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Supplementary Material

Supplementary Text: Detailed Description of Underlying Models

The Statistical Model

The statistical model was based on the database of the PREDICTS (Projecting Responses of Ecological Diversity in Changing Terrestrial Systems) Project (Hudson et al. 2017). These data describe the abundance (or for 17% of records only occurrence) of species sampled at different levels of human pressure (generally different land uses or land-use intensities), collated from numerous published sources (or unpublished sources with a published methodology). This model did not consider the effects of climate change. If sampling effort varied among the sites sampled within a source dataset, abundance values were corrected by assuming that recorded abundance increased linearly with increasing sampling effort (Newbold et al. 2014). Land use at each of the sites in the PREDICTS database was classified based on the description of the habitat, given in the source paper or provided by its authors (see Supplementary Table 1 for criteria). Land use was classified as primary vegetation, secondary vegetation, plantation forest, cropland, pasture or urban (Hudson et al. 2014). This land-use classification is coarse, but was selected so that the models could be generalized over large areas, and for correspondence with available land-use projections. Importantly for this study, pasture describes sites regularly or permanently grazed; sites with some grazing, but not sufficient to substantially alter the habitat architecture, were classified as primary or secondary vegetation (depending whether the natural habitat was destroyed historically). Sites where fire occurs at natural frequency were classified as primary vegetation. In order to understand the effects of small human disturbances – such as grazing or altered fire regimes – within natural (primary and secondary) habitat, we distinguished between minimally and substantially used natural vegetation. The latter incorporated the ‘light’ and ‘intensive’ use-intensity classifications adopted in the PREDICTS database (Hudson et al. 2014; Supplementary Table 1). The baseline for the models and projections – minimally used primary vegetation – does not preclude some human disturbances, of small extent or magnitude, and does not necessarily imply the potential climax vegetation (for example where grassland is maintained naturally through fire). This coarse abstraction of land use, and a degree of subjectivity in the classification, will mean that some potentially important details are lost (land-use classification is particularly challenging for grasslands); but this is necessary in order to develop broad-scale models.

We developed a model of sampled species richness and sampled total abundance, as a function of land use, using data from tropical grasslands and savannas in Africa. The initial filtering of data was done by overlaying the global data – extracted from the PREDICTS database on 29th September 2015 – onto a map of biomes (http://maps.tnc.org/). We then manually checked each dataset and excluded studies from biomes other than grassland and savanna. The resulting data comprised 170,878 records, for 1,830 uniquely named taxa, from 922 sites. The sites were distributed patchily, but showed a reasonable representation of land uses (Supplementary Figure 2). We fitted generalized linear mixed-effects models with land use as a single categorical fixed effect, and random effects representing the identity of the source study – to capture the wide heterogeneity in sampled taxa, sampling methods and sampling effort among studies – and the spatial blocking structure of sampled sites within each study. Within-sample species richness was modelled using a generalised linear mixed-effects model with a Poisson error distribution. In this model we included an additional observation-level (i.e. site-level) random intercept to control for overdispersion (Rigby et al. 2008). Within-sample total abundance was log transformed and modelled using a linear mixed-effects model (many abundance measurements were non-integers). To assess whether biodiversity in tropical grassland biomes is responding to land use differently to biodiversity globally, we also developed models using the global data across all biomes (2.8 million records, for over 45,000 uniquely named taxa, from 17,064 sites; Supplementary Figure 2). The global models of sampled species richness and total abundance had exactly the same structure as the models for the tropical grassy biomes.

To project the models of species richness and total abundance onto estimates of current and future land-use patterns, we followed the methods in Newbold et al. (2015). Mapped estimates of land use were taken from the harmonized land-use data associated with the Representative Concentration Pathways scenarios (Hurtt et al. 2011). These data describe the proportion of each half-degree grid cell occupied by the six above-named land-use classes. The model-estimated intactness of biodiversity in each land use was applied, and then values averaged across the land uses in each grid cell, weighted by proportional area. We used land-use estimates for 2005 from the HYDE land-use reconstruction (see ‘Land-use Scenarios’, in the main text, for more details), and for 2095 under the MESSAGE and MINICAM Representative Concentration Pathways scenarios of future change in human populations and socio-economic systems (Hurtt et al. 2011). For more details, see ‘Land-use Scenarios’ in the main text.

The Mechanistic Ecosystem Model

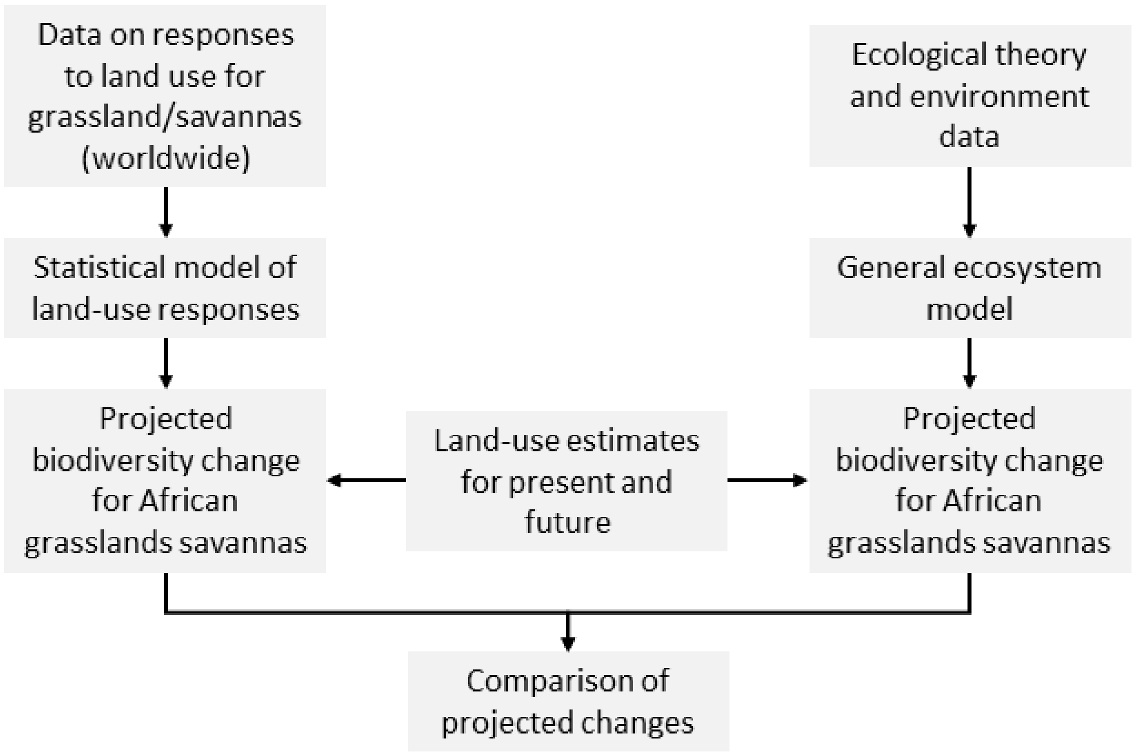
In the Madingley general ecosystem model (Harfoot et al. 2014), organisms are divided into functional groups: on land, divisions are made between trophic levels (autotrophs, herbivores, omnivores and carnivores), between endotherms and ectotherms, and between semelparous and iteroparous reproductive strategies. Organisms are also characterized by their body mass (juvenile, adult and current body masses). The model includes all photoautotrophs and all heterotrophs of body mass > 10^{-5} g. Ecological processes that involve animals act upon individual organisms (although organisms in the same functional group and with similar masses are grouped together for computational convenience; Purves et al. 2013).

The dynamics of plants are modelled using a terrestrial carbon model (Smith et al. 2013), where plant biomass depends upon primary productivity, the division of productivity between evergreen and deciduous plants, the allocation of productivity to leaves, structural tissues or roots, and mortality, all of which depend upon climatic variables (Smith et al. 2013). The plant model was chosen because future projections of the driving climate variables are readily available. Non-climatic factors important in shaping grassland/savanna plant dynamics, such as fire, are captured implicitly to the extent that they correlate with climatic variables (Smith et al. 2013). However, explicit representation of processes such as fire and phenology in future might allow better predictions for grasslands and savannas (e.g. Scheiter and Higgins 2009). The dynamics of heterotrophic animals are based on five ecological processes: 1) predator-prey relationships (including herbivory), which are based on a Holling’s Type III functional response (Denno and Lewis 2012), and for predation on a size-based model of predator-prey feeding preferences (Williams et al. 2010); 2) metabolism, which is based on empirical relationships with temperature (Brown et al. 2004); 3) reproduction, which is based on a simple allocation of surplus mass to reproductive potential followed by reproductive events once a threshold ratio of reproductive potential to adult body mass is reached ; 4) mortality (in addition to predation mortality), which is of three sources (a constant background rate, starvation if insufficient food is obtained, and senescence, which follows the Gompertz Model (e.g. Pletcher 1999) in assuming an exponentially increasing rate of mortality with time after reproductive maturity is reached); and 5) dispersal, which in the terrestrial realm is either random diffusive dispersal of juvenile organisms or directed dispersal of organisms in response to starvation (Harfoot et al. 2014).

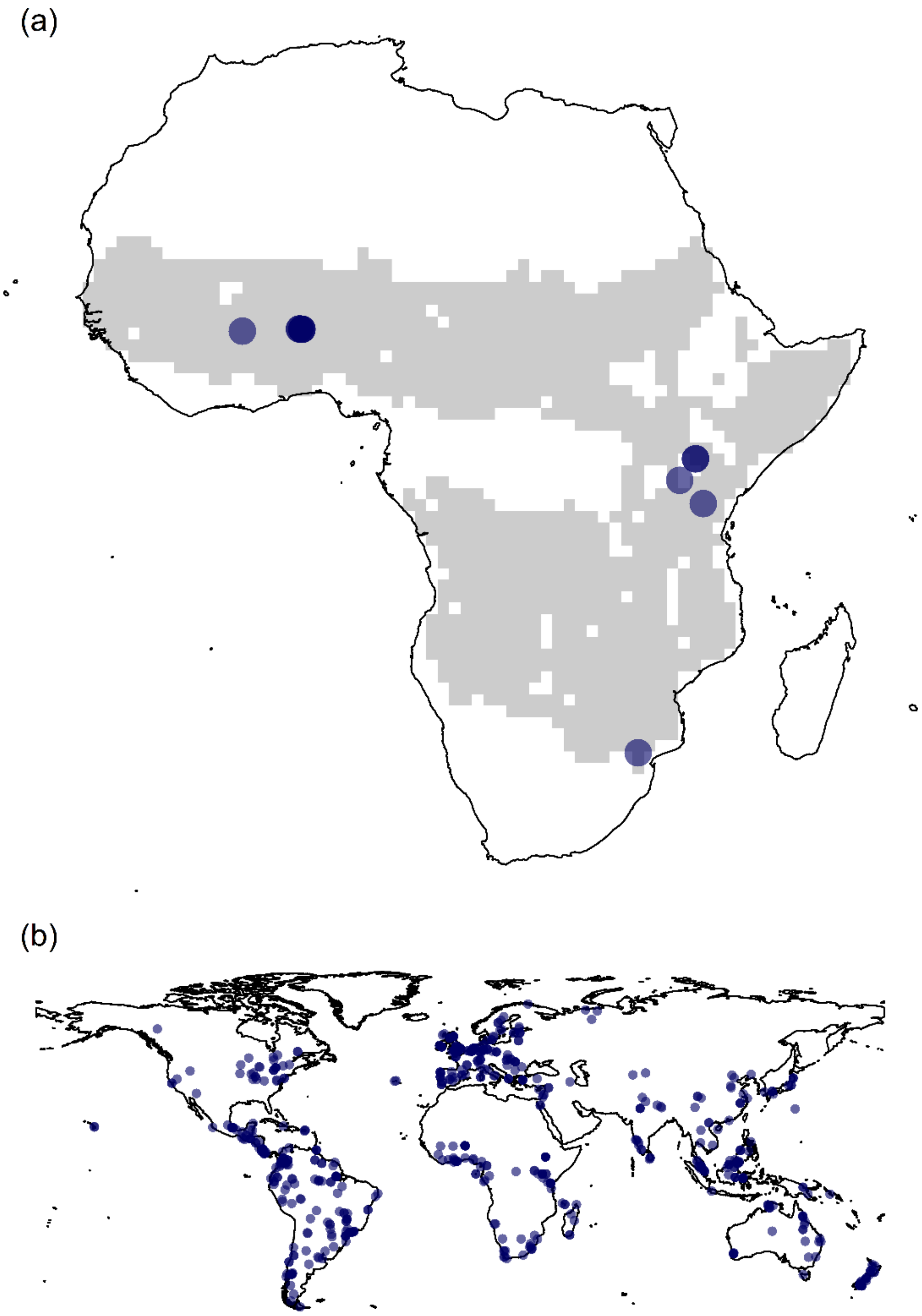
For simulating undisturbed ecosystems, the model takes as environmental input the following variables, which determine the rates of ecological processes: monthly near-surface air temperature, diurnal air temperature range, monthly precipitation, soil water capacity, monthly number of frost days, and satellite-derived net primary productivity (used only to determine seasonal patterns). We used a monthly time step.

The model has been shown to capture observed properties of individual organisms and the coarse structure of ecosystems reasonably well under environmental conditions without human impact, especially in grassland ecosystems (Harfoot et al. 2014). To simulate land-use impacts in the model, we removed from the model plant biomass calculated as a certain proportion of net primary production, following the Human Appropriation of Net Primary Production (HANPP) paradigm (Haberl et al. 2007). We used published data on HANPP for the year 2000, compiled based on statistics on permanent agricultural and forestry (excluding wood-fuel harvesting), and estimates of global patterns in land use and soil degradation, excluding the effects of shifting cultivation and vegetation loss from fire (important limitations in its application to grassland/savanna systems; Haberl et al. 2007). HANPP estimates are separated into two components: primary production lost as a result of land-use conversion itself, and primary production lost directly to human harvesting (Haberl et al. 2007). To project these estimates, we developed simple spatial models of estimates of each of the two components of HANPP within each half-degree grid cell within African tropical grassland biomes. Estimates of land-use loss and harvest loss were modelled, using linear models, as a function of the total areas of cropland, pasture and urban land use within each cell, and UN subregion (to control for some of the socio-economic factors that might drive spatial differences in human use of the land). Land-use data at half-degree resolution were taken from the HYDE estimates in the harmonized land-use data of (Hurtt et al. 2011). UN subregion was taken from (Sandvik 2009). Land-use areas were fitted with quadratic polynomials and UN subregion as a factor. Land-use HANPP losses are right-skewed but contain negative values (agricultural areas can be more productive than the natural vegetation; Haberl et al. 2007); therefore, we employed a cube-root transformation, preserving the sign of the values. Directly harvested losses of HANPP are also right-skewed, but without negative values, and we therefore employed a simple log transformation. These models explained a substantial proportion of the estimated spatial variation in HANPP (R^2 values were 0.42 for land-use losses and 0.53 for harvest losses). The spatial models of HANPP were then applied to HYDE estimates of land use in 2005, and to estimates of land use in 2095 under two of the Representative Concentration Pathways scenarios (MINICAM and MESSAGE; see 'Land-use Scenarios' in the main text).

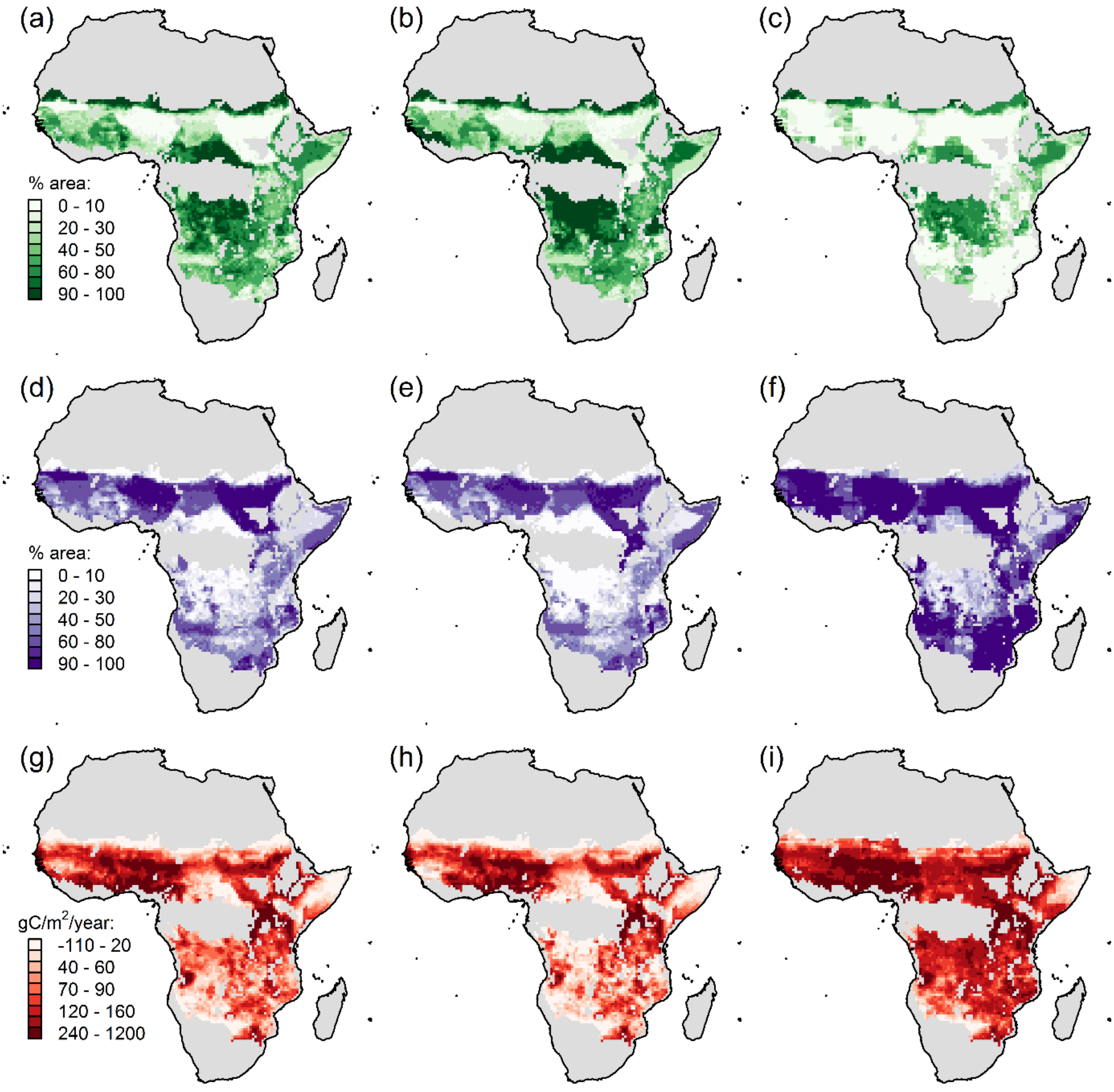
Supplementary Tables and Figures



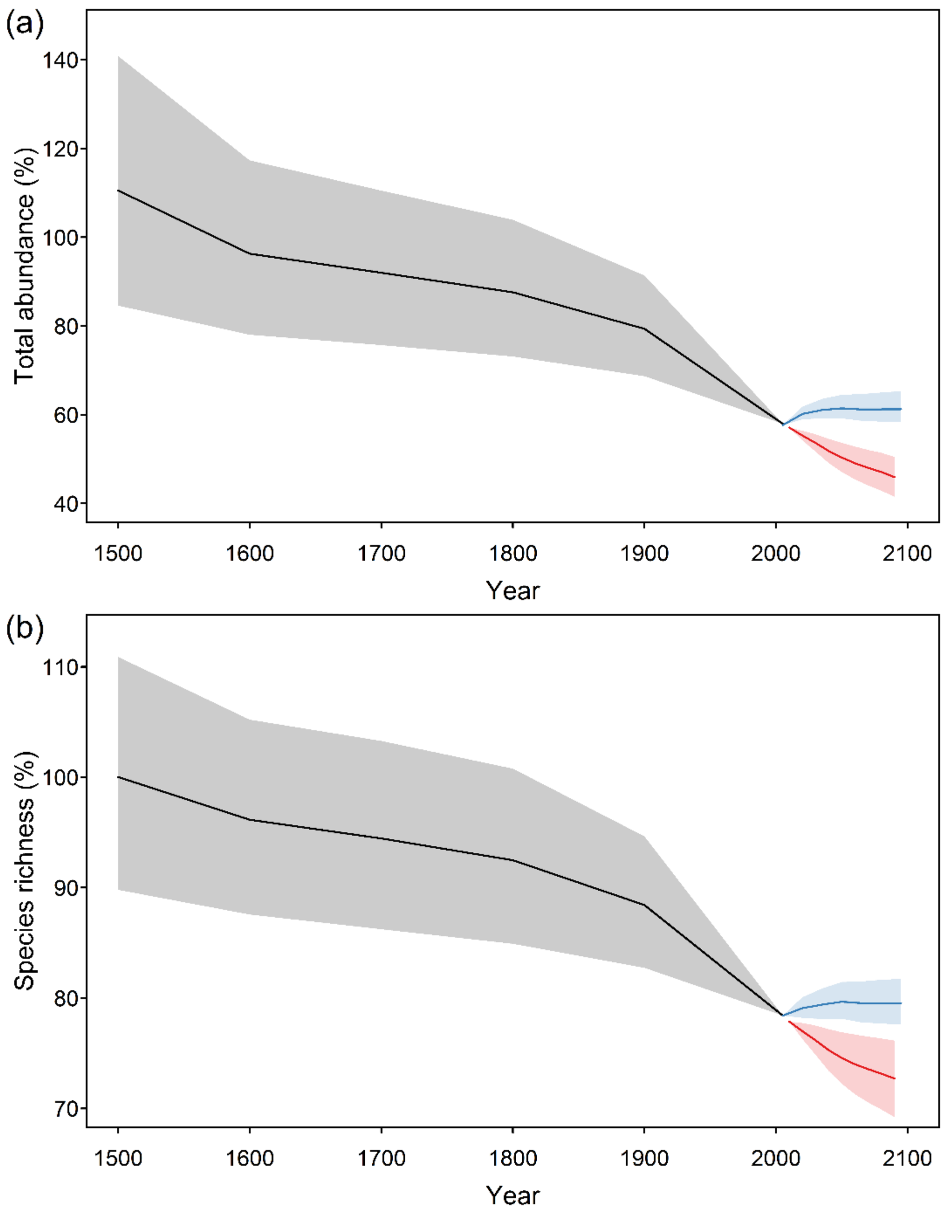
Supplementary Figure 1. The structure of this study.



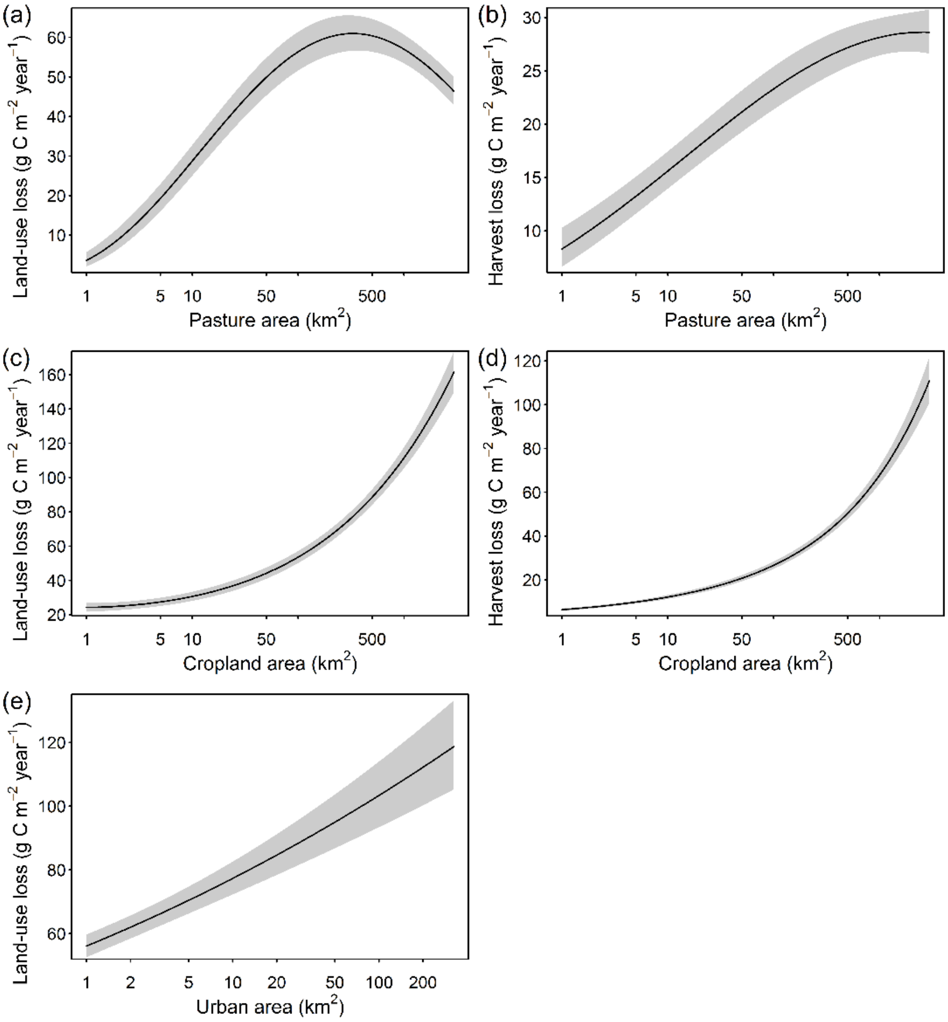
Supplementary Figure 2. The location of sites (black points) used in the statistical model, from African grasslands and savannas (a) and worldwide (b). Grey shading in *a* shows the approximate extent of African grasslands and savannas. The 922 African grassland/savanna sites showed a reasonable representation of land uses: 231 in minimally used primary vegetation, 50 in substantially used primary vegetation, 36 in minimally used secondary vegetation, 33 in substantially used secondary vegetation, 378 in cropland, and 194 in pasture.



Supplementary Figure 3. Estimates of land-use change in African tropical grasslands. a-c: natural (primary and secondary) vegetation; d-f: human land uses (plantation forest, cropland, pasture and urban); g-i: human appropriation of net primary production (HANPP; sensu Haberl et al. 2007). Estimates are for 2005 (a, d, g), for 2100 under the MINICAM scenario (b, e, h), and for 2100 under the MESSAGE scenario (c, f, i).



Supplementary Figure 4. Predicted temporal changes in the average total abundance of organisms and species richness in local ecological communities in African tropical grasslands and savannas. Shaded areas show ±95% confidence intervals. Land-use change estimates until 2005 were from the HYDE model (Klein Goldewijk et al. 2011). Future estimates were from the harmonized land-use estimates (Hurtt et al. 2011) for two of the Representative Concentration Pathways scenarios: MINICAM (blue) and MESSAGE (red).



Supplementary Figure 5. Relationship between the area of pasture (a, b), cropland (b, c) and urban habitat, and the removal of net primary production from ecosystems by humans. Removal could either be caused directly by the conversion of land from natural vegetation to human use (a, c, e) or by the harvesting of vegetation by humans (b, d). The relationships (quadratic polynomials) were modelled using linear models (one model for land-use losses and one model for harvesting losses). UN sub-region (Sandvik 2009) was also included in the models to account for some of the spatial variation in the absolute magnitude of vegetation removal, caused by socio-economic differences among regions.

Supplementary Table 1. The land-use and land-use-intensity classification criteria (Hudson et al. 2014).

Level 1 Land Use	Predominant Land Use	Minimal use	Light use	Intense use
No evidence of prior destruction of the vegetation	Primary forest	Any human disturbances identified are very minor (e.g., a trail or path) or very limited in the scope of their effect (e.g., hunting of a particular species of limited ecological importance).	One or more human disturbances of moderate intensity (e.g., selective logging) or breadth of impact (e.g., bushmeat extraction), which are not severe enough to markedly change the nature of the ecosystem. Primary sites in suburban settings are at least Light use.	One or more human disturbances that is severe enough to markedly change the nature of the ecosystem; this includes clear-felling of part of the site too recently for much recovery to have occurred. Primary sites in fully urban settings should be classed as Intense use.
	Primary Non-Forest	As above	As above	As above
Recovering after destruction of the vegetation	Mature Secondary Vegetation	As for Primary Vegetation-Minimal use	As for Primary Vegetation-Light use	As for Primary Vegetation-Intense use
	Intermediate Secondary Vegetation	As for Primary Vegetation-Minimal use	As for Primary Vegetation-Light use	As for Primary Vegetation-Intense use
	Young Secondary Vegetation	As for Primary Vegetation-Minimal use	As for Primary Vegetation-Light use	As for Primary Vegetation-Intense use
	Secondary Vegetation (indeterminate age)	As for Primary Vegetation-Minimal use	As for Primary Vegetation-Light use	As for Primary Vegetation-Intense use
Human use (agricultural)	Plantation forest	Extensively managed or mixed timber, fruit/coffee, oil-palm or rubber plantations in which native understorey and/or other native tree species are tolerated, which are not treated with pesticide or fertiliser, and which have not been recently (< 20 years) clear-felled.	Monoculture fruit/coffee/rubber plantations with limited pesticide input, or mixed species plantations with significant inputs. Monoculture timber plantations of mixed age with no recent (< 20 years) clear-felling. Monoculture oil-palm plantations with no recent (< 20 years) clear-felling.	Monoculture fruit/coffee/rubber plantations with significant pesticide input. Monoculture timber plantations with similarly aged trees or timber/oil-palm plantations with extensive recent (< 20 years) clear-felling.
Human use (agricultural)	Cropland	Low-intensity farms, typically with small fields, mixed crops, crop rotation, little or no inorganic fertiliser use, little or no pesticide use, little or no ploughing, little or no irrigation, little or no mechanisation.	Medium intensity farming, typically showing some but not many of the following: large fields, annual ploughing, inorganic fertiliser application, pesticide application, irrigation, no crop rotation, mechanisation, monoculture crop. Organic farms in developed countries often fall within this category, as may high-intensity farming in developing countries.	High-intensity monoculture farming, typically showing many of the following features: large fields, annual ploughing, inorganic fertiliser application, pesticide application, irrigation, mechanisation, no crop rotation.
	Pasture	Pasture with minimal input of fertiliser and pesticide, and with low stock density (*not* high enough to cause significant disturbance or to stop regeneration of vegetation).	Pasture either with significant input of fertiliser or pesticide, or with high stock density (high enough to cause significant disturbance or to stop regeneration of vegetation).	Pasture with significant input of fertiliser or pesticide, *and* with high stock density (high enough to cause significant disturbance or to stop regeneration of vegetation).
Human use (urban)	Urban	Extensive managed green spaces; villages.	Suburban (e.g. gardens), or small managed or unmanaged green spaces in cities.	Fully urban with no significant green spaces.

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