offs among services[4], this often comes at the expense of other services, including the protection of biodiversity[5]. Because stakeholder groups differ in their demands, these changes result in ‘winners’, ‘losers’ and inequities regarding distribution and access[6,7].

To understand how landscapes can be managed to best supply multiple ecosystem services and to minimize conflicts between land users, a range of modelling approaches have been applied[8–12]. These typically focus on the impact of land-use changes on ecosystem service supply, but without quantifying their impact on stakeholders. Meanwhile, assessment of the societal impact of land-use change has been largely conducted within social-ecological and landscape management research, via interviews, scenario workshops or surveys[13,14].While insightful, these assessments rarely provide quantitative outputs that can be used in decision making, e.g. specific land-use proportions which minimise conflicts (but see [15]). Clearly, quantitative tools are needed that can guide decision making and help structure the participatory approaches that aim to resolve such conflicts[16]. Such quantitative tools should consider both the supply of ecosystem services, but also the equity of this supply across society, as equity in the access, supply and management of ecosystem services is increasingly recognized as an essential aspect of successful and sustainable land management[17].

Recently, interest in quantifying the supply of multiple ecosystem services has led to the development of multifunctionality metrics[18,19]. One of these metrics, ecosystem service multifunctionality (hereafter multifunctionality), quantifies the simultaneous supply of multiple ecosystem services, relative to their human demand[9,20]. It advances previous approaches, such as the identification of supply and demand bundles[21], by combining biophysical indicators of ecosystem service supply with measures of demand for multiple stakeholder groups. While economic valuation approaches often ignore or underestimate the importance of cultural ecosystem services[22], with the risk of overlooking resulting trade-offs, the multifunctionality approach values services based on their relative priority to stakeholders. This use of standardised priority scores helps overcome some of the difficulties of integrating material and non-material values within a single metric[23]. Also, as multifunctionality scores contain measures of the supply of all prioritised services the overall impact of changes in ecosystem service supply on stakeholder groups can be assessed, as can the equity of this supply across society.

In this study, we compare multifunctionality scores among stakeholder groups to assess both i) the overall impact of land use strategies on a stakeholder community, and ii) how changes to ecosystem service supply affect social equity. As our measure of equity, we focus on distribution equity, defined as the equitable access of multiple stakeholder groups to ecosystem service supply[17], which we measure as the homogeneity of multifunctionality across groups. Hereafter, for simplicity, we refer to this as equity. Our assessment was conducted using data from three regions of rural Germany in which we quantified the societal impacts of landscape change by simulating changes in the proportion of land-use types and measuring their impact on multifunctionality and equity. We base our metrics of multifunctionality on the eleven terrestrial services that are most prioritized by local stakeholders in these regions[24] (Figure 1). All of these are directly linked to final benefits (*sensu* the cascade model[25]). The supply measure of each service was based on multiple indicators collected at 150 forest and 150 grassland sites that vary greatly in their management, located in three German regions[26]. These were augmented by literature-based estimates of arable cropland services. In addition, data on ecosystem service priorities was collected from 321 respondents belonging to 14 stakeholder groups in a social survey in the same regions[24]. To assess the impact of landscape composition on ecosystem service supply, we assembled artificial landscapes with varying proportions of grasslands, forests and different management types within them, by randomly picking plots of each considered land use and management type, and then measured their aggregated ecosystem service supply. Standardized ecosystem service supply values were multiplied by stakeholder priority scores to give multifunctionality values for each stakeholder group. The resulting multifunctionality and equity scores were then compared to the baseline landscape, i.e. the current landscape composition, averaged across the three study regions, to identify land-use strategies that are broadly applicable to rural Germany.

Figure 1. Eleven ecosystem services included in the multifunctionality metric and their indicators. Symbols indicate the land-use types that provide each service (forests, grasslands, croplands). Arrow widths pointing to multifunctionality are proportional to the mean priority score given to the service across all stakeholder groups. Multifunctionality is calculated as the sum of the standardised landscape-level supply of each service, weighted by stakeholder priority, as measured in a social survey[24]. Yellow-to-brown colours, shades of blue, and teal are used throughout the manuscript to represent provisioning, cultural and regulating services, respectively.



Results

Current landscape is close to optimum

First, we explored the societal impact of >6000 landscape scenarios, that cover the full range of landscape compositions (see methods), by varying the proportions of forests and grasslands under different managements, and measuring the multifunctionality and equity of each landscape. Arable crop cover was kept constant primarily due to limited data on cropland ecosystem services, but also because it is likely to be affected by drivers external to the local community, such as national and global food consumption (see supplementary information). This scenario ensemble revealed that the baseline landscape composition is close to optimum, in that

87% of possible landscape compositions had either a lower community-level multifunctionality (calculated as average multifunctionality across groups) or equity score, or both, than the baseline composition (Figure 2b, c) and only 13% improved both, with potential gains marginal compared to potential losses (few scenarios in the high multifunctionality-high equity area i.e. blue top-right corner, Figure 2a).

Services contribution to baseline multifunctionality

The failure of most potential landscape compositions to improve multifunctionality and equity relative to the baseline landscape, can be understood by examining the multifunctionality scores of each stakeholder group and the relative contribution of different services to these. The baseline landscape composition is composed on average of 38% cropland, 20% grassland and 42% forest (Figure 3a), and was thus close to the national average (relative proportions of 43%, 21%, and 37% respectively, based national-level Corine land cover data). This baseline landscape provides moderate to high levels of most ecosystem services. This results in relatively similar and high multifunctionality levels across stakeholder groups (Figure 3f). Because most stakeholder groups prioritised a wide range of services, and due to inherent synchronies and trade-offs among services (Figure S 3), current supply meets the demand of all groups approximately equally well, with overall multifunctionality ranging between 0.5 and 0.55 between stakeholder groups, where 1 means that all prioritised services are provided at the maximum level (Figure 3f). Despite this, the relative contribution of different services to the multifunctionality of each group differed significantly. For example, more than half of the multifunctionality of the tourism, nature conservation and economic sectors is related to cultural services, while the overall demand of landowners and the agricultural and forestry sectors is mostly met through provisioning services (Figure 3f).

Specific land-use change scenarios

Within society, there are numerous calls for land-use strategies to meet specific goals including greatly increased area dedicated to biodiversity conservation, e.g. 'half earth'[27], large-scale tree planting to mitigate climate change[28], increased local food production to support food security[29,30], and the application of agri-environmental schemes that will de-intensify landscapes[31,32]. These strategies are widely debated and often controversial[33]. To gain a more detailed understanding of how such land-use strategies would affect the stakeholder community, we explored several specific land-use change scenarios (detailed in Table S9). All scenarios involving deforestation (see scenario 1 in Figure 2b,c), forest homogenisation (scenario 2-4, 7) or grassland intensification (scenario 5,6) decreased community multifunctionality, and were often also associated with a decrease in equity (Figure 2b,c). However, some scenarios led to marginal increases in both multifunctionality and equity (e.g. scenarios 8 to 10). In these, there was usually moderate conversion of grasslands to forests, with multifunctionality and equity increasing gradually from a current forest cover of 42% up to about 47% before steadily decreasing beyond this point (Extended Data Figure 1). This increase in multifunctionality was likely due to some services being predominantly or exclusively provided by forests, e.g. hunting and timber production (Figure S1). Unsurprisingly, increased forest cover increases multifunctionality for groups that favour forest services, e.g. hunters and foresters. As these groups currently have relatively low multifunctionality scores (Figure 3f), afforestation simultaneously increases equity.

Figure 2. Characterisation of optimal landscape composition. (a) Conceptual representation and (b, c) empirical estimation in simulated German landscapes. (a) Optimal landscape compositions (blue area) have both higher multifunctionality (overall ecosystem service supply) and higher equity (measured as equitable access to ecosystem services) than the baseline (i.e. current) landscape composition. The size of the stakeholder icons represents the landscape multifunctionality for a given stakeholder group. (b) Change in multifunctionality (x-axis) and equity (y-axis) compared to the baseline landscape composition in predefined scenarios of land-use change (large coloured dots: each dot shows the average of all landscape compositions that fit the criteria (e.g. 50% less forest than the baseline; numbered for reference in the text)) and in all possible simulated landscape compositions (small black dots; each shows the mean of 200 replicates for each composition). Clusters of highlighted dots and corresponding shaded polygons show the landscape compositions which were used to calculate the results shown in Figure 3 and Figure 4. (c) Subset of b) for highest-scoring landscapes. For description of the full range of scenarios and their associated changes in multifunctionality and equity see Extended Data Figure 4 and Table S9.

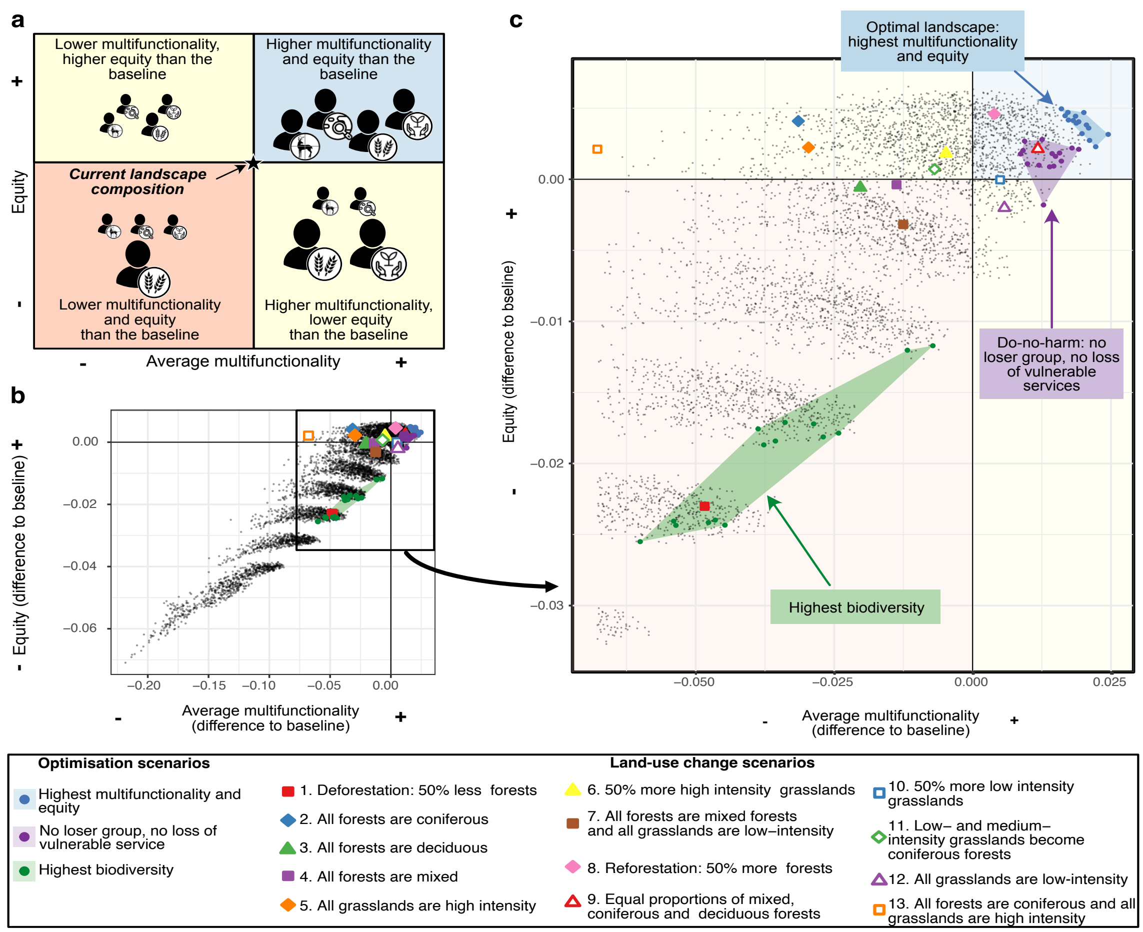
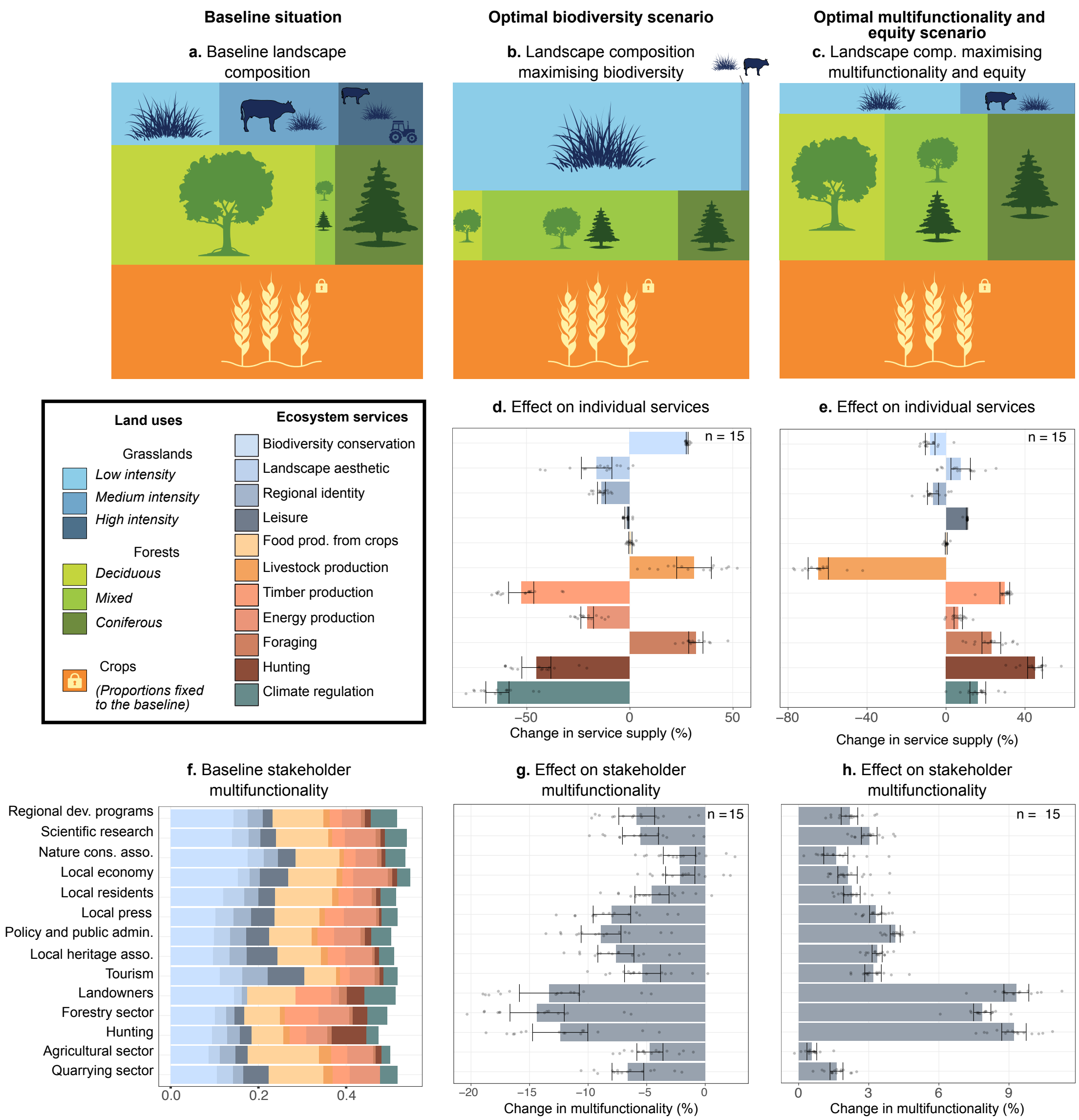


Figure 3. The impact of land-use changes on ecosystem service supply and multifunctionality relative to the baseline (current) landscape composition. The impact of three contrasting land-use change scenarios is shown. (a-c) Landscape composition under selected scenarios. The area of each land use in (a-c) is proportional to its area in the considered scenario. (d-e) Average difference in the supply of each service compared to baseline landscape composition, as percentage of current supply. (f) Relative contribution of each service (current service supply × stakeholder group priority) to total multifunctionality (total bar height) for each stakeholder group in the baseline landscape. (g-h) Average difference in multifunctionality for each stakeholder group compared to the baseline landscape, as percentage of baseline multifunctionality. Data in d-e and g-h are presented as mean and 95% confidence intervals, calculated on n = 15 landscape compositions, each averaged across 200 replicated simulations.



Impact of optimising landscapes for individual services

As certain land-use strategies aim to maximise the supply of specific services, such as carbon storage or biodiversity conservation[27,34,35], we also explored the impact that maximising a landscape for a particular ecosystem service would have on the provision of other ecosystem services and the stakeholder community. This was done first for biodiversity conservation. We identified the 15 landscape compositions with highest biodiversity scores, calculated their average proportions of land uses, and also the changes in ecosystem service supply, multifunctionality and equity relative to the baseline landscape. High biodiversity landscapes increased low-intensity grassland area while reducing forest and intensive grassland cover compared to the baseline landscape (Figure 3b). This sharply decreased the supply of all ecosystem services, except livestock production and foraging (Figure 3d), and in turn reduced multifunctionality for all groups (Figure 3g) and led to community inequity (highlighted in green in Figure 2b,c) compared to the baseline landscape. We also investigated the impact of optimising a landscape for carbon storage, by identifying the landscape composition in which this was highest, using the same method. This carbon-rich landscape composition was forest-dominated (only 1% grasslands on average), and had low levels of many services, including livestock production, biodiversity conservation, aesthetic value and foraging, and led to low community-level multifunctionality and high inequity (11 groups out of 14 significantly losing multifunctionality, Extended Data Figure 2). These results indicate that any land-use strategy that prioritises a single service without considering the diversity of land-user demands could have severe impacts on other services[36] and as a result on the whole community, potentially increasing conflict between stakeholder groups.

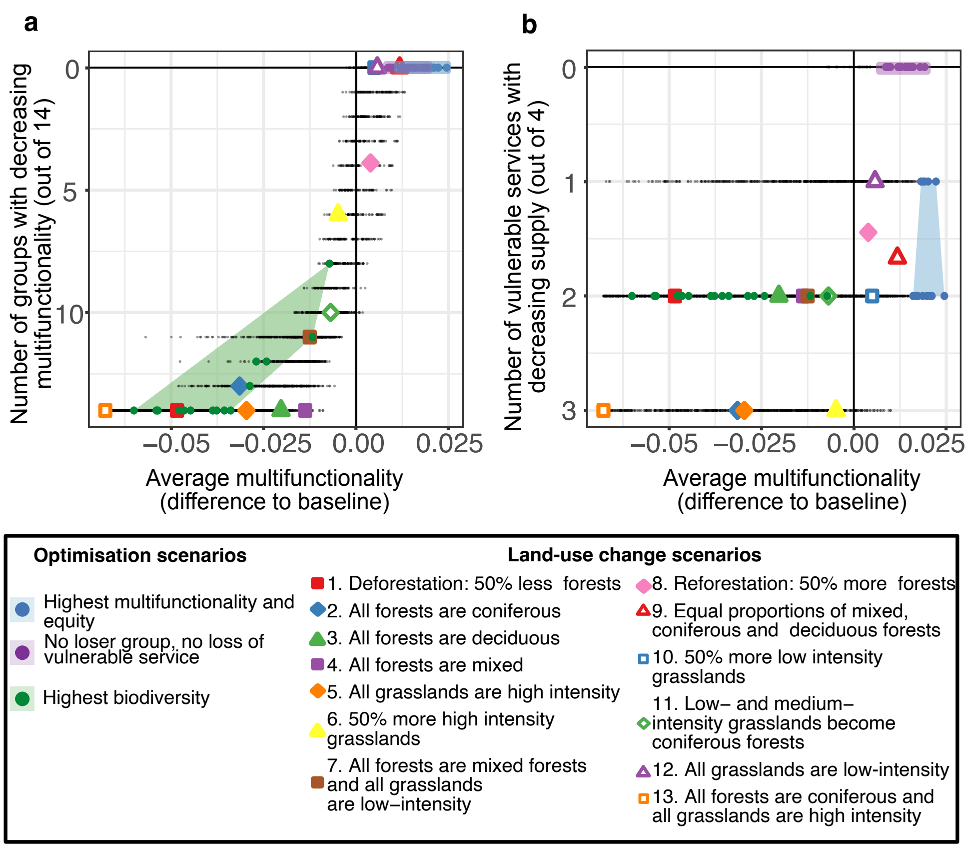
Optimising land use for entire stakeholder communities

In further analyses we identified the optimum landscape composition, i.e. that which delivers the highest possible community-level multifunctionality and equity. To do so, we selected the 15 landscape compositions which simultaneously maximised both equity and multifunctionality and averaged their compositions (highlighted in blue in Figure 2b,c). Relative to current conditions these landscapes are characterised by grassland extensification, an increase in the proportion of forests by approximately 10% and increased proportions of mixed forests (Figure 3c). These changes would increase the supply of most services (except biodiversity conservation, aesthetic value and livestock production, Figure 3e), leading to increases in multifunctionality for all stakeholder of up to 9% for individual groups, and 3.7% on average (Figure 3h).

'Do-no-harm' scenario

Although certain landscape compositions are optimal for community multifunctionality and equity, their adoption could lead to decreases in the supply of already vulnerable services, such as biodiversity conservation, and in decreased multifunctionality for particular stakeholder groups. To address these issues, we further identified a 'do-no-harm' scenario, in which no stakeholder group loses multifunctionality, and which would cause no loss of vulnerable services (purple area in Fig. 2b, c and 4). Vulnerable services were identified during the stakeholder survey, as those whose supply was deemed “threatened” or “insufficient” by most (>65%) stakeholders, namely: biodiversity conservation, foraging, climate-change mitigation, and regional identity. We then identified landscape compositions in which the supply of those services and the multifunctionality for all groups was at least as high as in the baseline landscape (i.e. 0 groups losing multifunctionality, Figure 4a, and 0 vulnerable services with decreased supply, Figure 4b). The landscape composition identified was consistent with the optimal scenario, in that it involved increased forest cover and grassland extensification, although with more moderate changes. It led to small but still significant multifunctionality gains of up to 5.6% (2.6% on average, Extended Data Figure 3).

Figure 4. Identification of ‘do-no-harm’ landscape compositions in which (a) no group sees a reduction in multifunctionality and (b) no ecosystem services deemed vulnerable (biodiversity conservation, foraging, climate-change mitigation, and regional identity) are lost. In both cases, the ‘optimal’ landscape composition, if present, would be in the top right corner. Change in multifunctionality (x-axis) and number of losing groups or services (y-axis) are shown compared to the baseline (current) landscape composition, in predefined scenarios of land-use change (large coloured dots) and in all simulated landscape compositions (small black dots; each represents the mean of 200 replicates for the given composition). Coloured dots and corresponding shaded polygons show the position of the ‘optimal’ landscape compositions which were used to calculate the results shown in Figure 3. For presentation, only a subset of landscape compositions is shown, the rest extending beyond the bottom left corner of the plot (see Extended Data Figure 4 for the full range).



Finally, to assess the sensitivity of our results to a range of factors, additional sensitivity analyses were conducted. The results were not sensitive to the weighting of equity and multifunctionality by stakeholder groups' perceived power (Figure S 8, Figure S 9), or correction for environmental covariates (Figure S 10, Figure S 11). Classification of forests into even- or uneven-aged forests, instead of by tree type, did not change the finding that increased forest cover and grassland extensification was the optimal scenario (Figure S 12, Figure S 13). The introduction of service-specific 'supply-benefit' relationships (Figure S 14, Figure S 15), or changes in cropland cover changed the optimal land use proportions (Figure S 16, Figure S 17), but optimum in these cases also involved increased forest and cover and grassland deintensification. Region-specific optimisation (Figure S 18 to Figure S 23) showed that the outcomes of land use change scenarios were partly dependent on regional specificities. For instance, optimising for biodiversity in the Central region could be achieved via a more moderate increase in grassland cover than in other regions, and so led to concurrent increases in landscape aesthetic and foraging values.

Discussion

By combining natural and social science data with a landscape simulation approach, we show that the baseline landscape composition of our German study regions is close to optimal with respect to both the overall supply of demanded ecosystem services (multifunctionality) and equity. While small increases in these properties are achievable with deintensification, most land-use change scenarios would reduce community-wide ecosystem service supply and lead to unequal service provision, potentially triggering conflicts between stakeholder groups. As our baseline was close to the national average, demand patterns do not differ between regions[24], and the three regions are broadly representative of north, central and southern Germany[26], we expect our results to be broadly applicable for rural Germany.

The fact that the baseline landscape is close to optimal may reflect the history of the study regions and the policy and governance within them. Governance in all three regions has historically aimed to balance the conservation of biodiversity with support for a diverse local economy that includes tourism, forestry and agriculture. This may explain the breadth of services requested by all groups, who are aware of the need for multiple services and might mediate their priorities to acknowledge those of others[24]. This is furthered in two of the regions, Schwäbische Alb and Schorfheide-Chorin by their designation as UNESCO Biosphere Reserves, which aim "to balance human responsibility for maintaining nature and the human need to use natural resources to enhance social and economic well-being"[37]. The studied regions are also cultural landscapes[38] that have been shaped by centuries of interactions between humans and nature. Thus, we hypothesise that people living in these areas have shaped the landscape to meet their needs, while also adapting their demand to what these managed ecosystems supply. This coevolution process is also constrained by biophysical factors that might limit the expansion of some land uses as well as external drivers such as national policies. We hypothesise that very different results will be found in areas where rapid changes in land use have occurred recently, as this leads to a mismatch between demand and supply for most stakeholder groups[9]. Also, in systems where demand is more polarised, it may be more difficult to find an optimum in which all groups are supplied with their demanded ecosystem services (e.g. [9]).

The finding that most major land-use changes will lead to inequalities in ecosystem service supply to the stakeholder community is an important one, as it provides quantitative evidence that landscape planning that focuses on one or few selected services can be detrimental to rural communities. Indeed, while previous studies have shown that focusing on biodiversity can maximise several other services[39] these studies mostly focused on cultural and regulating services, without considering their relative importance to stakeholders. By including all terrestrial final benefits valued by local stakeholders, and by weighting their relative priority to stakeholders a more complete picture emerges. These results demonstrate that while large-scale strategies to protect biodiversity and increase carbon storage are clearly needed[1], these must carefully account for the existing needs of the local communities[40]. For large-scale land-use changes to be acceptable, in our study regions at least, there are only two solutions. First, the supply of ecosystem services on existing land must be increased, e.g. via the development of innovative land-use options that allow for higher-than-current agricultural production, or a restoration to higher local biodiversity levels than are currently observed. The other, and less explored, alternative is to alter priorities and demand[13]. In our study, stakeholders prioritised a wide range of services. If priorities and demand shifted, e.g. due to changes in awareness, consumption patterns, or policies (subsidies or payments for ecosystem services), then land-use changes may be implemented without loss of multifunctionality or equity. For instance, a shift towards a higher priority for cultural compared to provisioning services would allow a deintensification or ‘nature first’ strategy to become more acceptable. While the management and alteration of societal demand presents significant challenges, we propose that it may be more successful in finding sustainable land strategies than finding optimal land-use transformations, especially where biophysical trade-offs in ecosystem service supply limit ecosystem service co-supply[8,41].

Although large increases in multifunctionality and equity were not possible under current levels of supply and demand, our results indicate that deintensification of land use could offer moderate benefits to local communities. The scenarios that outperformed the baseline landscape composition had two main characteristics: an increase in forest cover, associated with an increase in the proportion of mixed forests; and a simultaneous extensification of grasslands. Our results indicated that moderate afforestation, especially with mixed forests[42], which is one of the major land-use trends in Germany[43], could provide many benefits to local communities. This finding also corresponds to the identification of forests as multifunctional hotspots in other European landscapes[13]. In this regard, our ‘optimal’ deintensification scenario is consistent with the objectives of both EU and national policies which aim to decrease land-use intensity and increase forest cover (EU Biodiversity Strategy, Green Deal, new EU Forest Strategy; Federal level: National Biodiversity Strategy, Action Programme Insect Protection, Bund-Länder-Gemeinschaftsaufgabe Agrarstruktur und Küstenschutz (GAK), Forest Strategy 2050). Such changes would reduce livestock production and grassland biodiversity, but this would be compensated by gains in most other services (i.e. a “small loss, big gain” situation[12]), though clearly certain stakeholder groups would gain more than others. However, while this scenario is optimal at the level of local communities, the loss of livestock production could have external impacts in a globalised world.

For example, if demand for food remained constant, deintensification in Europe could lead to agricultural expansion and biodiversity loss in other areas of the world[44].

The modelling approach employed here allowed us to investigate the impact of a wide range of landscape composition changes on both the supply of ecosystem services, and the stakeholder communities who use these services. This is achieved by integrating supply and demand data for more services than are usually included - meaning all the trade-offs are better represented and the picture more complete, as we include non-material benefits that are not captured by monetary valuation approaches[22]. Because stakeholder groups prioritise multiple, but different, ecosystem services[13,24], such a comprehensive approach is important if we are to understand the direct implications of landscape strategies for the well-being of stakeholder communities[45] and the causes of rural conflicts.

While powerful, and potentially applicable to a wide range of social-ecological systems, some aspects that would refine model predictions are missing from our current approach. First, the inclusion of ecosystem services from a wider range of land-use types, including unmanaged land, urban and peri-urban areas and water bodies would better represent the services provided by a landscape, including water-based services. In particular, croplands (whose area was large but fixed here due to lack of reliable data) provide important services and should be more accurately characterised in future studies. Second, the simple equity measure used here could be expanded upon by accounting for the population size of the different groups, their degree of dependency on the considered services, or other factors deemed important by policy-makers. Third, the current model allows investigation of the effect of a landscape's composition on multifunctionality, but not its configuration. Future models should aim to integrate aspects of landscape configuration, as they are known to affect ecosystem service supply[46]. This means that spatial interactions between landscape units, e.g. the runoff of agricultural pollutants and the movement of matter or organisms across the landscape[47] should be accounted for[48]. Further, we recommend the inclusion of local biophysical constraints into spatially-explicit models (e.g. limits on which soil types can support certain land uses) as well as 'path-dependency'- limits on converting one land use to another[49] (e.g. it is difficult to rapidly restore fertilised intensive grasslands to a species-rich state). These measures would ensure only realistic scenarios are considered. Our scenarios did not incorporate feasibility, and it is possible that the some of the land use change scenarios we explored may be challenging to implement. For example, large-scale grassland deintensification, which would require many years to implement due to nutrient retention[50]. Future models could also connect regional demand to global and interregional supply, for instance using telecoupling methods[44]. Finally, integration of long-term ecosystem dynamics, in both supply and demand would allow future studies to assess the sustainability of land-use strategies and the time lags before new outcomes are realised. On the demand side, the modelling of demographic changes, as well as changes in consumption patterns, e.g. a switch to more plant-based diets, could also be considered.

The approach presented here provides detailed information of the potential impact of land-use changes on local communities. However, because of the aforementioned uncertainties, and unrepresented complexity of the social system, we advise that it should viewed as a decision support tool that is best used to identify and plan land-use strategies within a participatory approach, though it may also be presented in the form of online tools[8]. Participatory approaches are increasingly seen as beneficial for assessing and discussing the choice and social impact of land-use change, one example being the 'landscape approach'[16], which aims to balance competing land-use priorities to promote environmental conservation and human well-being (e.g. the African Forest Landscape Restoration Initiative[51]). The quantitative tool presented here can also help government and corporate policy makers to assess strategies for improved land use, and identify means of implementing them, e.g. via agri-environment schemes that encourage different land-use types or land-use intensities within certain parts of the landscape[52].

By applying our approach at different spatial scales, it can provide different types of information and recommendation. For example, the approach adopted here, i.e. using results averaged across three regions that are broadly representative of rural Germany, can provide information that can inform national or regional-level guidelines and policies (e.g. to encourage moderate increases in forest cover, and grassland deintensification nationally). However, the best places in which to implement these strategies should be identified at the local level, where local conditions may require the modification of general guidelines[53]. For example, across our study regions, stakeholder demand is consistent[24] but initial land use proportions are very different and the relationship between land-use intensity and service supply also differs[8]. By tailoring and parameterising our model for local conditions our approach can be applied within specific regions to determine the optimal land use in these areas and prevent the application of land-use strategies that may be locally inappropriate (see Figure S 18 to Figure S 23).

At even larger scales, the approach presented here can potentially be used to explore the societal impacts of the major land use changes that are currently advocated, including large-scale tree planting[28] or half-earth[27] policies. While we note that reliable results are contingent on the availability of high-quality and region-specific supply and demand data, we also believe outputs of this approach can inform landscape-level decision-making. By doing so it can help identify land use strategies that are sustainable and equitable, and which can lead to more harmonious relationships between local stakeholders.

Methods

Ethics

Senckenberg Gesellschaft für Naturforschung employed the researchers who conducted the social survey in this study and its subsequent use. They did not have an ethics committee for social science research at the time when the data were collected. However, the standards and recommendations of the German Data Forum (2017)[54] were followed and employed. This includes that a written consent for the collection and processing of the anonymised personal survey data was obtained before starting the survey. Participation in the survey was voluntary. At any time, the participants were able to cancel the survey or withdraw their consent.

Field work permits were issued by the state environmental offices of Baden-Württemberg, Thüringen, and Brandenburg.

Study area

We used data from 150 grassland and 150 forest sites (hereafter plots) studied within the large-scale and long-term Biodiversity Exploratories project in Germany[26] (https://www.biodiversity-exploratories.de/). The plots are located in three regions including two hilly regions with calcareous bedrock: the UNESCO Biosphere Reserve Schwäbische Alb and its surroundings (South-West region), and the Hainich-Dün region comprising the National Park Hainich and its surroundings (Central region); and the flat area of the UNESCO Biosphere Reserve Schorfheide-Chorin with sandy and organic soils (North of Germany). Plots measured 50 m × 50 m for grasslands and 100 m × 100 m for forests and were selected to span the full range of land-use intensity in grassland and forest management within the regions, while minimising variation in potentially confounding environmental factors.

Population density ranges from 39 km^{-2} in Schorfheide-Chorin (Uckermark) to 106 km^{-2} in Hainich (Unstrut-Hainich-Kreis) and 262 km^{-2} in the Schwäbische Alb (Reutlingen County) (2017)[55–57]. All three regions are historically mostly agricultural with contrasting historical legacies, e.g. large-scale agriculture persists from the former German Democratic Republic era in the Schorfheide-Chorin and Hainich-Dün, while smaller farms of the former West Germany dominate in Schwäbische Alb. The population directly involved in the forestry and agricultural sectors have steadily declined in the past decades as the activities of other interest groups, e.g. tourists and nature conservation associations, have become more economically important.

Land-use

Grassland sites were classified according to a Land Use Intensity index (LUI) based on grazing, mowing and fertilisation intensity data collected annually from site owners using a questionnaire between 2008 and 2015[58]. These three land-use factors were summed after standardisation by their mean value across all three regions in the same period. LUI was then calculated as the square-root of the sum. We classified all grasslands as low-, medium- or high-intensity based on whether their LUI index (averaged over time) belonged to the 0-33%, 33-66% or 66-100% quantiles of all LUI indices[8].

While forests of all regions are dominated by European beech (*Fagus sylvatica*), Scots pine (*Pinus sylvestris*) and oak (*Quercus* spp.) are relatively common in Schorfheide-Chorin, and Norway spruce (*Picea abies*) in Schwäbische Alb[59]. Forest plots were classified as ‘deciduous’ or ‘coniferous’ if >80% of the basal area belonged to deciduous, or coniferous trees, or as ‘mixed’ otherwise.

Ecosystem services priority

We conducted one expert-workshop in each region in 2018, with representatives of some pre-selected stakeholder groups. These led to the identification of 14 stakeholder groups and a list of all terrestrial ecosystem services of importance to this community[24]. We restricted the list to services with direct links to final benefits (*sensu* the cascade model[25]), thus excluding regulating services (e.g. pollination) that underpin the supply of other services (e.g. food production) but do not provide direct benefits to humans. This prevents double counting of ecosystem service benefits in the multifunctionality metric. We also excluded water-based services and the production of energy from technology, which were outside the scope of this study[24]. The final list consisted of 11 ecosystem services (Figure 1).

Following the workshops, we conducted an online and postal survey across all 14 stakeholder groups in 2019 and received 321 responses. When respondents belonged to multiple stakeholder groups, they were asked to identify their main one and answer the survey as a representative of this group. In the survey, respondents were requested to distribute a maximum of 20 points across the eleven pre-identified services to quantify their personal priorities. The number of points given for each service was then normalised by the total number of points given by the respondent. Respondents were also requested to indicate whether they considered the supply of a service to be sufficient, barely sufficient, or insufficient, for services to which they assigned more than two points. Services for which 65% or more respondents (among those who attributed at least two points to the service) answered 'barely sufficient' or 'insufficient' were characterised as vulnerable: foraging (65%), regional identity (74%), carbon storage (88%) and biodiversity (89%). Details and socio-demographic data on this survey can be found in ref[24], and the relative priority scores of each group for the 11 services considered can be found in Figure S 2.

All participants took part in the workshops and the survey voluntarily. Their anonymity is guaranteed in all subsequent research steps. Participants could withdraw at any time and the traceability to individuals is made impossible by the data analysis, following the standards of [54].

Ecosystem service supply

In grasslands and forests, ecosystem service supply was quantified based on plot-level indicators collected in all plots between 2008 and 2015 (with actual year and measurement frequency depending on the service). For cropland, artificial 'plots' were created in which indicator values were derived from literature sources (see supplementary information). Plot-level indicators were then corrected for the environment (see below) and aggregated to the landscape level to quantify landscape-level service supply. Unless stated otherwise, the plot-level indicators were scaled between 0 and 1 and averaged to obtain ecosystem service supply (in some cases, indicators were not directly comparable across land uses and so were scaled between 0 and 1 within each land-use) and landscape-level service supply was calculated as the sum of plot-level supply values. Details on the measurement of each indicator can be found in the supplementary methods and in Table S 1.

Provisioning services included food, fodder, timber and energy production, as well as hunting and foraging opportunities. Cropland plots were randomly assigned a crop type based on the proportion of crop types in each region[60]. **Food production** was then quantified as the product of national yield averages and market values for each crop type[60] (Table S 2). We estimated **fodder production** in grasslands as the average grassland productivity (plant biomass collected in spring, and corrected for the number of cuts and livestock units – assuming that the full field biomass production is used by the owners[61] – multiplied by average hay market value in Germany (123€/ton[62])). Fodder production in croplands was quantified as crop yield (acquired from yearly biomass measurements and mowing and grazing data from farmer survey[58] – see supplementary methods) multiplied by market values, of the main crops used as fodder (e.g. alfalfa, silo maize) and square-transformed for further use. For **timber production**, indicators were the total wood volume and annual increment of all marketable species from selected european timber companies[63,64]. Increment and volume were then split into proportions of wood used respectively for timber, firewood, and energy wood based on national statistics[65], and then multiplied by each species' timber and energy wood market values in Germany. Timber production in grasslands and croplands was set to zero. **Energy production** was calculated in forests and croplands as the production of energy crops or firewood, respectively. Firewood production was calculated as the annual volume increment dedicated to firewood (see above) and multiplied by firewood market value. Energy crop value was calculated as described above. **Hunting** opportunity was estimated as the habitat suitability the landscape for the most commonly hunted species in Germany: wild boar and roe deer[66]. Both are generalist and adaptable species, so we used broad indicators representing the suitability of forest habitats (forest type, square-transformed shrub cover[67]) and the availability of other habitats (availability of cropland or grassland in the landscape). The landscape-level hunting service was averaged across both species. **Foraging** opportunity was quantified as the abundance of edible wild plant species (square-transformed) and the richness of edible mushrooms (species lists in Table S 6 and Table S 7). In both cases the most harvested species were double-weighted. The landscape-level supply was calculated as the sum of the total cover of edible plant species and the gamma-diversity of edible mushrooms across the landscape, both scaled between 0 and 1.

We considered only one **regulating service**, carbon storage. **Carbon storage** in grasslands was calculated as the total soil organic carbon stock in the 0-10 cm layer, which is the layer most responsive to management. In forests, total carbon storage was calculated as the sum of soil carbon stocks (0-10 cm layer) and the above-ground tree C stock. Crop plots were given fixed values for carbon stocks, corresponding to 72% of the regional average of C stocks in grasslands[68].

Cultural services included aesthetic value, biodiversity conservation, regional identity and recreational value. Indicators for cultural services were chosen based on existing literature and from semi-structured interviews with stakeholders conducted in the regions[24] (see supplementary methods). **Aesthetic value** was divided into two subcomponents: naturalness and diversity, in line with the landscape aesthetic quality framework[69,70]. In forests, naturalness was quantified based on equally weighted measures of bryophyte cover and forest openness[71]. In grasslands, naturalness was quantified from flower cover, butterfly abundance (both square-root-transformed) and the normalized difference soundscape index[72]. In both forests and grasslands, the diversity component was quantified from measures of plot-level acoustic diversity index and landscape-level land-use diversity (calculated as Shannon diversity of the land-use types). Crops were assigned the lowest observed score of grassland naturalness and acoustic diversity. **Biodiversity conservation** value was quantified as the sum of the gamma-diversity of birds and plant species at the landscape level (both scaled between 0 and 1 before). Plant species richness and abundance were recorded in annual botanical surveys of grassland and forest plots between 2009 and 2015. Bird species richness was based on annual point-count surveys in grassland and forest plots between 2008 and 2012. Artificial plant and bird communities were simulated for crops, based on known frequencies of the different species in German croplands[73,74] (see supplementary methods). **Regional identity** was considered to be related to the uniqueness of a given environment. For both grasslands and forests, it was quantified as the average of a plot-level 'historical or cultural habitat' score (grasslands with *Juniperus communis*; *Carpinus* and *Fagus* cover in forests), and a 'cultural species' score, based on the abundance (square-transformed) and richness of culturally important plants and birds (Supplementary Tables S4 and S5). As the area surveyed was different in forests and grasslands (Table S1), plant cover was not directly comparable across land uses, and was independently scaled in each land use. The **recreational/leisure value** of a landscape depends on large-scale factors such as infrastructure and accessibility, which couldn't be assessed within this study. However, European studies on recreational preference also identified site-level drivers, with visitors preferring natural, low-intensity open land and forests to anthropized land-uses[75] while also favouring land-use diversity[76]. Thus, the suitability of each landscape for outdoor activities was calculated as the proportion of low- and medium-intensity grasslands (saturating at 50%) plus the proportion of forests (also saturating at 50%): i.e., maximum suitability was reached for landscapes composed of 50% low and medium-intensity grasslands and 50% forests.

Landscape simulations

All steps of data preparation and analyses were conducted using R 4.2.1[77]. Landscape simulations were conducted using the Rust programming language[78], which provided a faster environment for data-intensive simulations. Simulations were run using data from all three regions simultaneously, which allowed us to identify general strategies that improve either one service or community-level multifunctionality, relative to the baseline landscape (average current landscape composition of the three regions).

In our landscape simulations, we initially considered landscape compositions spanning the whole range of landscape compositions (from 100% crops to 100% forests and 100% grasslands, with varying proportions of land management within grasslands and forests). These results can be found in Figure S 16 and Figure S 17; and we focus in the main text on a subset of combinations with a fixed proportion of crops corresponding to the baseline landscape composition (see below), corresponding to around 6000 possible landscape compositions (small black dots in Figure 2). For each of the considered landscape compositions, we simulated 200 artificial landscapes by randomly drawing, without repetition, the corresponding proportion of existing plots (out of a total of 20 plots) in each of the land-use categories. Landscape-scale services were then scaled between 0 and 1 by subtracting the minimum and dividing by the range (97.5% quantile to avoid the outliers, minus the minimum) across all landscapes. This scaling was required for the standardised weighting of each service within the multifunctionality metric (see below and Figure 1). Among the 6000 landscape compositions, we also identified a range of predefined land-use change scenarios (large coloured dots in Figure 2), such as increasing forest cover by 50% or converting all grasslands to high-intensity. A description of the scenarios is shown in Table S 9.

To characterise the baseline landscape composition, we averaged relative proportions of crops, grasslands and forests, as well as proportions of forest types (coniferous, deciduous or mixed), obtained from local CORINE land-use land-cover maps (Corine Land Cover (CLC) 2018; excluding settlement areas) across the three study regions. For comparison, we also calculated relative proportions of crops, grasslands and forests from German-level CLC maps. In order to estimate the current proportions of grassland intensity classes, we used grassland management data obtained in 1000 plots in each region in 2007. This data (estimates of grazing units, fertilisation, and cuts each year) was used to calculate an index similar to the LUI used for the 150 intensively studied grasslands. We then calibrated the LUI with this new index on all 150 intensively studied grasslands (correlation = 0.73, $p < 10^{-6}$), and used the LUI thresholds for low-, medium- and high-intensity classes to estimate the proportion of these 1000 plots that fell in each land-use intensity class.

Correction for environmental conditions and area

In order ensure that the observed variation in multifunctionality was due to differences in the land use and land management of landscapes, rather than other factors (e.g. differences in soil types), we conducted an environmental correction of all service indicators. Plot-level indicators (i.e. all except plant, bird and fungi diversities, land-use type diversity, and proportions of forests or low-intensity grasslands) were corrected at the plot level to account for environmental drivers of services unrelated to land use. This was done for all three regions at once but separately for forests and grasslands, by running linear models of each indicator with mean annual temperature, precipitation, soil pH, soil depth, topographic wetness index (a good proxy for soil humidity[79]) and soil texture (clay content) as the explanatory variables, using stepwise selection to select only relevant variables and avoid overfitting. The residuals were then extracted and added to the predicted mean of the variable to keep the data in the same range as the raw data, so that cross-land-use comparisons remained possible where applicable, before use in further analyses.

For plant diversity, the area sampled in forests was larger than that in grasslands (see Table S1). This meant that forest diversities were initially overestimated compared to grasslands, leading to incompatible plant diversities in landscapes composed of different sizes (i.e., the diversity sampling area in a landscape composed of 20 forest plots would comprise 20 x 400 m^2, while a landscape composed of 20 grassland plots would sample 20 x 16 m^2). To correct for this, we first modelled species-area curves by randomly drawing a variable number of forest and grassland plots and assigning size as the sum of sampled areas in all plots. The diversities of the landscapes simulated as described above were then corrected by the predicted diversity of a landscape of similar size, as per the species-area curve (Figure S 7).

Finally, bird and fungi diversities and area-corrected plant diversity were corrected using the same method as other services, but at the landscape level. Gamma diversities (area-corrected as described above for plants) were first calculated at the landscape level and then regressed on landscape conditions, using as explanatory variables the landscape mean of the aforementioned environmental variables, as well as landscape heterogeneity. Landscape heterogeneity was calculated as the volume of the convex hull of the selected sites in a PCA that included all environmental variables.

Landscape-level ecosystem multifunctionality and identification of optimal scenarios.

Ecosystem service multifunctionality is a measure of the simultaneous supply of multiple prioritized ecosystem services, relative to their human demand[9,20]. Here we use it to quantify how well the demand of a stakeholder group is met by the service supply. For each replicate landscape, multifunctionality was calculated for each stakeholder group as the average of the considered services, weighted by the group's priority scores.

We then identified optimal landscape compositions based on different sets of criteria (Table S 9):

- Optimisation of individual services: identification of landscape compositions which maximise one service
- Optimisation of multifunctionality and equity.
    - Community-level multifunctionality was calculated as the average of the stakeholder multifunctionality scores, weighted by the relative power of each group.
    - Community-level equity. We focus here on distribution equity[17] which we calculated as the negative index of the Gini index of multifunctionality values across groups, weighted by each group's power (ranging from -1, maximal inequity, to 0, perfect equity). The Gini index is a measure of statistical dispersion, which was initially designed as a measure of wealth inequality[80].

To identify the landscape composition which maximises these properties, we selected the 15 landscape compositions (each with 200 landscape replicates) that maximised the supply of the considered service, or the sum of equity and multifunctionality (both scaled and transformed to square-root beforehand). The number 15 was chosen to provide a sufficient range of the composition space, while also ensuring that the selection was restricted to only high-scoring landscapes.

- ‘Do-no-harm’ scenario: No loss of vulnerable service supply and no loser groups.
  - Groups were considered to lose multifunctionality if there was a significant decrease in their multifunctionality score compared to the baseline landscape, i.e. the upper limit of the confidence interval of the groups’ multifunctionality change in the new scenario compared to the baseline was under 0.
  - There was a loss in vulnerable services (see ‘Ecosystem service demand’) if there was a significant decrease in their supply compared to the baseline landscape, i.e. the upper limit of the confidence interval of the service-supply change in the new scenario compared to the baseline was under 0.

All landscape compositions that had both no group losing multifunctionality and no loss in vulnerable services were selected. If more than 15 fit these criteria, the 15 with highest multifunctionality were selected.

In both cases, we then calculated the average landscape composition (average proportion of each land-use type) across these landscapes, as well as the average change in service supply (from values scaled between 0 and 1) and group-specific multifunctionality, compared to the baseline landscape composition, by subtracting the average baseline value from the average composition value, divided by the average baseline value.

Data availability

This work is based on data collected by several projects of the Biodiversity Exploratories program (DFG Priority Program 1374). Most datasets are publicly available in the Biodiversity Exploratories Information System (http://doi.org/10.17616/R32P9Q). However, to give data owners and collectors time to perform their analyses the Biodiversity Exploratories' data and publication policy includes by default an embargo period of three years from the end of data collection/data assembly, which applies to the remaining datasets. These datasets will be made publicly available via the same data repository. All datasets and their current status (publicly available or not) are listed in Table S1 and corresponding references.

Code availability

The full code to replicate the analyses can be found on GitHub (DOI: 10.5281/zenodo.7019909, https://github.com/mneyret/landscape-equity).

All correspondence and requests should be addressed to Margot Neyret (margot.neyret@senckenberg.de); or when concerning a specific dataset to the data owners (see dataset references).

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Author contributions statement

M. N., S. P, G. L. P. and P. M. conceived the study, designed and performed the analyses. M. N., S. P, G. L. P. and P. M. wrote the manuscript with significant inputs from A. L. B, S. B., J. B., N. H., V. H. K, T. K., J. K., J. M., S. M., and contributions from all authors. Data were contributed by S. P., G. L. P., S. B., N. H., V. H. K., J. K., S. M., C. A., F.B., M. E., M. F., K. G., K. J., S. C. R., P. S., M. S-L., C. W., T. W., P. M. Authorship order was determined as follows: (1) core authors; (2) other major contributors (alphabetical); (3) other contributors incl. data contributors (alphabetical); (4) senior author.

Competing Interests Statement

The authors declare no competing interests.

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