HOW LAND USE AFFECTS BIODIVERSITY: AN ANALYSIS OF THE DIFFERENCES IN THE EFFECTS RECORDED ON DIFFERENT CONTINENTS

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ABSTRACT

Biodiversity provides humans with abundant natural resources, but due to human activities, land use has become one of the main factors determining the loss of biodiversity. Previous research has shown that land use has different effects on different species. To illustrate this phenomenon, this study used a wide range of sets of data to determine how land use affects species diversity worldwide, and whether this effect depends on the continent. This study mainly uses linear mixed-effects models (LMM) and generalized linear mixed-effects models (GLMM) to address the questions from two aspects: abundance and species richness. The results show that the responses of both abundance and species richness differ significantly between continents, which in Europe are significantly lower than in countries with primary vegetation. However, due to the sample size for Europe being much larger than that for Asia and Oceania, this result also indicates that the level of sampling could have biased the results.

Keywords: biodiversity; continents; land use; impact

Introduction

Biodiversity, the number of species, differs across the planet. There are three highly correlated levels of biodiversity: genetic diversity, ecosystem diversity and species diversity (Glowka et al. 1994). The number and variety of species in an ecosystem determine the biological characteristics that affect ecosystem processes, so species diversity has functional consequences. Species diversity also affects the resistance and adaptability of the ecosystem to environmental change (Chapin III et al. 2000). As a species, human beings depend on the oxygen and food provided by nature to sustain life. However, organisms not only provide humans with abundant natural resources, but also indirectly provide many other basic ecological services and economic values. They provide a variety of market-oriented products, such as wood, resin, fibre and organic chemicals; and have an aesthetic value (Alho 2008), which also provides an economic return. While benefiting mankind, it also provides a living environment for the animals, plants, and various microorganisms in forests. But since the 1970s, human influence on life on earth has increased dramatically, due to the demand created by an increase in the per capita income and population growth. Humans are rapidly changing the world landscape by cutting down forests and turning natural habitats into areas for subsistence farming (Foley et al. 2005). Therefore, there has been much research into how biodiversity responds to human threats, such as land use and agricultural intensification.

China is one of the most diverse countries in terms of biodiversity and ranks third in terms of the number of species (after Brazil and Colombia) (Anonymous 1996). But due to the increasing size and wealth of the human population, China's biodiversity is facing tremendous pressure from human activities. China's land use, as in many other countries in the region, has undergone tremendous changes in the past few decades. The area of cultivated land in northern China has increased, while the area of cultivated land in the south has decreased and the centre of reclaimed cultivated land has shifted from northeast to northwest. The urban areas surrounding cities in East China are expanding and gradually developing in central and western regions. The total area of grassland and woodland is also decreasing (Li et al. 2010; Zhao et al. 2015). Given the rapid economic development of China over recent decades, the original plan was to ask Chinese researchers who have undertaken comparable biodiversity surveys at multiple sites that differed in land use or levels of management for access their data. Each of the raw data sets of each of these authors were curated and uploaded to the PREDICTS database.

Nature is now providing more resources and products for humans than before, but at a high cost: The scope and integrity of ecosystems around the world are declining at an unprecedented rate, the uniqueness of local ecological areas, the numbers of wild species and that of local livestock have also declined dramatically (Diaz et al. 2019). Currently, land use or habitat change is one of the main factors that is reducing biodiversity in many areas (De Baan et al. 2013). Several previous syntheses have shown that in terms of changes in the composition of the atmosphere and extensive current changes in the earth's ecosystem, global land use has had a huge effect on the environment (Matson et al. 1997; Vitousek et al. 1997; Tilman et al. 2001; Wackernagel et al. 2002). But most of the case

Yidi, J., Purvis, A.: How land use affects biodiversity: an analysis of the differences in the effects recorded on different continents
European Journal of Environmental Sciences, Vol. 13, No. 1, pp. 15–22
https://doi.org/10.14712/23361964.2023.2

studies consider changes in one place and often assume that the changes are much the same everywhere (Newbold et al. 2015), so there are still very few articles exploring the differences in the effects recorded on different continents in the world.

Past research has shown that disturbance has a greater effect on the biodiversity in tropical forests in Asia than in other regions (South America, Central America, and Africa) (Gibson et al. 2011). There are several possible reasons for this. Firstly, the types of land use and intensities vary in different regions and the sampling of different taxa varies, so the biodiversity recorded may differ (Phillips et al. 2017). In addition, there are differences in the sensitivity of species to land use and land use intensity. This sensitivity is mainly the intrinsic sensitivity of biological communities, determined by natural selection (Gibson et al. 2011; Gerstner et al. 2014; De Palma et al. 2016; Newbold et al. 2016). The reasons for this difference in sensitivity may be the difference in the size of the geographical range or difference in regional land use (Lambin et al. 2003; Schipper et al. 2008). That is, in some areas, long-term land use might have already filtered out relatively sensitive species, so the current difference in land use has less effect. This is also known as the "extinction filter" (Balmford 1996).

This study is part of the ongoing PREDICTS project. The data on abundance, species richness and the GPS coordinates of each research site come from the PREDICTS database (Hudson et al. 2014, 2017). The PREDICTS project (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems; www.predicts.org.uk) is a collaboration between the Natural History Museum London, the United Nations Environment Program-World Conservation Monitoring Centre and others in the development of better models of how human activity affects biodiversity, which is endorsed by the Group on Earth Observations Biodiversity Observing Network (GEO-BON). Because of the hierarchical structure of the PREDICTS data the statistical analysis used in this study is a generalized linear mixed-effects model (GLMM) if the biodiversity values for two sites in the same study will tend to be much more similar than values for two sites chosen at random. The purpose of this study is to investigate how land use affects the level of biodiversity worldwide and to see if the effects differ on different continents. Three questions are addressed: 1. How do species richness and abundance respond to land use worldwide? 2. Are there any significant differences in the effect of land use on the level of biodiversity on different continents? 3. What are the possible reasons and mechanisms determining the results?

Methods

Data

The data came from numerous published studies on the effects of land use on abundance and species richness. Since 2012, the PREDICTS project has been collating records on the abundance and composition of species, and composition and diversity information on communities to simulate likely local changes in biodiversity attributable to human activity at a global scale (Hudson et al. 2017).

The predominant types of land use in the PREDICTS project are primary vegetation (local vegetation that is not known or inferred to have ever been completely destroyed), secondary vegetation (where the original primary vegetation was completely destroyed), forest plantations (previously cleared areas that were planted with crop trees or shrubs for commercial or subsistence harvesting, in which the trees are not harvested), cropland (land that people have planted with herbaceous crops), pasture (land where livestock is known to be grazed regularly or permanently) and urban areas (areas with human habitation and/or buildings, where the primary vegetation was removed) (full descriptions are given in Hudson et al. 2014). All the research sites in the database were classified according to the description in the source document or text provided by the author. The data are arranged into Sources (= papers), within which there are one or more Studies (= sampling methodology). That is why the data are hierarchical and mixed-effects models are needed.

Data analysis

Due to the differences in sampling standards and methods all the statistical analysis was done using R v4.0.0 with the "lme4" package (to run mixed-effects models, which could be used to analyse very heterogeneous data compilations). Therefore, when random effects are involved, generalized linear mixed models (GLMMs) provide a method of analysing non-normal data (Bolker et al. 2009). Several packages were used in the analysis. The first two packages "predictsFunctions" and "StatisticalModels" were useful for dealing with PREDICTS data and plotting PREDICTS models and testing spatial autocorrelation, respectively. Another package called "raster" was used for dealing with spatial data. Both "dplyr" and "tidyr" were used as handy functions for manipulating data. Package "car" was used to produce ANOVA tables with significance values and "DHARMa" to produce model criticism plots. Finally, "MuMIn" was used to check the explanatory power of mixed-effects models.

To select the random-effects structure, the method using the most complex fixed-effects structure, including all interactions, was used to test the second stage of the modelling, while comparing the fit of different random-effects structures (Zuur et al. 2009). When the response variable was abundance, a linear mixed-effects model (LMM) was used in this study. Abundance was also transformed into rescaled abundance (abundance divided by the maximum recorded in each study) for calculation. Source was included as a random intercept (termed Source_ID). As the differences in methods and sampling effort in the different studies result in differences in the diversity metrics, the study identity was also included as a random intercept (termed SS). Block was often used as a random intercept (termed SSB) to reflect the spatial configuration of sites into spatial blocks within some studies. Sometimes the mixed-effects model included random slopes within a study so that the effects of the explanatory variables varied from study to study. When species richness is the response variable, a generalized linear mixed-effects model (GLMM) with a Poisson distribution of errors was adopted and due to overdispersion, a site-level random effect (SSBS) was added, together with (SS) and (SSB), which effectively turned the model into a quasipoisson model. The basic structure of the mixed-effects models looked roughly like this (taking predominant land use as the fixed effect as an example):

Species_richness ~ Predominant_land_use + (1|SS) + + (1|SSB) + (1|SSBS)

(1|SS) is the study-level random intercept, and (1|SSB) the block-level random intercept, both of which were considered to be random effects.

Another model used the interaction between land use and continents as a fixed effect to explain the relationship between it and biodiversity:

Species_richness ~ Predominant_land_use × UN_region + + (1|SS) + (1|SSBS)

In the PREDICTS database, UN_region is a geographical factor, with Asia, Americas, Europe, Africa and Oceania as the levels.

Model simplification, which produced the minimal adequate model (MAM), was done by checking the ANOVA table, deleting variables that had no significant effect and gradually deleting the next most complex and least important term and repeating the process until everything in the model was statistically significant. More specifically, if $p > 0.05$, the interaction variable was deleted first and then any single variable that did not participate in the remaining interactions when $p > 0.05$ (Zuur et al. 2009). The remaining model was the minimal adequate model. The "ANOVA" function in the "car" library was used to obtain the p value.

Results

Overall, the data contained 480 sources, 666 studies and 22678 sites. These sites are distributed in various countries in the world, across five continents (Fig. 1). As shown in Fig. 2, compared with the primary vegetation, the abundance in plantation forest, pasture, cropland and urban areas is significantly lower while that in young secondary vegetation and intermediate secondary vegetation is lower but not significantly so. In contrast, the abundance of mature secondary vegetation is a little bit higher than that of primary vegetation. The (square root rescaled) abundance of primary vegetation is 0.66 and pasture is 0.05 lower. This means that the (square root rescaled) abundance of pasture is 0.66 – 0.05 = 0.61 (Table 1). This model includes Study (SS), Block (SSB) and (Source_ID) as random intercepts, also, a random slope of Predominant_land_use to allow the effects of explanatory variables to vary among studies. It is worth mentioning that when the abundance is used as the response variable, the data is continuous and normally distributed, so the Student's t test is used to test whether the abundance has changed significantly from that of the primary vegetation, which it has when the absolute value of t is greater than 2.

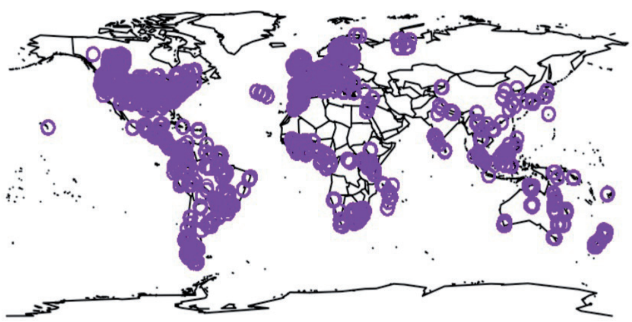

Fig. 1 Geographic distribution of the studies.

Table 1 Result of the linear mixed-effect model (LMM) with land use classes as fixed effects related to abundance, with 95% confidence intervals.

Terms	Estimate	Standard error	*t*-value
Primary vegetation	0.66	0.011	58.67
Young secondary vegetation	−0.02	0.015	−1.30
Intermediate secondary vegetation	−0.01	0.015	−0.48
Mature secondary vegetation	0.02	0.016	1.32
Plantation forest	−0.04	0.017	−2.58
Pasture	−0.05	0.017	−3.01
Cropland	−0.08	0.020	−3.78
Urban areas	−0.06	0.024	−2.59

In addition, the types of land use at all research sites were modelled with species richness as a response variable (Fig. 3). Considering overdispersion and convergence, the random effects in this model are SS and SSBS. Also, due to the overdispersion of data, this model is a quasipoisson model, so the p value is used to test the significance. The result of the GLMM shows that the species richness in young secondary vegetation, intermediate secondary vegetation, plantation forest, pasture, cropland, and urban areas is significantly lower than in primary vegetation (Table 2). Regardless of whether the response variable is abundance or species richness, the level of biodiversity in each of the four types of land use (plantation forest, pasture, cropland and urban areas) is significantly less than recorded in primary vegetation.

Table 2 Result of the generalized linear mixed-effect model (GLMM) with land use classes as fixed effect related to species richness, with 95% confidence intervals (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Terms	Estimate	Standard error	*p* value
Primary vegetation	2.62	0.049	<2e–16 ***
Young secondary vegetation	–0.16	0.017	<2e–16 ***
Intermediate secondary vegetation	–0.16	0.016	<2e–16 ***
Mature secondary vegetation	–0.04	0.021	0.09
Plantation forest	–0.28	0.015	<2e–16 ***
Pasture	–0.20	0.014	<2e–16 ***
Cropland	–0.27	0.016	<2e–16 ***
Urban areas	–0.25	0.031	<2e–16 ***

To test whether continent matters, ANOVA (Analysis of Variance) was used to compare the model that included it with a model in which predominant land use was the only fixed effect. The results indicate that not only do these two fixed effects have significant effects on biodiversity, but the effect of their interaction is also significant (Table 3). In addition, the model of the interaction between the two fixed effects fits the data better (the lower AIC value).

Table 3 Result of the one-way and two-way ANOVA with different fixed effects related to abundance and species richness, with 95% confidence intervals (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Terms	Fixed effect	Df	*p* value
One-way ANOVA	Predominant_land_use	7	< 2e–16 ***
Two-way ANOVA	Predominant_land_use: UN_region	28	< 2e–16 ***

A model in which the combination of land use types and the world's five continents (Asia, Americas, Europe, Africa, and Oceania) were included as fixed effects was developed. This model indicates the relationship between each land use type and each continent and provides a comparison between continents. As shown in Fig. 4, the effect of land use on abundance varies significantly from region to region. In Africa, abundance in young secondary vegetation, mature secondary vegetation, pasture, and cropland is significantly lower than in primary vegetation. The abundance in Americas is less sensitive to land use, but in plantation forest and urban areas is significantly lower than in primary vegetation but is significantly higher in mature secondary vegetation. In Asia, abundance in young secondary vegetation, plantation forest and cropland are significantly lower, whereas in Oceania, abundance is significantly lower in young secondary vegetation and pasture. Moreover, abundance in Europe is significantly lower in all types of land use and is also the lowest of all the continents in intermediate secondary vegetation.

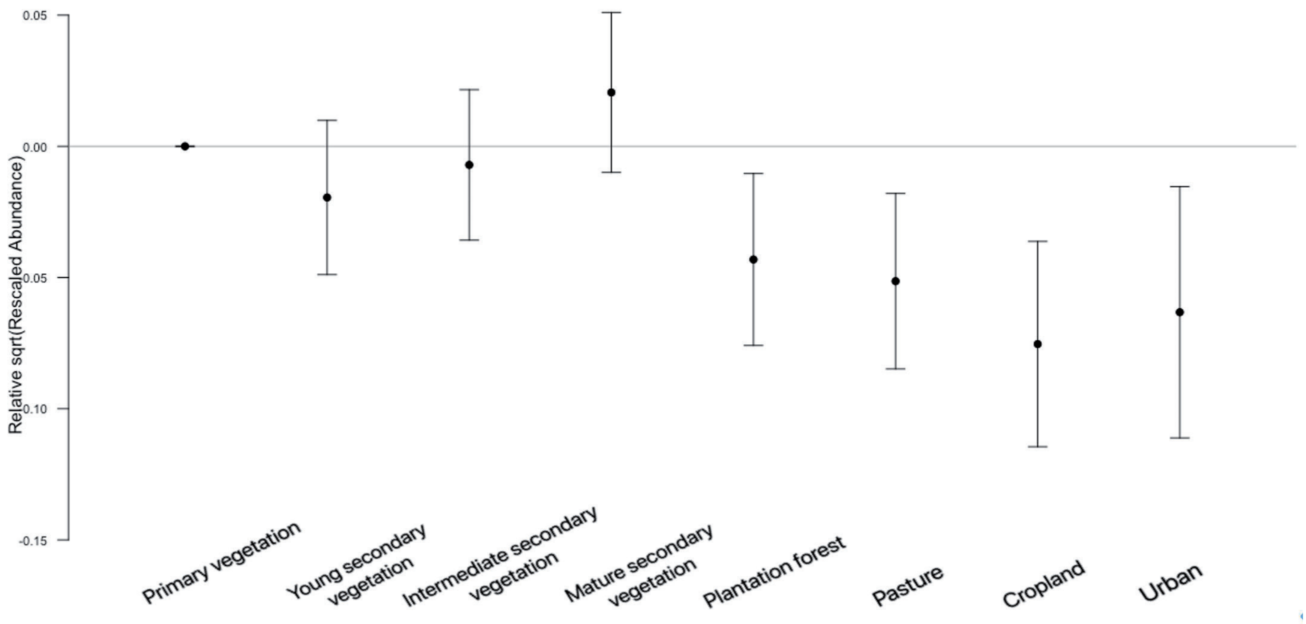

Fig. 2 Estimated average effect worldwide of different classes of land use on (square root rescaled) abundance. Error bars show 95% CIs.

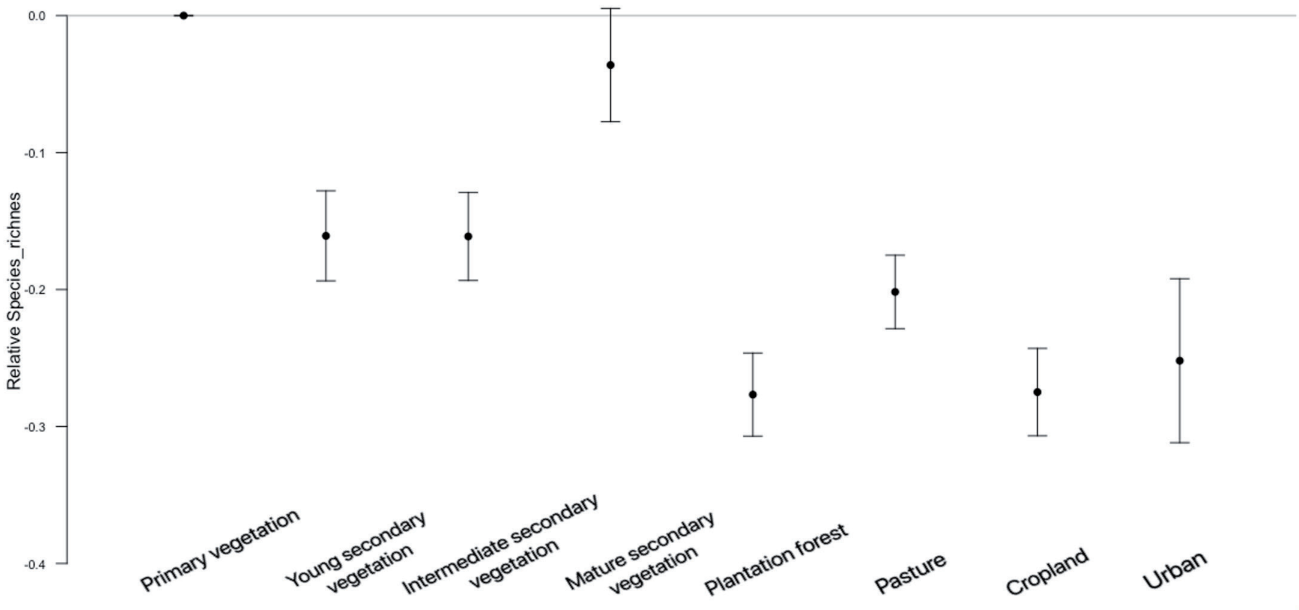

Fig. 3 Estimated average effect worldwide of different classes of land use on species richness. Error bars show 95% CIs.

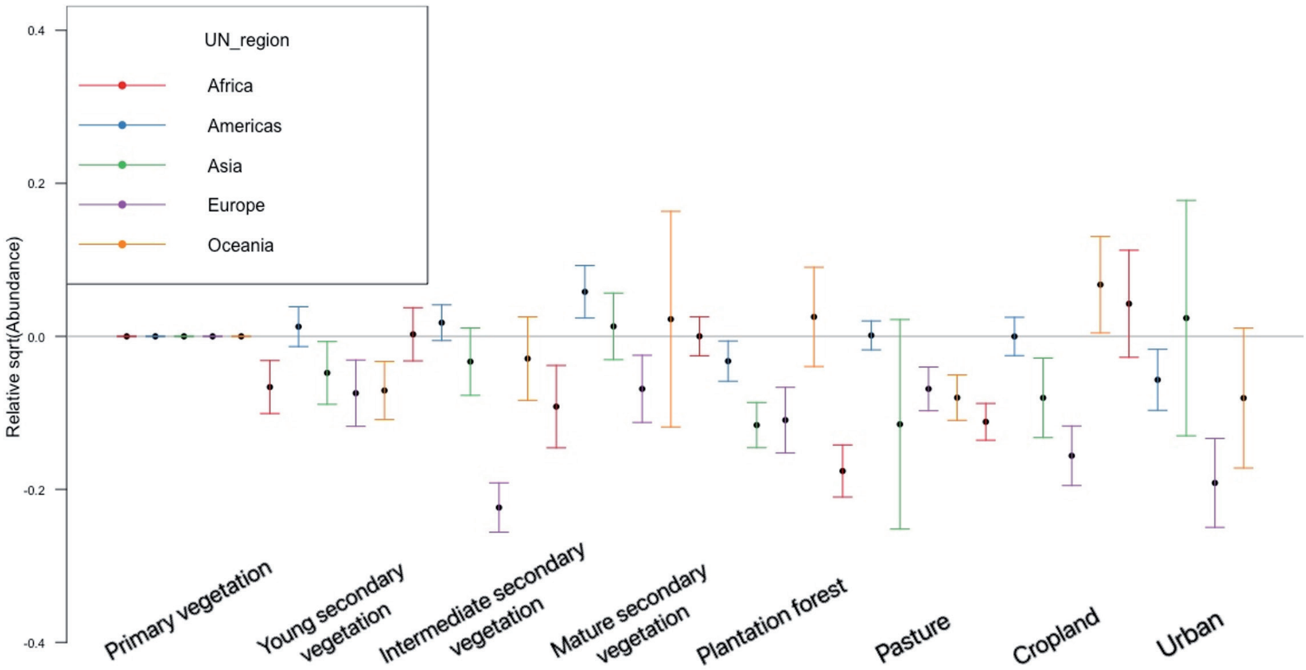

Fig. 4 Estimated average effect of different classes of land use and continents on (square root rescaled) abundance. Error bars show 95% CIs.

When species richness is the response variable, the results for Africa and Europe are similar, that is, species richness in almost all classes of land use is significantly lower than in primary vegetation (Fig. 5). Species richness in young secondary vegetation, plantation forest and pasture in America, Asia and Oceania is also significantly lower than in primary vegetation. In addition, species richness in cropland and urban areas in the Americas and intermediate secondary vegetation and cropland in Asia is significantly lower.

Discussion

The global models presented indicate that abundance and species richness recorded in plantation forest, pasture, cropland, and urban areas, are significantly lower than those in primary vegetation, with particularly low levels of diversity in cropland (Figs 2–3). Today, nearly 38% of the world's total land area is farmland (Ramankutty et al. 2008). Cropland accounts for 12% of the world's land area (about 1.53 billion hectares) and the net

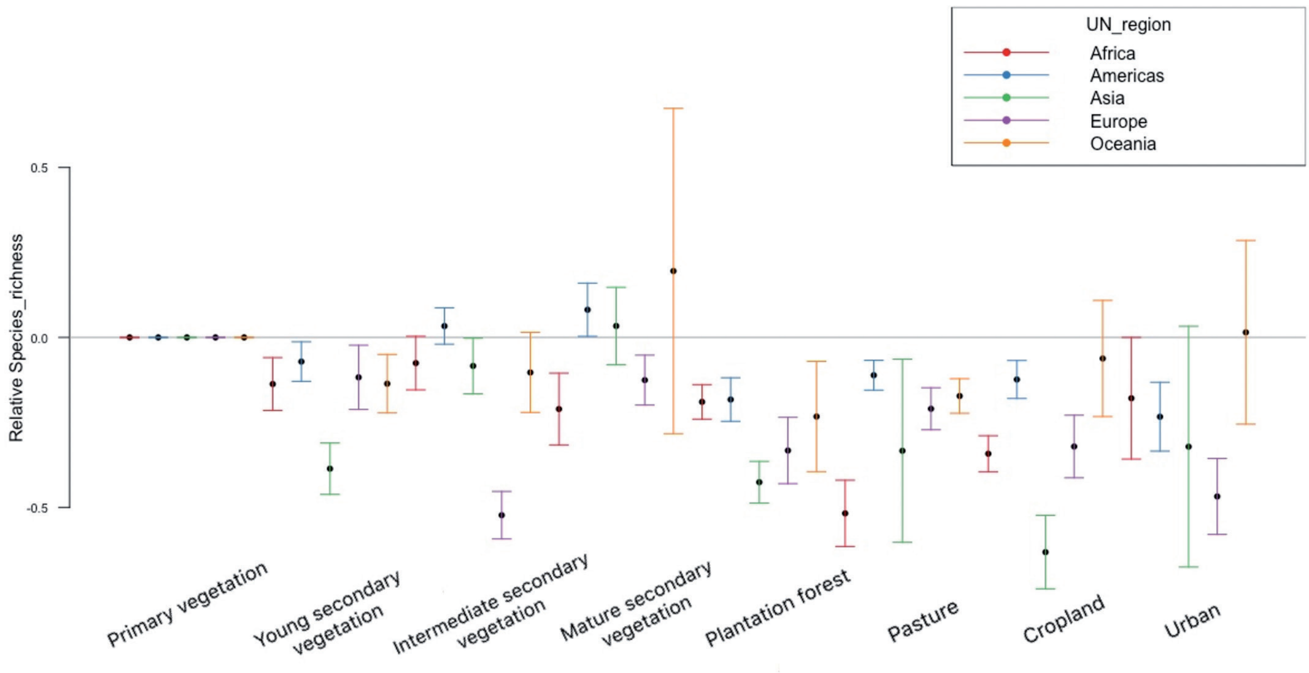

Fig. 5 Estimated average effect of different classes of land use and continents on species richness. Error bars show 95% CIs.

primary production suitable for human use is about 30% (FAOSTAT 2011; Haberl et al. 2007). It is also estimated that by 2050, the world will need to increase food production by 60–110% to feed the growing population (Tilman et al. 2011; Kastner et al. 2012). As a result, the global population growth and increase in human demand for food and energy, the expansion and intensification of cropland has become the main method of promoting agricultural production, which has resulted in a decrease in biodiversity (Garnett et al. 2013; Zabel et al. 2019).

The regional models show that the effects of land use on biodiversity differ in the five major regions (Figs 4–5). Both abundance and species richness in Europe in all types of land use are significantly lower than in primary vegetation due to the change in land use. In Europe, farmland is the most important type of land use, with 34% of its land area used for agricultural production, and grassland accounting for 14% (Reidsma et al. 2006; Verburg et al. 2006). In addition, due to the agricultural intensification that has occurred during recent decades, Europe currently also has some of the most intensively used arable lands in the world (Haberl et al. 2007; Mueller et al. 2012; Kuemmerle et al. 2016). But this result may have limitations because statistical significance depends on two things: effect size and sample size. Europe has a very large sample size, so the confidence intervals are narrow. However, perhaps its effect size is greater (more negative) than elsewhere. In addition to the models showing European biodiversity to be badly affected by changes in land use, it also faces a major effect of climate change. With global warming and significantly increasing extreme weather events, the annual average temperature in Europe has risen by over 1.1 degrees compared to the pre-industrial period, which is higher than the global average increase (Change IPCC 2007). The largest increases have occurred in southwestern and north-eastern Europe, central Europe, and alpine regions. Climate change has resulted in a high loss of species in mountainous areas, such as the mid-altitude Alps, central Spain, the Balkans, mid-altitude Pyrenees, French Cévennes and the Carpathians in Europe (Thuiller et al. 2005). In addition, in the past two decades, frequent droughts, severe fires and many destructive storms have resulted in a decline in forest productivity and the loss of biodiversity (Schelhaas et al. 2003; Ciais et al. 2005; Dobbertin and DeVries 2008).

The main limitation of this study is that data on the biodiversity in urban areas are only available for far fewer sites than for other types of land use. The PREDICTS database includes 6926 sites of primary vegetation, 3788 sites of secondary vegetation (excluding indeterminate age and undecidable types), 2345, 3275, and 3179 sites of plantation forest, pasture and cropland, respectively. But there are only 922 sites for urban areas. Therefore, the relative lack of data on types of urban land use may cause errors in the response of abundance and species richness to different types of land use. In addition, because the data in the PREDICTS database comes from articles and data collected by scholars from different regions and countries, there are biases caused by factors such as regional differences in biophysics, evolution, and socioeconomic history (Sodhi et al. 2005; Corlett et al. 2006; Gardner et al. 2009, 2010), also, different levels in taxonomic understandings, which may result in unobjective data. Considering the above limitations, future research should collect and include more data on urban land use types, as well as data for Asia (great difficulty experienced in getting data for China) and Oceania as there are only 2719 and 2320 research sites in Asia and Oceania, respectively, whereas for the other three continents there are at least 4500. Since biodiversity in different areas is affected differently by land use, comparing the effect of land use on different continents and on different species or considering countries rather than regions may also increase the level of understanding of the interaction between continents and land use.

Data and code availability

The data and code can be obtained from https://data.nhm.ac.uk/dataset/the-2016-release-of-the-predicts-database and https://github.com/didi970428/How-Land use-Affects-Biodiversity-an-Analysis-of-Differences-in-Impacts-between-Continents.

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