Locally rare species influence grassland ecosystem multifunctionality

Santiago Soliveres¹, Peter Manning¹,², Daniel Prati¹, Martin M. Gossner³,⁴, Fabian Alt⁵,
Hartmut Arndt⁶, Vanessa Baumgartner⁷, Julia Binkenstein⁸, Klaus Birkhofer⁹, Stefan Blaser¹,
Nico Blüthgen¹⁰, Steffen Boch¹, Stefan Böhmi¹¹, Carmen Börschig¹², Francois Buscot¹³,¹⁴,
Tim Diekötter¹⁵, Johannes Heinze¹⁶, Norbert Hölzel¹⁷, Kirsten Jung¹¹, Valentin H. Klaus¹⁷,
Alexandra-Maria Klein¹⁸, Till Kleinebecker¹⁷, Sandra Klemmer¹³, Jochen Krauss¹⁹, Markus
Lange³,²⁰, E. Kathryn Morris²¹,²², Jörg Müller¹⁶, Yvonne Oelmann⁵, Jörg Overmann⁷, Esther
Pašalić³, Swen C. Renner¹¹,²³, Matthias C. Rillig²²,²⁴, H. Martin Schaefer²⁵, Michael
Schloter²⁶, Barbara Schmitt¹, Ingo Schöning²⁰, Marion Schrumpf²⁰, Johannes Sikorski⁷,
Stephanie A. Socher²⁷, Emily F. Solly²⁰, Ilja Sonnemann²², Elisabeth Sorkau⁵, Juliane
Steckel¹⁹, Ingolf Steffen-Dewenter¹⁹, Barbara Stempfhuber²⁶, Marco Tschapka¹¹, Manfred
Türke¹⁴,²⁸, Paul Venter⁶, Christiane N. Weiner¹⁹, Wolfgang W. Weisser³,⁴, Michael Werner¹⁹,
Catrin Westphal²⁹, Wolfgang Wilcke³⁰, Volkmar Wolters³¹, Tesfaye Wubet¹³, Susanne
Wurst³², Markus Fischer¹,², Eric Allan¹

¹Institute of Plant Sciences, University of Bern, Altenbergrain 21, 3013 Bern, Switzerland.
²Senckenberg Gesellschaft für Naturforschung, Biodiversity and Climate Research Centre
BIK-F, Senckenberganlage 25, 60325 Frankfurt, Germany. ³Institute of Ecology, Friedrich-
Schiller-University Jena, Dornburger Straße 159, D-07743 Jena, Germany. ⁴Technische
Universität München, Terrestrial Ecology Research Group, Department of Ecology and
Ecosystem Management, School of Life Sciences Weihenstephan, Hans-Carl-von-Carlowitz-
Platz 2, 85354 Freising, Germany. ⁵Geocology, University of Tuebingen, Ruemelinstr. 19-23,
72070 Tuebingen, Germany. ⁶Universität zu Köln, Biozentrum Köln, Zülpicher Str. 47b,
50674 Köln. ⁷Leibniz Institute DSMZ-German Collection of Microorganisms and Cell
Corresponding author: santiago.soliveres@ips.unibe.ch
Abstract

Species diversity promotes the delivery of multiple ecosystem functions (multifunctionality). However, the relative functional importance of rare and common species in driving the biodiversity-multifunctionality relationship remains unknown. We studied the relationship between the diversity of rare and common species (according to their local abundances, and across nine different trophic groups) and multifunctionality indices derived from 14 ecosystem functions on 150 grasslands across a land-use intensity gradient. The diversity of above- and belowground rare species had opposite effects, with rare aboveground species being associated with high levels of multifunctionality, probably because their effects on different functions did not trade-off against each other. Conversely, common species were only related to average, not high, levels of multifunctionality, and their functional effects declined with land-use intensity. Apart from the community-level effects of diversity, we found significant positive associations between the abundance of individual species and multifunctionality in 6% of the species tested. Species-specific functional effects were best predicted by their response to land-use intensity: species that declined in abundance with land-use intensification were those associated to higher levels of multifunctionality. Our results highlight the importance of rare species for ecosystem multifunctionality and help guiding future conservation priorities.

Keywords: biodiversity, common species, ecosystem function, ecosystem services, grasslands, identity hypothesis, land use, multi-trophic
1. Introduction

Many studies have demonstrated that high species diversity enhances ecosystem functioning both in experimental and natural assemblages (1-4; reviewed in [5] this issue). However, it has been argued elsewhere that it is not the total number of species per se, but the functional properties of the most locally abundant ones (hereafter common species) that drive ecosystem functioning (mass-ratio hypothesis; [6]). Other work has shown that each common species can only provide a limited number of functions [1, 7-8]. Extending the mass-ratio hypothesis to the simultaneous provision of multiple ecosystem functions at high levels (multifunctionality), we might therefore predict that several common species would be needed to maintain multifunctionality and that the diversity of common species, rather than overall diversity, would be its main biotic driver. In contrast to this argument, less locally abundant (hereafter rare) species have been shown to play a crucial role in affecting several ecosystem functions [9-11]. Rare species comprise the vast majority of the species in any natural community and are more sensitive to anthropogenic disturbances [12, 13]. Thus quantifying the functional consequences of their loss is of particular importance to predict the provision of ecosystem services in the future. The functional importance of common vs. rare species could depend on the ecosystem functions under scrutiny. Studies focused on productivity and pollination have found common species to be the main driver (e.g., [9, 14-17]) while those focusing on functions associated with some regulating (e.g., invasion resistance) or recreational (e.g., bird watching) services highlight the importance of rare species [18-20]. Due to their contrasting effects depending on the function considered, studies measuring multifunctionality are required to comprehensively assess the relative functional importance of rare and common species [8, 11].

Studies across large temporal or spatial scales have shown that the relationship between diversity and ecosystem functioning may change with abiotic conditions or land-use intensification [21-25], the level of multifunctionality desired [8, 26] or the type of organism.
being considered [23]. Land-use intensification promotes shifts in the functional composition of multiple taxa (e.g., 27), potentially dampening the generally positive relationship between diversity and ecosystem multifunctionality (25). The effects of biodiversity might also depend on the level of multifunctionality considered [26, 28]. High levels of many functions can be difficult to achieve if there are strong trade-offs between functions or between diversity effects on these functions. Finally, different components of biodiversity may differ in their functional effects. Above- and belowground organisms differ in their sensitivity to climate or anthropogenic disturbances, with rare aboveground species being the most sensitive (e.g., [13, 29]), and can also have different effects on ecosystem multifunctionality, with stronger effects found for aboveground organisms [23, 30]. The context-dependencies of the biodiversity-functioning relationship are poorly understood, particularly in terms of how they might modify effects of rare and common species. Existing comparisons of the functional role of rare vs. common species have seldom been extended beyond single taxa, individual ecosystem functions or a particular study site (but see [11]). In order to understand the response of natural and semi-natural ecosystems to ongoing global change, we therefore need to examine the relationships between different components of diversity (above- vs. belowground, common vs. rare) and ecosystem multifunctionality across environmental gradients [23] (see also [31]; this issue).

It has also been hypothesized that the presence of certain species can be of particular importance for ecosystem functioning, regardless of their abundance or whether they are above- or belowground organisms (identity hypothesis; [32, 33]). This hypothesis has received empirical support from studies focusing on individual functions such as litter decomposition, parasitism or predation [34-36]. However, studies have not yet tested whether there are species that can drive overall ecosystem multifunctionality, which would require lack of trade-offs in their effects on different functions. If there are influential species, it is important to understand the characteristics that they possess and how they respond to land-use
intensification. If such species decline in abundance as land use intensifies then, in addition to effects of biodiversity loss, compositional change driven by land use may have large effects on ecosystem multifunctionality.

Here, we assess the functional role of the diversity of rare and common species (based on their local abundance), both above- and belowground, on several multifunctionality indices derived from 14 ecosystem functions, related to the delivery of supporting, provisioning, regulating and cultural services (\textit{sensu \cite{37}}). Our hypotheses are: i) the diversity of common species is a more important driver of ecosystem multifunctionality than the diversity of rare species, ii) the positive effect of diversity on multifunctionality will decline with land-use intensity due to the associated changes in functional composition, iii) the diversity of aboveground organisms is the strongest biotic predictor for ecosystem multifunctionality \cite{23}, iv) there are particular species, across multiple trophic levels, that can promote high multifunctionality and land-use intensification changes the abundance of these species.

2. Material and methods

(a) Study sites

We sampled 150 grassland plots (50 m \times 50 m) equally distributed over three regions across Germany: the UNESCO Biosphere Reserves Schwäbische Alb (located in the Southwest) and Schorfheide-Chorin (in the Northeast), and the area in and around the National Park Hainich-Dün (in central Germany; \cite{38}). The 50 grassland plots per region were selected to span a gradient of the full range of land-use practices and intensities found in Central European grasslands. Information about land-use intensity was obtained directly from the land owners via questionnaires \cite{38}. We used this information to calculate a compound measure of land-use intensity (LUI) which summarizes the three major components of land-use in these grasslands: intensity of fertilization, mowing and grazing- with the following formula: LUI = \sqrt{(F_i/F_R) + (M_i/M_R) + (G_i/G_R)}), where F_i, M_i and R_i are the amount of fertilizer applied,
frequency of mowing cuts, and standardized units of livestock density within each sampling site per year, respectively. All three components were standardized by the average across the 50 grassland plots within each region (Fr, Mr and Gr; see [39] for full methodological details). We averaged LUI across 2006-2010, the period when most diversity and functioning data was collected.

(b) Analyses at the community level

(i) Diversity measures

At each site, we measured the abundance and richness of nine trophic groups using standard methodology (see Table S1 for details). Overall, our sampling included ~4300 taxa (the taxonomic unit varied between groups [Table S1] but we refer to all as species, for simplicity). The groups were: autotrophs (plants and bryophytes), belowground herbivores (insect larvae), belowground predators (insect larvae), detritivores (insects and millipedes), soil microbial decomposers (bacteria), aboveground herbivores (insects), aboveground predators (insects, spiders and centipedes), arbuscular mycorrhizal fungi and belowground bacterivores (bacterivorous protists). Omnivorous arthropods were not considered in our analyses as there were too few of them.

Using data for each of these nine trophic groups we calculated multidiversity, i.e., a measure of overall diversity at the community level obtained by averaging standardized diversity measures across trophic groups [13]. To calculate multidiversity we first classified the species into two groups according to their abundance (which was measured differently for the various groups [Table S1]): common (the top 10% species in terms of total abundance) and rare species (the bottom 90% of species). Abundance is widely accepted as a measure of rarity (e.g., [40]); therefore, we chose abundance across all study sites to be the most representative measure of the overall rarity of our target species. The top 10% species (common species hereafter) accounted for 80% of the total abundance sampled, whereas the
bottom 90% of species (rare species hereafter) made on average 20% of the total abundance (ranging from 6% in bacteria to 30% in belowground herbivores; Fig. S1). A second step in the calculation of our multidiversity metric was to standardize all variables to a common scale (between 0 and 1) by subtracting the minimum value and dividing by the maximum value found across the 150 sites to avoid the influence of different ranges in diversity characterizing each group. Third, we classified the trophic groups into above- and belowground organisms (plants were considered aboveground organisms). Finally, we averaged their standardized values to obtain four measures of multidiversity: above- and belowground common species multidiversity, and above- and belowground rare species multidiversity.

(ii) Ecosystem function measures

At each site, we measured 14 different ecosystem functions. These were: aboveground and belowground plant biomass, root decomposition rates, potential nitrification, soil phosphorus retention, arbuscular mycorrhizal fungal root colonization, stability of soil aggregates, soil organic carbon, forage quality, resistance to aboveground plant pathogens, aboveground pest control, pollinator abundance, bird diversity and flower cover (see [25] and Table S2 for detailed methodology). These ecosystem functions are related to nutrient cycling, food provision, sustainable soil use, pest resistance, or cultural and recreational services. We calculated three ecosystem multifunctionality metrics using these 14 functions and following the multiple threshold approach of Byrnes et al. [26], which sum up the number of measured functions that exceeds a given threshold. These thresholds are defined as a given percentage of the maximum level found for each function, and we used three thresholds (50%, 75% and 90%) to represent a wide spectrum. In order to reduce the influence of outliers the maximum was defined as an average of the top five values for each function across our study sites.
(iii) Statistical analyses

We used multi-model inference based on information theory [41] to analyze the response of ecosystem multifunctionality to the multidiversity of above- and belowground common and rare species. We performed a different analysis for each of the three multifunctionality metrics. Large-scale studies such as ours allow quantifying the relative importance of diversity regarding other drivers of ecosystem functioning, and also to evaluate changes in diversity-functioning relationships across contrasting environmental conditions. However, it is difficult from observational studies to infer causality as diversity-functioning relationships could be confounded by environmental factors affecting both diversity and ecosystem functioning. To avoid the latter, we controlled for factors that could affect both multidiversity and ecosystem functioning in our analyses; these were study region, environmental variables (pH, soil depth and topography [an index based upon the position and steepness of each site, which is related to the accumulation of soil material and water availability; [42, 43]) and LUI. We removed elevation from the set of environmental predictors because it was highly correlated with soil depth (Spearman’s rank correlation $\rho = -0.91$). We also accounted for potential context-dependencies in the diversity-multifunctionality relationship by including the interactions between LUI, region, and the four multidiversity predictors.

To analyze the relative importance of environmental conditions, the multidiversity of above- and belowground common and rare species, and the interactions between them, as drivers of ecosystem multifunctionality, we built a set of competing models including either: environmental variables only, environmental + diversity variables, or environmental + diversity variables and the interactions between diversity and region and/or land-use intensity; see Table S3 for the full list of models). From these competing models we selected those that best fit our data according to the Akaike Information Criterion (AICc, corrected for small sample sizes). Thus, those models differing less than 2 AICc units from the most parsimonious model ($\Delta$AICc < 2) were included in the set of best-fitting models. We also
calculated the importance of our different predictors as the sum of the AICc weights (a comparison with each model’s AICc with the minimum AICc) of the models in which each predictor appears. To allow comparisons between main effects and interaction terms, we divided the importance of each predictor by the number of models in which it was included (16 for the diversity predictors [maximum importance 1/16], and eight for their interactions with region and LUI [maximum importance 1/8]; see [44] for a related approach).

As a sensitivity analysis, we repeated our multi-model selection but used the multidiversity of the bottom 50% species, instead of the bottom 90%, as an alternative measure of rarity. These bottom 50% species made up on average 3% of the total abundance (ranging from 0.04% in bacteria to 6% in belowground herbivores; Fig. S1; see Table S4 for detailed results). We also repeated our analyses using the abundance, instead of the species richness, of above- and belowground common and rare species (Table S5). Results of sensitivity analysis were broadly similar to the main ones and therefore are not further discussed.

(c) Analyses at the species level

(i) Selection of species

We selected a subset of individual species that occurred in all three study areas, and in at least 10 of the 150 sites to obtain reliable parameter estimates (see Estimation of the functional role of each species below). Some of the trophic groups measured (detritivores, and belowground herbivores and predators) were not included in these species-level analyses as they contained too few species fulfilling our selection criteria. Of those that did, soil microbial decomposers and bacterivorous protists were overrepresented. Thus, in order to obtain a balanced sampling size for each trophic group, we only selected the most and least abundant 25 species within each trophic group that met the criteria. These species roughly corresponded to those classified as common and rare in the community-level analyses (Table S6). Thereby, we
obtained a balanced sample size of 50 species per trophic group (~50% of them common, 
~50% rare), with the exception of aboveground predators, for which only 20 species met our 
criteria (270 species considered overall).

(ii) Estimation of the multifunctional role of each species

To estimate the multifunctional role of each species, we used the null model approach of 
Gotelli et al. [45] as implemented by the software Impact [46]. This analysis allowed us to 
identify the presence of influential species, and whether or not the degree of functional 
influence was related to the average species’ abundance, to their functional traits or to their 
response to land-use intensity. The latter allowed us to test for the effects of compositional 
changes, across trophic levels, driven by land-use intensification on multifunctionality. This 
analysis further allows us to identify whether there are functional trade-offs within each 
trophic level; i.e. whether some species within a group are significantly associated with 
multifunctionality. The null-model approach used performs linear regressions between the 
abundance of each species and a given function, and then compares the observed slope with 
1000 random permutations of the values of the functional variable. From the randomizations, 
a standardized effect size (SES) for each species is calculated as: $SES = (S_{obs} - S_{sim})/SDev$; 
where $S_{obs}$ and $S_{sim}$ are the observed and the average of the 1000 simulated regression slopes, 
respectively, and SDev is the standardized deviation of the slopes obtained from these 1000 
randomizations. SES values higher than 2 or lower than -2 show significant relationships 
between the abundance of a given species and the function used as a response. We used our 
three multifunctionality measures as a response and thus obtained three functional effect sizes 
for each of our target species (270 target species × 3 multifunctionality scenarios = 810 
comparisons). Due to the increased type II error derived from multiple testing, 40 of these 810 
comparisons would be expected to be significant only by chance; we found two times more
significant results (Table S7), implying that our results are unlikely caused by multiple testing only.

By randomizing the functional variable instead of the species abundances, the null model approach takes partially into account the structure of the biotic community (including species interactions and non-independent effects; see full discussion in [45]). However, this method is purely correlative and prone to confounding factors which could be driving both the function and the abundance of the target species. To control for the latter we used the residuals of both the abundance of each species and the multifunctionality metrics after filtering for the same environmental variables used in the multi-model selection (region, LUI, soil pH and depth, elevation, and topography). Despite its limitations, this is to our knowledge the best method available to estimate the functional effects of many species (which would be logistically prohibitive to address experimentally).

(iii) Statistical analyses

We performed two complementary analyses at the species-level. First, to assess the functional importance of above- and belowground groups, and of rare and common species, we compared their number of significant positive and negative standardized effect sizes (SES) in each of the four categories of species, using Fisher’s exact tests (better suited for low sample sizes than $\chi^2$ analyses). This allowed us to assess if there are influential species related to multifunctionality, and if these are either common or rare, or mainly represented by above- or belowground organisms. The second analysis aimed to understand further which features makes a species influential for multifunctionality. To do this we performed multiple regressions with the SES of the functional effect of each species as a response variable, and the "response to land-use intensity" as a predictor. To correct for other species characteristics that might affect their multifunctional importance, we also included their average abundance (across all sites in which each species occurred) and functional traits (plant height and specific
leaf area for plants, and body size for herbivores and predators; obtained from available databases [47, 48]). "Response to land-use intensity" was the standardized coefficient of a linear regression between each species’ abundance and LUI. The number of sites in which each species occurred (which was correlated also with the range in abundance values; \( \rho = 0.45 \)) was introduced as covariate in our analyses as it could affect slope estimates in the null-model approach used. The traits selected are related to species responses to LUI [25, 49, 50] and also play an important role for ecosystem functioning [25, 51]. Data on functional traits was not available for microbial decomposers, bacterivorous protists and symbionts. Context-dependencies in the species-level analysis were accounted for by including the interaction between region, trophic group, and abundance or response to LUI as extra predictors. The interactions with region were not significant in any case and therefore they are not considered further. All analyses were performed using R version 3.0.2 [52].

3. Results

(a) Community level

Between 10% and 18% of the variation in multifunctionality was explained by study region, environmental variables, land-use intensity (LUI) and our multidiversity metrics (Fig. 1). All the best models (those with \( \Delta AIC < 2 \)) included at least one of the four multidiversity metrics, with models only including environment and LUI performing less well (\( \Delta AIC \) between 2.6 and 7.1; Table S3). The effects of multidiversity on multifunctionality differed depending on the metrics considered. Aboveground multidiversity of common species was not significantly related to any of the multifunctionality measures, whereas the multidiversity of common species belowground was positively related to multifunctionality at the 50% threshold, but not to the other multifunctionality measures (Table S3). The multidiversity of rare species both above- and belowground was significantly, but oppositely (positive for above- and negative
for belowground), related to multifunctionality at the highest thresholds (75% and 90%; Figs. 1 and 2).

The relationships found between multidiversity (both above- and belowground) and multifunctionality at the highest thresholds did not depend on LUI or study region (Fig. 1). The best models for both the 75% and 90% thresholds did not include interactions between region and/or LUI and multidiversity (Table S3). The best models for the 50% multifunctionality threshold, however, included interactions between region, and/or LUI, and one or more multidiversity metrics (Fig. 1; Table S3), thus demonstrating that multidiversity-multifunctionality relationships were context-dependent for the low threshold measure.

Indeed, for multifunctionality at the 50% threshold the interactions were as important as the main effects (Fig. 1), and not including them increased the AICc by more than 3 units in all cases, suggesting a strong decline in model performance (Table S3). Interactions with region or LUI affected the associations between belowground, but not aboveground, multidiversity and multifunctionality. The association between the multidiversity of belowground common species and multifunctionality was positive in the southwest, neutral in the central region and negative in the northeast (see interaction coefficients in Fig. S2). LUI also influenced the effect of belowground multidiversity, with associations between the multidiversity of both rare and common species and multifunctionality becoming more positive with decreasing LUI (Fig. S2). Regardless of the interactions with region and LUI, we found a higher importance of aboveground multidiversity for the 75% and 90% thresholds, which shifted towards a higher importance of belowground multidiversity components at the 50% thresholds (Fig. 1; Table S3).

(b) Species level

Apart from the community-level effects of multidiversity, we found significant positive associations between the abundance of individual species and multifunctionality in 6% of the...
species tested, whereas we found negative relationships for 4% of the species (Table S7).

Aboveground rare species had significantly more positive, and fewer negative, relationships with multifunctionality than the aboveground common species did (Fig. 3), a trend not found in belowground organisms. The ratio between positive and negative relationships differed substantially depending on the trophic group studied. Microbial decomposers had more positive than negative relationships with multifunctionality (11% vs. 1%), with the opposite pattern observed in symbionts (4% vs. 10%, Table S7). The remaining trophic groups showed slightly more positive than negative relationships.

Including the abundance, functional traits and response to LUI of the individual species allowed us to predict 13-16% of the variance in the strength of species – multifunctionality associations. The multiple regressions performed revealed that response to LUI was the strongest predictor of the associations between individual species abundance and multifunctionality. Species that increased in abundance in response to LUI were negatively correlated with multifunctionality at the 75% and 90% thresholds (Fig. 4; Table S8).

4. Discussion

(a) Effects of the multidiversity of rare and common species on multifunctionality

The important role that rare species play in maintaining individual ecosystem functions and, to some extent, multifunctionality has been highlighted previously [8, 11, 18-20]. Here, we extend those results to multитrophic assemblages in realistic landscapes, and show that: i) the relative importance of rare species increases when multifunctionality is defined using higher thresholds for the functions and ii) that this relationship remains relatively consistent across study regions and land-use intensities (Fig. 2). Our results show that the ability of ecosystems to maintain a large number of functions at average levels (50% threshold) is mainly driven by
the diversity of common species and, intuitively, by the prevailing environmental conditions (as shown by the significant interactions found in our models). However, the delivery of a smaller number of functions, but at very high levels (75% and 90% thresholds), was mainly related to the multidiversity of rare species. The level of multifunctionality required will depend on stakeholder preferences, but the performance of many functions at their highest potential (high multifunctionality values at high thresholds) can be generally interpreted as a more desirable state of natural ecosystems. Overall, our study shows that the diversity of rare species is consistently and positively related to multifunctionality at the highest levels, thus implying the existence of "win-win" scenarios between biodiversity conservation and ecosystem service provision.

A high diversity of rare species might be more beneficial for multifunctionality than a high diversity of common species if rare species are less likely to negatively affect ecosystem functions. We found that functional trade-offs between species, where some species have positive effects on multifunctionality and others negative effects, were less common amongst rare than common species (Fig. 3). This could explain the stronger positive effect of rare species diversity on multifunctionality. Our correlative study does not allow us to investigate the mechanisms behind the lower incidence of such functional trade-offs in rare species. However, we speculate that if functional effects are driven by the presence of a given species, rather than by its abundance, they are much less likely to be negative. In the case of presence-based functional effects the species is either there, and promotes a given function, or is absent and has no effect. For example, the presence of certain species can promote recreational services such as birdwatching [20], or prevent plant invasions [18, 19]). Such presence-based effects are likely to be the dominant ones amongst rare species. In contrast, functional effects that are proportional to a species' abundance [6] may also be negative. Abundant species can reduce, instead of promote a given function, e.g., species with low specific leaf area can reduce rates of nutrient cycling. Common species are more likely than rare species to have
such abundance-related effects. Therefore, even if the common species are functionally
relevant, they may have opposing functional effects (e.g., the positive effects of a common
productive plant on forage production might be balanced by negative effects of a common
herbivorous insect that feeds upon it). Such strong functional trade-offs between common
species could therefore result in a small effect of common species diversity on
multifunctionality and a greater importance of rare species diversity in promoting
multifunctionality. A complementary explanation for the higher functional importance of rare
species is that they tend to be less redundant than common species in the functional traits they
possess and, therefore, support communities with more distinct combinations of functional
traits [53]. This enhanced functional diversity could also explain the positive functional effect
of the multidiversity of rare species, as functional diversity is related to the provision and
stability of multiple ecosystem functions [54, 55].

While our study provides unique insights regarding the role of community-level
diversity on the provision of multiple functions simultaneously, the use of these aggregate
metrics obscures detailed information regarding the relationships between specific taxa and
functions. A full description of such functions is outside the scope of this study but could
partially explain the relatively low $R^2$ of our models ($< 0.20\%$; see [56] for a full discussion
on the topic). The trade-offs we observed in the functional effects of common species would,
obviously, not apply when studying ecosystem functions in isolation. Another reason for the
relatively low proportion of explained variance could be the influence of factors operating at
large spatial (i.e., surrounding landscape) and temporal scales (i.e., legacy effects of past land-
uses), which were not considered in this study [57].
(b) On the functional role of above- vs. belowground multidiversity

Belowground and aboveground biotic components are known to respond differently to anthropogenic disturbances and are likely to differ in their effects on ecosystem functioning (e.g., [13, 30]); however, very few studies have explored their separate functional roles [23]. We found that aboveground multidiversity, particularly of rare species, was often positively related to multifunctionality at the highest levels, whereas belowground multidiversity was negatively associated with it. Aboveground rare species are highly sensitive to anthropogenic disturbances [13, 29] and these findings suggest that they are also amongst the most functionally important species. Our results support the crucial role of the diversity of aboveground organisms, e.g., plants [1-4, 8], but also herbivores [28] or predators [58] in determining ecosystem multifunctionality.

The stronger positive relationship between above- than belowground diversity with multifunctionality concurs with the only previous study including these two groups separately [23]. It may be argued that the higher importance of above- than belowground components is dictated by the selection of ecosystem functions studied; however, this is unlikely as both our study and Jing et al. [23] included a high proportion of soil-related variables. It seems that, when considered alone, belowground diversity explains variation in multifunctionality that could be mainly due to its correlation with aboveground diversity [23, 58], but further studies are required to test whether the pattern we observed holds across a wide variety of ecosystems and environments. Importantly, our snap-shot sampling design may have reduced our capacity to compare the effects of both above- and belowground multidiversity, as belowground organisms are less sensitive to anthropogenic disturbances [13] and thus they could increase the stability in ecosystem functioning by increasing response diversity [59].

The negative relationship between belowground diversity and ecosystem multifunctionality, however, is surprising and contrasts with previous research (e.g., [23, 60,
Soil biota effects are often driven more by functional composition than by species richness per se (see [60] for a review). Hence, the negative relationship between belowground multidiversity and ecosystem functioning could reflect compositional changes rather than diversity effects [23, 24]. Another potential explanation for these results is that the functional effects of belowground diversity are context-dependent and change with climate or soil (regional differences in our study sites [62]), or with land-use intensification (Fig. S2; see also [23]). The latter could obscure the overall effect of belowground multidiversity on ecosystem functioning, when it is investigated across wide environmental gradients. In this regard, we found strong context-dependency for low (50%) levels of multifunctionality, as the relationship between belowground multidiversity and multifunctionality changed both with study region and land-use intensity (Fig. S2). Regardless of the underlying mechanisms, the contrasting relationships between above- and belowground biotic components and multifunctionality highlight the necessity to consider both in order to better understand the functional consequences of biodiversity loss in realistic landscapes.

(c) Individual species’ effects on multifunctionality

Substantial research effort has been devoted to explain the functional role of individual species in natural ecosystems. Previous research suggests that the most abundant species [6], or a few key species with particular functional traits [32], will have the strongest effect on ecosystem functioning. These two hypotheses have received substantial empirical support across a large variety of systems and individual functions [6, 14, 15, 17, 33-36], but have rarely been tested for multiple functions simultaneously, or across multiple trophic groups. In addition to the effects of the diversity of the entire community, for 10% of the species tested, we found a significant relationship between their abundances and multifunctionality. This suggests that, despite potentially contrasting functional effects (positive, negative or neutral,
depending on the function), some species, even individually, influence the overall ability of ecosystems to simultaneously provide multiple functions. This result supports the identity hypothesis [32, 33], extending it to multiple functions and trophic levels. An example of one of these particularly influential species is *Hieracium pilosella*, plant native to central Europe and locally rare in our study sites. This species was positively associated with multifunctionality according to our method and has previously been shown to increase soil organic C, litter decomposition and microbial biomass in comparison to other grassland species [63], to attract a variety of pollinators [64] and to have a relatively high resistance to pathogenic fungal infections [65]. We found a similar number of influential species for both common and rare species, and for both above- and belowground organisms; indicating that individual species within these biotic components are equally important for multifunctionality. Understanding the attributes of these particularly influential species, and their effects on multifunctionality should be a research priority if we are to predict the consequences of biodiversity loss and compositional changes for ecosystem service provision.

The direction of the relationship between the abundance of individual species and multifunctionality was best predicted by their response to land-use intensification, even after accounting for the range in abundance across the plots and important functional traits. Previous studies have shown that land-use intensification shifts plant functional composition and leads to an increase in the abundance of productive species, which enhance some provisioning services but compromise regulating and cultural services such as carbon storage or aesthetic value, therefore reducing overall multifunctionality [25]. Similarly, changes in the ratio between soil fungi and bacteria with land-use intensification may speed-up nutrient recycling but reduce ecosystem recovery after disturbances [24]. We show here that, alongside reducing their diversity, land-use intensification may substantially influence the effect of multiple trophic levels, via compositional changes, on ecosystem functioning. Our results, therefore, suggest that the negative effect of LUI on multifunctionality at high
thresholds could be, at least partly, caused indirectly by the negative response of particularly influential species to land-use intensification. Such compositional changes might be particularly relevant for belowground communities, whose relationships with multifunctionality (50% threshold) became negative under increasing land-use intensity (Fig. S2).

(d) Conclusion

Substantial research effort has raised awareness of the functional consequences of losing biodiversity. However, we are still far from fully understanding which species or biodiversity attributes conservation efforts should focus on if ecosystem services are to be conserved. Our results suggest that locally rare aboveground species are the most important diversity component to preserve high levels of ecosystem multifunctionality in managed grasslands, perhaps due to their lower proportion of negative functional effects. Our multitrophic approach also supports the identity hypothesis, and extends it to multiple trophic groups and functions by showing, for the first time, that ~10% of the species tested can be particularly associated to overall ecosystem functioning. We also found that the effect of an individual species on multifunctionality is related to its response to land-use intensity, which will help to anticipate the functional consequences of compositional changes across multiple trophic groups caused by land-use intensification.

Authors’ contributions

SS and EA conceived the study, all the authors but SS and EA gathered the data, MG compiled the trait data, SS and EA did the analyses, SS wrote the first draft and all co-authors significantly contributed to improve it.
Competing interests
We declare we have no competing interests.

Funding
This work was funded by the DFG (Deutsche Forschungsgemeinschaft; German Research Foundation) Priority Program 1374 “Infrastructure-Biodiversity Exploratories” (WE 3018/21-1, Li150/22-1). Fieldwork permits were given by the responsible state environmental offices of Baden-Württemberg, Thüringen, and Brandenburg (according to §72 BbgNatSchG).

Acknowledgements
We thank the managers of the three exploratories, Sonja Gockel, Kerstin Wiesner, and Martin Gorke for their work in maintaining the plot and project infrastructure; Simone Pfeiffer and Christiane Fischer giving support through the central office, Birgitta König-Ries and Michael Owonibi for managing the central database, and Eduard Linsenmair, Dominik Hessenmöller, Jens Nieschulze, Ernst-Detlef Schulze, and the late Elisabeth Kalko for their role in setting up the Biodiversity Exploratories project. We are further grateful to Boris Büche, Roland Achtziger, Thomas Wagner, Torben Kölckebeck, Frank Köhler, Theo Blick, Franz Schmolke, Michael-Andreas Fritze, and Günter Köhler for arthropod species identification.

References
1. Hector A, Bagchi R. 2007 Biodiversity and ecosystem multifunctionality. *Nature* **448**, 188–190. (doi:10.1038/nature05947)
2. Zavaleta ES, Pasari JR, Hulvey KB, Tilman D. 2010. Sustaining multiple ecosystem functions in grassland communities requires higher biodiversity. *Proc. Ntl Acad. USA* **107**, 1443-1446. (doi: 10.1073/pnas.0906829107)
3. Maestre FT, Quero JL, Gotelli NJ, Escudero A, Ochoa V, Delgado-Baquerizo M, et al. 2012. Plant species richness and ecosystem multifunctionality in global drylands. *Science* 335, 214–218 (doi: 10.1126/science.1215442)

4. Craven D, Isbell F, Manning P, Connolly J, Bruehlheide H, Ebeling A, et al. 2016. Plant diversity effects on grassland productivity are robust to both nutrient enrichment and drought. *Phyl. Trans. R. Soc. B, in press*

5. Brose U, Hillebrand H. 2016. Biodiversity and ecosystem functioning in dynamic landscapes. *Phyl. Trans. R. Soc. B, in press*

6. Grime JP. 1998 Benefits of plant diversity to ecosystems: immediate, filter and founder effects. *J. Ecol. 86*, 902–910. (doi: 10.1046/j.1365-2745.1998.00306.x)

7. Gamfeldt L, Hillebrand H, Jonsson PR. 2008 Multiple functions increase the importance of biodiversity for overall ecosystem functioning. *Ecology 89*, 1223–1231. (http://dx.doi.org/10.1890/06-2091.1)

8. Isbell F, Calcagno V, Hector A, Connolly J, Harpole WS, Reich PB et al. 2011 High plant diversity is needed to maintain ecosystem services. *Nature 477*, 199–202. (doi:10.1038/nature10282)

9. Lyons KG, Brigham CA, Traut BH, Schwartz MW. 2005 Rare Species and Ecosystem Functioning. *Cons. Biol 19*, 1019-1024 (doi: 10.1111/j.1523-1739.2005.00106.x)

10. McIntyre PB, Jones LE, Flecker AS, Vanni MJ. 2007 Fish extinctions alter nutrient recycling in tropical freshwaters. *Proc. Ntnl Acad. USA 104*, 4461-4466. (doi:10.1073pnas.0608148104)

11. Pendleton R, Hoeinghaus D, Gomes L, Agostinho A. 2014 Loss of rare fish species from tropical floodplain food webs affects community structure and ecosystem multifunctionality in a mesocosm experiment. *PLoS ONE 9*, e84568. (doi:10.1371/journal.pone.0084568).
12. Suding KN, Collins SL, Gough L, Clark C, Cleland EE, Gross KL, et al. 2005. Functional- and abundance-based mechanisms explain diversity loss due to N fertilization. *Proc. Natl Acad. USA* **102**, 4387-4392. (doi: 10.1073/pnas.0408648102).

13. Allan E, Bossdorf O, Dormann CF, Prati D, Gossner MM, Tscharntke T, et al. 2014 Interannual variation in land-use intensity enhances grassland multidiversity. *Proc. Natl Acad. USA* **111**, 308-313. (doi: 10.1073/pnas.1312213111)

14. Smith MD, Knapp AK. 2003 Dominant species maintain ecosystem function with non-random species loss. *Ecol. Lett.* **6**, 509–517. (doi: 10.1046/j.1461-0248.2003.00454.x)

15. Vile D, Shipley B, Garnier E. 2006 Ecosystem productivity can be predicted from potential relative growth rate and species abundance. *Ecol. Lett.* **9**, 1061–1067. (doi: 10.1111/j.1461-0248.2006.00958.x)

16. Longo G, Seidler TG, Garibaldi LA, Tognetti PM, Chaneton EJ. 2013 Functional group dominance and identity effects influence the magnitude of grassland invasion. *J. Ecol.* **101**, 1114–1124. (doi: 10.1111/1365-2745.12128)

17. Kleijn D, Winfree R, Bartomeus I, Carvalheiro L, Henry M, Isaacs R, et al. 2015 Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. *Nature Comm.* **6**, 7414. (doi:10.1038/ncomms8414)

18. Lyons KG, Schwartz MW. 2001 Rare species loss alters ecosystem function – invasion resistance. *Ecol. Lett.* **4**, 358–365. (doi: 10.1046/j.1461-0248.2001.00235.x)

19. Zavaleta ES, Hulvey KB. 2004. Realistic species losses disproportionately reduce grassland resistance to biological invaders. *Science* **306**, 1175–1177. (doi: 10.1126/science.1102643)

20. Booth JE, Gaston KJ, Evans KL, Armsworth PR. 2011 The value of species rarity in biodiversity recreation: A birdwatching example. *Biol. Cons.* **144**, 2728–2732 (doi: 10.1016/j.biocon.2011.02.018)
21. Steudel B, Hector A, Friedi T, Löftke C, Lorenz M, Wesche M, Kessler, M. 2012
Biodiversity effects on ecosystem functioning change along environmental stress gradients.
*Ecol. Lett.* **15**, 1397–1405 (doi: 10.1111/j.1461-0248.2012.01863.x)

22. Perkins DM, Bailey RA, Dossena M, Gamfeldt L, Reiss J, Trimmer M, Woodward G.
2015 Higher biodiversity is required to sustain multiple ecosystem processes across
temperature regimes. *Global Change Biol.* **21**, 396-406 (doi: 10.1111/gcb.12688)

23. Jing X, Sanders, NJ, Shi Y, Chu H, Classen AT, Zhao, K, *et al.* 2015 The links between
ecosystem multifunctionality and above- and belowground biodiversity are mediated by
climate. *Nature Comm.* **6**, 8159. (doi:10.1038/ncomms9159)

24. de Vries FT, Thébault E, Liiri M, Birkhofer K, Tsiafouli MA, Bjørnlund L, et al. 2013
Soil food web properties explain ecosystem services across European land use systems.
*Proc. Ntnl Acad. USA* **110**, 14296-14301. (doi: 10.1073/pnas.1305198110)

25. Allan E, Manning P, Alt F, Binkestein J, Blaser S, Blüthgen N, *et al.* 2015
Land use intensification alters ecosystem multifunctionality via loss of biodiversity and changes to
functional composition. *Ecol. Lett.* **18**, 834–843 (doi: 10.1111/ele.12469)

26. Byrnes JEK, Gamfeldt L, Isbell F, Lefcheck JS, Griffin JN, Hector A, *et al.* 2014
Investigating the relationship between biodiversity and ecosystem multifunctionality:
challenges and solutions. *Methods Ecol. Evol.* **5**, 111–124. (doi: 10.1111/2041-
210X.12143)

27. Flynn DFB, Gogol-Prokurat M, Nogeire T, Molinari N, Richers BT, Lin BB, *et al.* 2009.
Loss of functional diversity under land use intensification across multiple taxa. *Ecol. Lett.*
**12**, 22-33. (doi: 10.1111/j.1461-0248.2008.01255.x.)

28. Lefcheck JS, Byrnes JEK, Isbell F, Gamfeldt L, Griffin JN, Eisenhauer N, *et al.* 2015
Biodiversity enhances ecosystem multifunctionality across trophic levels and habitats. *Nat.
Commun.* **6**, 6936. (doi: 10.1038/ncomms7936)
29. Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J. 2000. Biodiversity hotspots for conservation priorities. Nature **403**, 853–858 (doi:10.1038/35002501)

30. Balvanera P, Siddique I, Dee L, Paquette A, Isbell F, Gonzalez A, *et al.* 2013 Linking Biodiversity and Ecosystem Services: Current Uncertainties and the Necessary Next Steps. *Bioscience** 64,** 49–57. (doi:10.1093/biosci/bit003)

31. Ott D, Guill C, Feudel U, Rall, BC. 2016. The impact of disturbance on biodiversity and ecosystem functioning in multi-trophic communities. *Phyl. Trans. R. Soc. B, in press*

32. Sala OE, Lauenroth WK, McNaughton SJ, Rusch G, Zhang X. 1996. *Biodiversity and ecosystem function in grasslands.* Functional Roles of Biodiversity: A Global Perspective (eds HA Mooney, JH Cushman, E Medina, OE Sala, ED Schulze), pp. 129–149. John Wiley & Sons, New York.

33. McLaren JR, Turkington R. 2010 Ecosystem properties determined by plant functional group identity. *J. Ecol.* **98**, 459–469. (doi: 10.1111/j.1365-2745.2009.01630.x)

34. Mitchell CE, Tilman D, Groth JV. 2002 Effects of grassland plant species diversity, abundance, and composition on foliar fungal disease. *Ecology** 83,** 1713–1726. (doi: http://dx.doi.org/10.1890/0012-9658(2002)083[1713:EOGPSD]2.0.CO;2)

35. Vivanco L, Austin AT. 2008 Tree species identity alters forest litter decomposition through long-term plant and soil interactions in Patagonia, Argentina. *J. Ecol.* **96**, 727–736. (doi: 10.1111/j.1365-2745.2008.01393.x)

36. Maas B, Tscharntke T, Saleh S, Dwi Putra D, Clough Y. 2015 Avian species identity drives predation success in tropical cacao agroforestry. *J. Appl. Ecol.* **52**, 735–743. (doi: 10.1111/1365-2664.12409)

37. Millennium Ecosystem Assessment. 2005 *Ecosystems and human well-being: biodiversity synthesis.* Washington, DC: World Resources Institute
38. Fischer M, Bossdorf O, Gockel S, Hänsel F, Hemp A, Hessenmöller D, et al. 2010 Implementing large-scale and long-term functional biodiversity research: the Biodiversity Exploratories. *Basic Appl. Ecol.* **11**, 473–485 (doi: 10.1016/j.baae.2010.07.009)

39. Blüthgen N, Dormann CF, Prati D, Klaus VH, Kleinebecker T, Hölzel N, et al. 2012. A quantitative index of land-use intensity in grasslands: integrating mowing, grazing and fertilization. *Basic Appl. Ecol.* **13**, 207–220. (doi: 10.1016/j.baae.2012.04.001)

40. Gaston KJ. 1994 *Rarity.* Springer, Cornwall, UK (doi: 10.1007/978-94-011-0701-3)

41. Burnham KP, Anderson, DR. 2002 *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach.* Springer-Verlag, New York, US.

42. Gessler PE, Moore ID, McKenzie NJ, Ryan PJ. 1995 Soil-landscape modelling and spatial prediction of soil attributes. *Internatnl J. Geogr. Info. Syst.* **4**, 421–432. (doi: 10.1080/02693799508902047)

43. Sørensen R, Sinko U, Siebert J. 2006 On the calculation of topographic wetness index: evaluation of different methods based on field observations. *Hydrol. Earth Syst. Sci.* **10**, 101–112. (doi: 1812-2116/hessd/2005-2-1807)

44. Kittle AM, Fryxell JM, Desy GE, Hamr J. 2008 The scale-dependent impact of wolf predation risk on resource selection by three sympatric ungulates. *Oecologia* **157**, 163–175. (doi: 10.1007/s00442-008-1051-9)

45. Gotelli NJ, Ulrich W, Maestre FT. 2011 Randomization tests for quantifying species importance to ecosystem function. *Methods Ecol. Evol.* **2**, 634–642. (doi: 10.1111/j.2041-210X.2011.00121.x)

46. Ulrich W. 2010. *Impact – a FORTRAN program for gradient analysis.* Version 1.0.

http::www.umk.pl/~ulrichw.

47. Kleyer M, Bekker RM, Knevel IC, Bakker JP, Thompson K, Sonnenschein M, et al. 2008 The LEDA Traitbase: a database of life-history traits of the Northwest European flora. *J. Ecol.* **96**, 1266–1274. (doi: 10.1111/j.1365-2745.2008.01430.x)
48. Gossner MM, Simons NK, Achtziger R, Blick T, Dorow WHO, Dziock F, et al. 2015. A summary of eight traits of Coleoptera, Hemiptera, Orthoptera and Araneae, occurring in grasslands in Germany. *Scientific Data* 2, 150013 (doi:10.1038/sdata.2015.13)

49. Simmons NK, Weisser WW, Gossner MM. 2015 Multi-taxa approach shows consistent shifts in arthropod functional traits along grassland land-use intensity gradient. *Ecology*, in press (doi: http://dx.doi.org/10.1890/15-0616.1)

50. Birkhofer K, Smith HG, Weisser WW, Wolters V, Gossner M. 2015 Land-use effects on the functional distinctness of arthropod communities. *Ecography* 38, 1-12 (doi: 10.1111/ecog.01141)

51. Garnier E, Lavorel S, Ansquer P, Castro H, Cruz P, Dolezal J, et al. 2007 Assessing the Effects of Land-use Change on Plant Traits, Communities and Ecosystem Functioning in Grasslands: A Standardized Methodology and Lessons from an Application to 11 European Sites. *Ann. Bot.* 99, 967–985(doi: 10.1093/aob/mcl215)

52. R Core Team. 2013 *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria

53. Mouillot D, Bellwood DR, Baraloto C, Chave J, Galzin R, Harmelin-Vivien M, et al. 2013. Rare Species Support Vulnerable Functions in High-Diversity Ecosystems. *PLoS Biol* 11(5): e1001569. (doi:10.1371/journal.pbio.1001569).

54. Mouillot D, Villéger S, Scherer-Lorenzen M, Mason NWH. 2011. Functional Structure of Biological Communities Predicts Ecosystem Multifunctionality. *PLoS ONE* 6(3): e17476. (doi:10.1371/journal.pone.0017476).

55. Valencia E, Maestre FT, Le Bagousse-Pinguet Y, Quero JL, Tamme R, Börger L, et al. 2015. Functional diversity enhances the resistance of ecosystem multifunctionality to aridity in Mediterranean drylands. *New Phytol.* 206, 660-671 (doi: 10.1111/nph.13268).

56. Bradford MA, Wood SA, Bardgett RD, Black HIJ, Bonkowski M, Eggers T, et al. 2014. Discontinuity in the responses of ecosystem processes and multifunctionality to altered soil
community composition. *Proc. Ntl Acad. USA* **111**, 14478-14483. (doi: 10.1073/pnas.1413707111).

57. Gámez-Virués S, Perović DJ, Gossner MM, Börschig C, Blüthgen N, Jong HD, *et al.* 2015. Landscape simplification filters species traits and drives biotic homogenization. Nature Communications, 6, 8568 (doi:10.1038/ncomms9568).

58. Birkhofer K, Diekötter T, Boch S, Fischer M, Müller J, Socher S, Wolters V. 2011 Soil fauna feeding activity in temperate grassland soils increases with legume and grass species richness. *Soil Biol. Biochem.* **43**, 2200–2207. (doi: 10.1016/j.soilbio.2011.07.008)

59. Karp DS, Ziv G, Zook J, Ehrlich PR, Daily GC. 2011. Resilience and stability in bird guilds across tropical countryside. *Proc. Ntl Acad. USA* **108**, 21134-21139. (doi: 10.1073/pnas.1118276108).

60. Bardgett RD, van der Putten WH. 2014 Belowground biodiversity and ecosystem functioning. *Nature* **515**, 505–511. (doi: 10.1038/nature13855)

61. Wagg C, Bender SF, Widmer F, van der Heijden MGA. 2014 Soil biodiversity and soil community composition determine ecosystem multifunctionality. *Proc. Ntl Acad. USA* **111**, 5266-5270. (doi: 10.1073/pnas.1320054111)

62. Birkhofer K, Schöning I, Alt F, Herold N, Klamer B, Maraun M, *et al.* 2012 General relationships between abiotic soil properties and soil biota across spatial scales and different land-use types. *PLoS ONE* **7**, e43292 (doi: 10.1371/journal.pone.0043292)

63. Saggar S, McIntosh PD, Hedley CB, Knicker H. 1999 Changes in soil microbial biomass, metabolic quotient, and organic matter turnover under *Hieracium* (*H. pilosella* L.). *Biol Fertil Soils* **30**, 232–238 (doi: 10.1007/s003740050613)

64. Butz Huryn VMH, Moller H. 1995 An assessment of the contribution of honey bees (*Apis mellifera*) to weed reproduction in New Zealand protected natural areas. *New Zealand. J. Ecol.* **19**, 111–122 (doi: 10.1080/00779962.2010.9722196)
65. Morin L, Syrett P. 1996 Prospects for biological control of *Hieracium pilosella* with the rust *Puccinia hieracii var. piloselloidarum* in New Zealand. *Proceedings of the IX International Symposium on biological control of weeds*, pp. 199-204 (Moran VC, Hoffmann JH, eds.) (ISBN: 0-7992-1759-X)

**Supporting Information**

Additional Supporting Information may be downloaded via the online version of this article at the journal website ([http://rstb.royalsocietypublishing.org](http://rstb.royalsocietypublishing.org)).

**Table S1.** Details of diversity measurements.

**Table S2.** Details of ecosystem functioning measurements.

**Table S3.** Multi-model selection presented in the main text.

**Table S4.** Multi-model selection of the analyses with the 50% (instead of the 90%) least abundant species as a measure of rare species.

**Table S5.** Multi-model selection of the analyses with abundance instead of diversity.

**Table S6.** Summary of the data at the species level (Excel file).

**Table S7.** Species-specific functional effects organized by trophic group.

**Table S8.** Multiple regression results (species-level analysis).

**Figure S1.** Abundance distribution of common and rare species within each trophic group.

**Figure S2.** Standardized coefficients obtained from model averaging.
**Figure captions.**

**Figure 1.** Importance of the different multifunctionality predictors as assessed by the sum of the AIC weights of the models in which each one was retained, divided by the number of models in which each variable was introduced. Green and brown indicate predictors associated with above and belowground multidiversity, which included the overall diversity of plants, bryophytes, and herbivore, carnivore and decomposer arthropods [aboveground] and soil bacteria, bacterivore protists, arbuscular mycorrhizal fungi and herbivore and carnivore insects [belowground]). Hatched bars indicate negative effects. Common = multidiversity of the top 10% most abundant species (80% of the individuals sampled), rare = multidiversity of the 90% least abundant species (20% of the individuals sampled). Region × indicates the interaction term between study region and a given multidiversity metric. LUI × indicates the interaction term between land-use intensity and a given multidiversity metric. The $R^2$ of the best model for each multifunctionality metric (first row in Table S3) is provided.

**Figure 2.** Effect of multidiversity of above- and belowground, common and rare species on the different levels of multifunctionality. Slopes (with confidence intervals) were calculated after controlling for the other predictors in the model, and are shown in blue if selected in the best models (see Table S3; Fig. S2). Note that dots are residuals of both multidiversity and multifunctionality metrics after filtering by study region, LUI, soil pH and depth and the topographic wetness index.

**Figure 3.** Summary of the relationships between individual species and multifunctionality. The percentage (according to the number of species tested) of significant positive (green) and negative (red) effects are shown. The averaged results across each category (common vs. rare species, aboveground and belowground) are shown. Significant differences ($P < 0.05$)
comparing the proportion of positive and negative effects in common and rare species according to Fisher’s exact test are highlighted as "*" ("ns" not significant).

**Figure 4.** Relationship between the effect of each species (dots) on multifunctionality (standardized effect size) and its response to land-use intensity (LUI). Different colors in dots and lines indicate the relationship found for each trophic group (slopes calculated after filtering by number of sites and average abundance). The black lines indicate the overall relationship (after filtering for the same factors, and trophic group). Response to land-use intensity was measured as the standardized slope of a regression between LUI and the abundance of each species.
Figure 1

Importance of effects on multifunctionality (unitless)

50% threshold
$R^2 = 0.18$

75% threshold
$R^2 = 0.16$

90% threshold
$R^2 = 0.10$

- Belowground
- Aboveground

Common, Rare, Region x Common, Region x Rare, LUI x Common, LUI x Rare
Figure 2
Figure 3

Percentage of significant species-specific effects (vs total effects tested)

- **50% threshold**: ns
- **75% threshold**: ns
- **90% threshold**: *

Legend:
- **Negative**
- **Positive**
Figure 4

Individual-species effect on multifunctionality (unitless)

50% threshold

75% threshold

90% threshold

Species response to land-use intensity (unitless)