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Grassland stability decreases with increasing number of global change factors: A meta-analysis

Zhaobin Song [a,b,c], Yann Hautier [d], Chao Wang [a,*]

[a] Institute of Grassland, Flowers and Ecology, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, China
[b] Urat Desert-grassland Research Station, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Science, Lanzhou 730000, China
[c] University of Chinese Academy of Sciences, Beijing 100049, China
[d] Ecology and Biodiversity Group, Department of Biology, Utrecht University, Padualaan 8, 3584 CH Utrecht, Netherlands

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ABSTRACT

Experiments manipulating a single global change factor (GCF) have provided increasing evidence that global environmental changes, such as eutrophication, precipitation change, and warming, generally affect the temporal stability of grassland productivity. Whether the combined impact of global changes on grassland stability increases as the number of global changes increases remains unknown. Using a meta-analysis of 673 observations from 143 sites worldwide, including 7 different GCFs, we examined the responses of grassland temporal stability of productivity to increasing numbers of GCFs. We quantified the links between community stability, biotic factors (i.e., species richness, species stability, and species asynchrony), and abiotic factors (i.e., aridity index, experimental duration, and experimental intensity). Although inconsistent responses of community stability were found with different GCF types and combinations, when integrating existing GCFs studies and ignoring the identity of GCFs, we found a general decrease in community stability as the number of GCFs increases, but the main drivers of community stability varied with the numbers of GCFs. Specifically, one GCF mainly reduced species stability through species richness and thus weakened community stability. Two GCFs weakened community stability via independently weakening species stability and species asynchrony. Three GCFs reduce community stability mainly via independently weakening species asynchrony. Moreover, for single factor, the impact of GCFs on community stability was weaker under dryer conditions, but stronger when two or three factors were manipulated. In addition, the negative effect of GCFs on community stability was weaker with increasing experimental duration. Our study reveals that reduced community stability with increasing numbers of GCFs is caused by a shift from reduced species stability to reduced species asynchrony, suggesting that persistent global changes will destabilize grassland productivity by reducing asynchronous dynamics among species in response to natural environmental fluctuations.

1. Introduction

Terrestrial ecosystems are facing multiple global changes caused by human activities, such as precipitation alteration, eutrophication, global warming, and increased CO_2 concentration (Hallett et al., 2014; Hautier et al., 2014; Zelikova et al., 2014; Wu et al., 2020). Many experiments have been conducted in grasslands during the last decades to investigate the impact of these global environmental changes on biodiversity usually measured as the number of plant species (Reich et al., 2001; Isbell et al., 2013) and temporal stability of grassland productivity, usually measured as the ratio of the temporal mean of productivity to its temporal variation (Tilman et al., 2006; Hautier et al., 2014; Hautier and Van Der Plas, 2022). However, while anthropogenic global changes generally co-occur (Zhou et al., 2023) and can have interactive effects on biodiversity and ecosystem stability (Harpole et al., 2016; Yue et al., 2017a; Zhang et al., 2017; Wu et al., 2020), our knowledge on whether and how grassland stability responds to increasing the number of global change factors(GCFs) mainly derived from studies manipulating a single GCF.

Previous experiments have shown that GCFs often show divergent impact on grassland community stability (Koerner et al., 2016; Dijkstra et al., 2018; Liu et al., 2019; Muraina et al., 2021; Ke et al., 2022). For

* Corresponding author at: Institute of Grassland, Flowers and Ecology, Beijing Academy of Agriculture and Forestry Sciences, No. 9 Shuguang Garden Middle Road, Haidian District, Beijing 100097, China.
E-mail address: wangchao@grass-env.com (C. Wang).

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example, increased precipitation and warming often promote the community stability in grassland (Hallett et al., 2014; Ma et al., 2017), while the addition of nitrogen (N) and elevated CO_2 concentrations often reduced it (Zelikova et al., 2014; Zhang et al., 2016; Zhang et al., 2017). The interactive effects of global changes on community stability usually can be divided into three patterns: synergistic, additive, and antagonistic effects (Berlinches De Gea et al., 2022). For instance, warming and N addition had additive, negative effects on the stability of community productivity in a desert steppe in northern China (Wu et al., 2020). A global meta-analysis found that water and nutrient addition increased community productivity more than the sum of their individual effects, creating synergistic effects (Demalach et al., 2017). Instead, previous manipulative experiment found that elevated CO_2 alleviated the negative effects of N enrichment on community diversity, resulting in antagonistic effects (Reich, 2009). Hence, with increasing number of GCFs, the response of community stability would be more complex. Recent studies proved that increasing the number GCFs reduced plant diversity, microbial biodiversity, and soil functions (Rillig et al., 2019), and eliminated the effects of soil microbial diversity on ecosystem functions (Yang et al., 2022), but enhanced community productivity (Speiβer et al., 2022). These results suggest that single factors in GCFs may have relatively minor impacts on the ecosystem, whether positive, negative, or neutral, and that the increase in the number of GCFs will have directional impacts on biodiversity and ecosystem functioning (Rillig et al., 2023). However, whether the directional impact of the number of GCFs on grassland stability will occur remains unclear at the global scale. Filling this knowledge gap is critical, as the stable provision of ecosystem services is essential for both the human world and nature, especially in the face of growing concerns about the widespread environmental conditions caused by anthropogenic impacts.

Worries that global change compromises stability have led to a growing number of theoretical and experimental studies investigating how GCFs influenced stability (Zelikova et al., 2014; Isbell et al., 2015; Hautier and Van Der Plas, 2022). Higher community stability can be achieved through two processes. First, community stability can be maintained via higher average temporal stability of all species in the community (species stability) because of the low annual variation in the production of individual species (Thibaut and Connolly, 2013; Wang et al., 2019). Second, community stability can be maintained via more asynchronous temporal dynamics among species in response to environmental fluctuations (species asynchrony), as declines in productivity of some species are compensated by increases in others over time (Thibaut and Connolly, 2013; Wang et al., 2019). Additionally, plant diversity can stabilize community productivity by increasing species stability and species asynchrony (Hautier et al., 2020; Yan et al., 2021). Previous shown that increasing GCFs number usually increase community productivity but decrease plant diversity (Speiβer et al., 2022). Higher GCFs number may therefore stabilize community stability by increasing the temporal mean of productivity or destabilize community stability through the reduction in species stability and species asynchrony. In addition, GCF numbers may destabilize community stability by weakening the stabilizing effect of plant diversity on community productivity (Yang et al., 2022). However, as the number of GCFs increases, it is currently unclear whether the contribution of diversity to grassland community stability will increase, or decrease as reported in a previous study (Hautier et al., 2014). To our knowledge, only one recent study examined the effects of GCF number on plant biodiversity and ecosystem functioning (Rillig et al., 2019). That study showed that higher numbers of GCFs lead to a decrease in biodiversity and an increase in productivity. Whether these effects propagate to impact on community stability is not clear.

In addition, there is increasing evidence that abiotic factors (climatic conditions, treatment intensity, and experimental duration) can influence plant community responses to GCFs (Komatsu et al., 2019; Song et al., 2019; Gilbert et al., 2020; Li et al., 2022; Su et al., 2022; Wagg et al., 2022). Recently, a meta-analysis presented direct evidence that these abiotic factors play an essential role in ecosystem stability through biodiversity effects (Su et al., 2022). For example, reduced precipitation tends to reduce community stability more because plants in wetter areas are less resistant to drought (Wilcox et al., 2020; Su et al., 2022). Similarly, high grazing intensity is more destabilizing to grassland stability than low grazing intensity (Tang et al., 2020). The effect of precipitation increase on community stability increases as the experimental period increases, but the effect of nutrient addition on community stability is relatively minor (Su et al., 2022). However, we know little about whether the effects of abiotic factors varied with the number of GCFs, which will hamper the predictions of grassland stability in the real world.

Here, we conducted a meta-analysis to assess the effects of GCF numbers (including single, two, and three GCFs) on grassland temporal stability at the global scale, using the published literature from 143 globally distributed field-manipulated experiments in grasslands. Specifically, our study addressed three questions: 1) whether the impact of global changes on community stability decreases as the number of GCFs increases, 2) whether the main drivers of community stability vary with GCF number, 3) whether the effects of abiotic factors on community stability vary with increasing the number of GCFs.

2. Materials and methods

2.1. Data collection

In order to investigate the effects of multiple GCFs on community stability as GCFs increased, we collected all peer-reviewed publications between 1980 and 2021 using ISI Web of Science (isiknowledge.com) and the China National Knowledge Infrastructure (CNKI, https://www.cnki.net). The keywords and terms used were as follows: ("production" OR "productivity" OR "biomass") AND ("stability") AND ("diversity" OR "climate change" OR "warming" OR "rising temperature" OR "increase temperature" OR "rainfall" OR "precipitation" OR "drought" OR "water" OR "N addition" OR "nitrogen addition" OR "nitrogen enrichment" OR "nitrogen deposition" OR "eutrophication" OR "P addition" OR "phosphorous addition" OR "fertility" OR "graze" OR "grazing") AND ("grassland" OR "steppe" OR "alpine" OR "meadow"). The following criteria were applied to select studies: (1) experiments conducted in the field that reported the effects of GCFs on community stability; and (2) experiments that had at least one pair of data points relationship between biotic factors (e.g., richness, species asynchrony and species stability) and community stability and that reported standard deviations/errors or numbers of replicates. Means, standard deviations/errors and sample sizes were extracted from tables or digital graphs using GetData Graph Digitizer (v.2.24; http://www.getdata-graph-digitizer.com/). The WorldClim database at http://world clim.org was used to extract mean annual precipitation (MAP) and mean annual temperature (MAT) using the location information (latitude and longitude). Given that some publications investigated site within a study across different period, the number of study sites (143; Fig. 1) was lower than the number of publications (155; Fig. S1 and Table S1). Overall, based on a total of 143 sites (Fig. 1), 4 biotic factors (Fig. S2) and 7 GCFs (Fig. S3) were reported in our meta-analysis.

For each study, we extracted the data in terms of community stability, mean of productivity/ biomass, standard deviation (SD) of productivity/ biomass, species richness, species stability, abundance, reference ecosystem types, experimental duration (year), treatment intensity, treatment type, longitude and latitude from the original papers. We derived the sample sizes corresponding to each observation based on the number of independent experimental units. We divided the reference GCFs combinations into three groups: single factor (106 sites), two factors (32 sites), and three factors (5 sites) (Fig. 1). We examined the potential influence of publication bias on our results via Egger's test (Fig. S2) with the "*metabias*" function in R 3.5.1 (R Core Team, 2018).

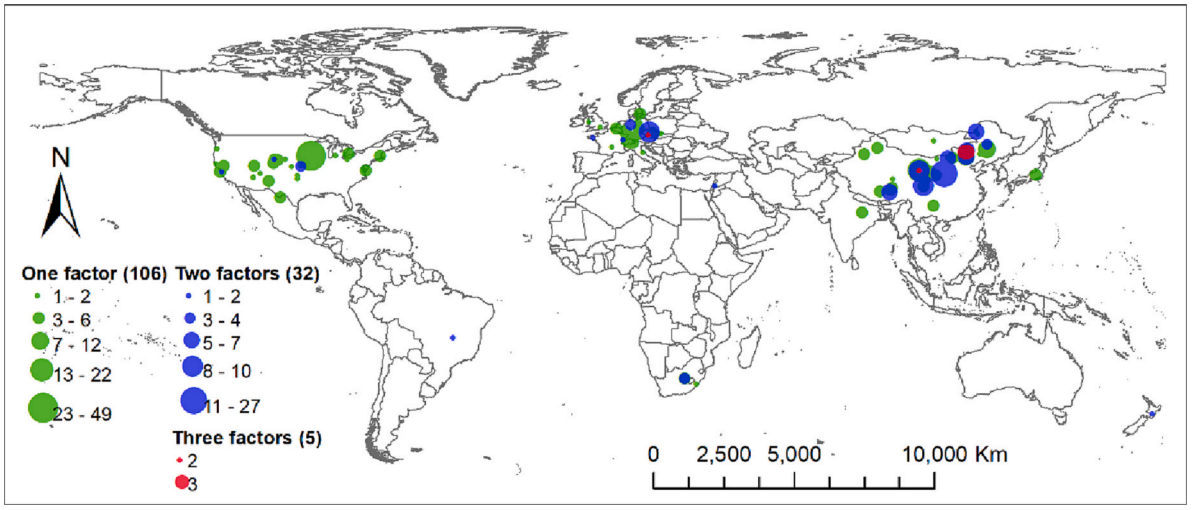

Fig. 1. Global distribution of selected experiments investigating the effects of global changes on community stability. Different-colored bubbles represent different number of global change factors. The size of the bubbles is the number of the samples.

2.2. Data analysis

In order to assess the effects of GCFs on community stability and its underlying mechanisms (species richness, species asynchrony and species stability, temporal mean and SD of productivity) under various GCF numbers, we used the techniques described by (Hedges et al., 2018) and (Gurevitch et al., 2018). The following formula was used to calculate the logarithmic response ratio (lnRR):

$$lnRR = ln\left(\frac{x_T}{x_\tau}\right) \quad (1)$$

where $\bar{x}_c$ and $\bar{x}_t$ are the means of the variable in control treatment and reference global change treatment, respectively. R 3.5.1 (R Core Team, 2018) was used to estimate the weighted average response ratios using random-effects models (Cooper et al., 2009). According to sample sizes and between-sample variability (Chen et al., 2019), weights for lnRR (W_R) were estimated:

$$W_R = \left(\frac{N_t \times N_c}{N_t \times N_c} + \tau^2\right)^{-1} \quad (2)$$

where N_c and N_t are the sample sizes for the variable in control treatment and reference global change treatment, respectively, τ^2 is the total amount of heterogeneity, and Q_M test was conducted to estimate the significance of the differences in the RRs among different numbers of the GCFs (Hedges et al., 2018; Fig. 2 and Fig. S3).

Using model-selection analysis in the R package "*glmulti*" (Terrer et al., 2016), explored the relative effects of multiple variables on community stability responses at different numbers of GCFs (Fig. 3). The relative importance for each variable was determined as the total of the Akaike weights for all the models in which the variable was included (Terrer et al., 2016). In order to distinguish between important and unimportant predictors, a cut-off of 0.8 was established. MAT, MAP, mean aridity index, treatment types, experimental duration, species stability, species richness, and species asynchrony were included in the model-selection. RR were grouped based on the numbers of the GCFs.

In order to investigate the relationships between the responses of community stability, the responses of biotic factors (i.e., species stability, species richness, and species asynchrony) (Fig. 4, Fig. S4, and Table S2), and the responses of abiotic factors (i.e., MAT, MAP, aridity index, treatment, and experimental duration) (Fig. 5 and Fig. S5), we performed meta-regressions using the inverse of the variance as the weight. Using the "*piecewiseSEM*" package in R 3.5.1 (Lefcheck, 2016), we conducted structural equation models (SEMs) to test the hypotheses

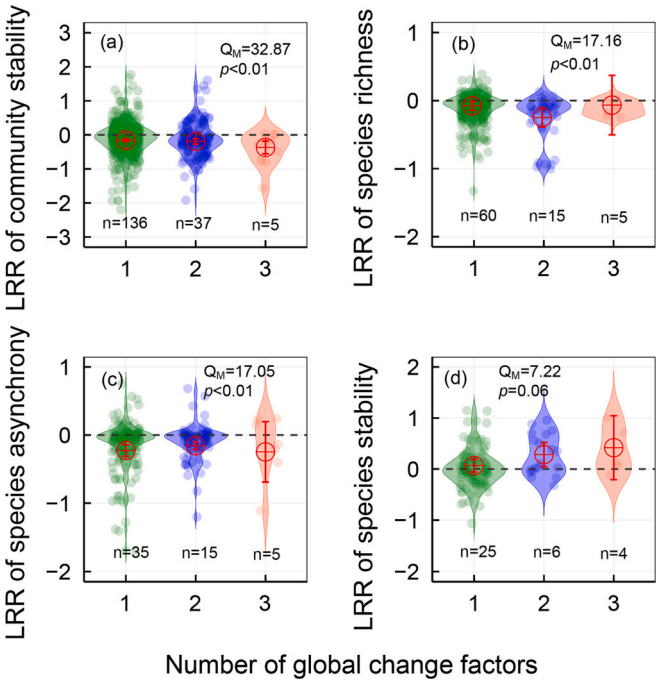

Fig. 2. Effects of different global change drivers on grassland community stability (a), species richness (b), species asynchrony (c), and species stability (d). Error bars depict 95 % confidence intervals. The effects of an individual global change driver are considered significant if the CIs do not overlap with zero. Q_M, the heterogeneity in effect sizes associated with moderator variable; 1, 2, and 3 represent single, two, and three global change factors, respectively. n represents the number of studies.

that biotic and abiotic factors influenced the effects of GCFs on community stability (Fig. 6, Fig. S6, Fig. S7, and Fig. S9). In addition, we analyzed the contribution of temporal mean and SD of productivity to community stability with increasing GCFs using SEMs (Fig. S9). First, a complete model that took into account all potential pathways was taken into consideration (Fig. S6). Then, non-significant pathways were gradually removed one by one until we attained the final model (Fig. 6). Model-fitting statistics were used to evaluate the reliability of models, including χ^2 tests and *p*-values for χ^2 tests ($p > 0.05$ represents that the model is reliable).

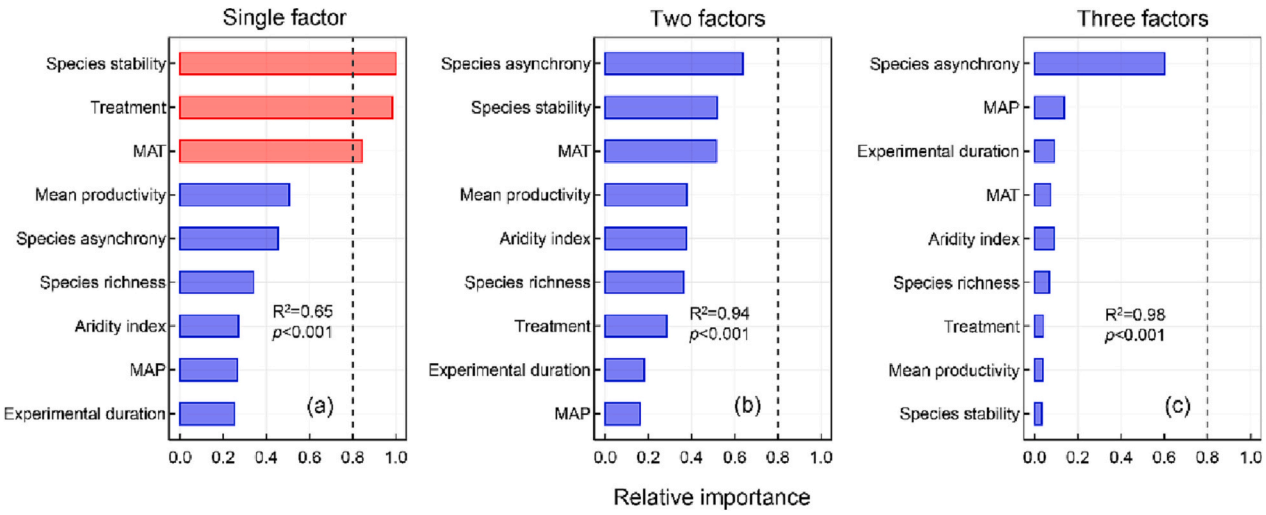

Fig. 3. Model-averaged importance of the predictors for the effects of global change on community stability at different number of factors. The relative importance value is based on the sum of the Akaike weights derived from the model selection using corrected Akaike's Information Criteria. Cutoff is set at 0.8 to differentiate between essential and nonessential predictors. MAP, mean annual precipitation; MAT, mean annual temperature.

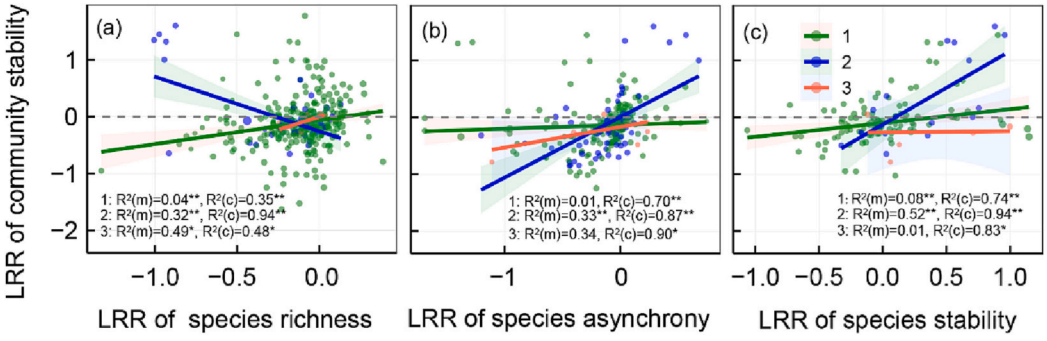

Fig. 4. The associations of community stability with species richness (a), species asynchrony (b), and species stability (c). Lines with different colors represent different global change factor levels. 1, 2, and 3 represent single, two, and three global change factors, respectively, from the mixed-effects models with site as random intercept. The shade areas indicate the 95 % confidence intervals for the regression lines. The R^2(m) and R^2(c) represent model variations explained by fixed effects and the combination of fixed and random effects respectively. Asterisk represents that coefficients are significant: $^{**}p \leq 0.01$, $^{*}p \leq 0.05$.

3. Results

3.1. Community stability response to increasing number of GCFs

Generally, increasing the number of GCFs had a strong impact on grassland community stability (Fig. 2a and Fig. S3). Specifically, community stability decreased with increasing number of GCFs considered integrating existing studies (Fig. 2a). In addition, the response of community stability depended on the types and combinatorial patterns of GCF manipulated (Fig. S3). Species richness and species asynchrony decreased under single and two factors, and species stability increased under two factors (Fig. 2b, c). But we did not find a significant change in these biotic factors under three factors (Fig. 2d). Besides, temporal mean and SD of productivity enhanced with increasing number of GCFs (Fig. S8).

3.2. Factors regulating community stability responses to increasing number of GCFs

The model-selection analysis showed that species stability, treatment, and MAT were the most important predictors for community stability responses to a single GCF, species asynchrony and species stability were the most important predictors under two GCFs, and species asynchrony was the most important predictor under three GCFs (Fig. 3). Meta-regression showed that community stability was positively associated with species richness and species stability under single GCF; it was positively associated with species asynchrony and species stability, but negatively associated with species richness under two GCFs; community stability was positively associated with species richness under three GCFs (Fig. 4). Furthermore, the drivers of community stability varied with type of GCFs (Fig. S4 and Table S2). In general, the community stability responses to global changes were affected by climatic conditions, treatment intensity, and experimental duration (Fig. 5 and Fig. S5). Specifically, the effect of global changes on community stability was negatively associated with aridity index under a single GCF, but was positively associated with aridity index under two GCFs (Fig. 5a). The negative effect of global changes increased logarithmically with experimental duration under single GCF (Fig. 5b).

3.3. The mechanisms of stability driven by biotic factors responses to the increasing number of GCFs

We finally used SEM to quantify the direct and indirect impacts of biotic factors and abiotic factors on community stability under multiple GCFs (Fig. 6, Fig. S6, Fig. S7, and Fig. S9). When abiotic factors were included, we did not find their role in driving grassland stability (Fig. S6), and we subsequently removed these abiotic factors and analyzed the mechanisms whereby biotic factors drive community stability (Fig. 6 and Fig. S7). We found that under overall scenarios, SEM revealed that the number of GCFs contributed to greater community

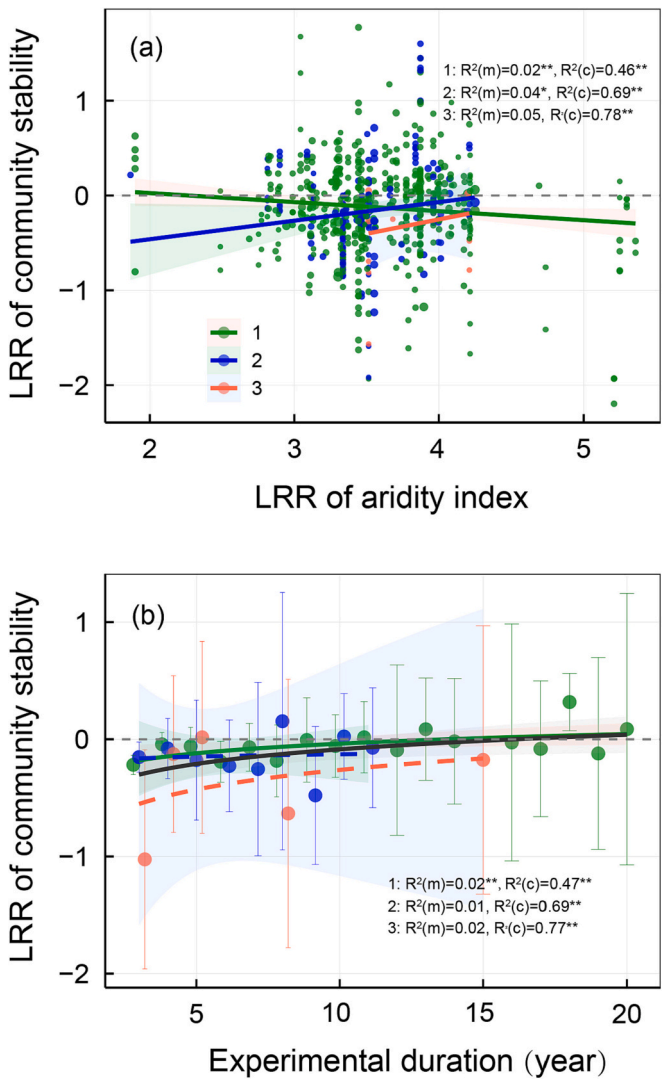

Fig. 5. The associations of community stability with aridity index (a) and experimental duration (b). The solid and dashed black lines indicate significant and insignificant overall relationships, respectively, from the mixed-effects models with site as random intercept. The shade areas indicate the 95 % confidence intervals for the regression lines. The R^2(m) and R^2(c) represent model variations explained by fixed effects and the combination of fixed and random effects respectively. Asterisk represents that coefficients are significant: $^{**}p \leq 0.01$, $^{*}p \leq 0.05$. Lines with different colors represent different global change factor levels. 1, 2, and 3 represent single, two, and three global change factors, respectively.

stability via promoting species stability, while the number of GCFs reduced the community stability by decreasing species asynchrony indirectly via reducing species richness (Fig. 6a). When considering single factor treatments (single scenario), we found that species richness contributed to community stability via species stability, and we also found species asynchrony contributed to community stability alone (Fig. 6b). The positive contribution of species stability and species asynchrony to community stability did not link to species richness and their contributions were nearly equivalent under two GCFs (Fig. 6c). In addition, species asynchrony positively contributed to community stability alone under three GCFs (Fig. 6d). Compared with the number of GCFs results, our SEM also revealed the various biotic mechanisms among the effects of GCFs on community stability (Fig. S7). Furthermore, our SEM also revealed that increased GCFs decreased community stability mainly by increasing productivity SD. Specifically, community stability was co-driven by temporal mean productivity and its SD under single GCF, but was mainly driven by SD of productivity under two and three GCFs (Fig. S9).

4. Discussion

Many studies have quantified the impact of GCFs on community stability based on synthesis analysis and field experiments (Hautier et al., 2015; Jia et al., 2022; Ke et al., 2022; Su et al., 2022; Xu et al., 2022). Unlike previous syntheses, this analysis mainly examined the number of GCFs direct and indirect effects on community stability. Our results show that an increased number of GCFs weakened community stability when ignoring the identity of GCFs. The indirect effect of GCFs on community stability is mediated by species richness, species asynchrony, and species stability. Most interestingly, the key driver of community stability gradually shifted from species stability to species asynchrony as the number of GCFs increase.

4.1. Increasing GCF numbers weakened community stability

Consistent with previous global studies reporting that increasing GCFs numbers weakened ecosystem functions (Rillig et al., 2021; Rillig et al., 2023), when integrating existing studies on GCFs and not considering GCF identity, we found that increasing the number of GCFs reduces the community stability. However, inconsistent responses were found with different GCF combinations. In our study, most of single GCF (6/7), two GCF combinations (8/10), and all three GCF combinations decreased community stability (Fig. S3). These suggest a strong sampling effect in our meta-analysis (Speiβer et al., 2022). Another possible explanation is that as more GCFs occur simultaneously, less species become adaptable (Zandalinas et al., 2021; Speiβer et al., 2022), which could lead to the destabilization of intrinsic dynamics within grassland communities (Jones et al., 2017; Liu et al., 2018; Komatsu et al., 2019). For instance, drought may expose plants to water stress, while warming may cause the loss of water from the soil, thereby exacerbating the water stress faced by plants (Liu et al., 2018). In addition, existing manipulative studies have shown that the increase of GCF number could destabilize community productivity via weakening soil microbial diversity and its positive impacts on soil function (Wagg et al., 2021; Yang et al., 2022). Given the tight interaction among soil microorganisms, soil functions, and plants communities (Liu et al., 2022), the negative effects of increasing numbers of GCFs on soil properties may affect community stability via the suppression of nutrient uptake and growth of plants (Sokol et al., 2022).

While a recent mesocosm pot experiment reported persistent negative effects of GCFs on plant community properties (Speiβer et al., 2022), we found that increasing numbers of GCFs have inconsistent effects on species richness, species asynchrony, and species stability in strength and direction. This is not surprising that this study incorporated a mix of GCFs identity and intensity, grassland types, experimental duration, and climate conditions, and it is challenging to observe directional changes of these biotic factors when the communities are sensitive to global change differently across regions (Seddon et al., 2016). In addition, we did not find significant changes in these biotic factors under the three GCFs. This may be attributed to the fact that the statistical power was limited by the small size data of three GCFs distributing in similar regions and containing relatively few grassland types (alpine meadow, temperate grassland and desert steppe) in our study (Yue et al., 2017b). Overall, our study further extends previous evidence of the aggravated impact of increasing numbers of GCFs on ecosystem functioning and services reported by integrative analyses at a global scale (Rillig et al., 2019; Rillig et al., 2023). The results suggest that the effect of global change on ecosystem functioning is a multi-factor process but cannot be predicted solely based on the effects of single factors, as the overall effect on the community is amplified and complex by their interactions (Komatsu et al., 2019).

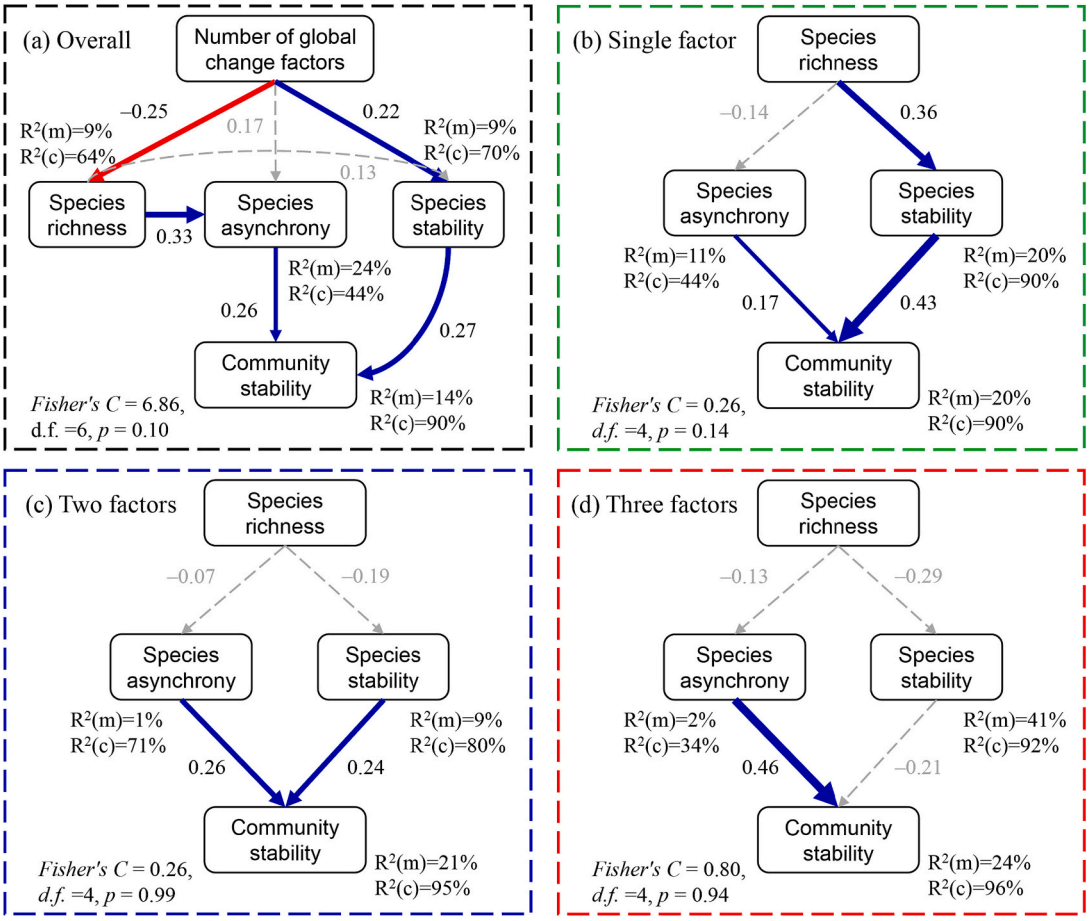

Fig. 6. Structural equation model exploring the effects of species richness, species asynchrony, and species stability on community stability under overall (a), single (b), two (c), and three (d) global change factors. Solid blue and red arrows represent significant ($p \leq 0.05$) positive and negative pathways, respectively. Grey dashed arrows represent insignificant pathways ($p > 0.05$). Standardized path coefficients are given next to each path.

4.2. Species asynchrony matters more than species stability and richness as GCFs increase

We found extensively documented positive relationships among species richness, species asynchrony, species stability, and community stability under most global change scenarios (Xu et al., 2015; Liu et al., 2021; Muraina et al., 2021; Quan et al., 2021; Wang et al., 2021). However, there is an inverse link between species richness and community stability under two GCFs, and again, under the P addition (Fig. S4), which may be because of the inconsistent response of species richness and community stability to specific GCFs (Speiβer et al., 2022), and thus determined the response of diversity-stability relationships to global change numbers. Furthermore, the model selection analysis indicates that species stability or species asynchrony is critical factors stabilize community productivity under different numbers of GCFs, while the SEM reveals that the effect of species richness on community stability was dismantled by species stability, species asynchrony, or a combination of both, which may be due to community evenness and functional traits play an essential role in mediating species asynchrony and species stability in plant communities as theoretical (Thibaut and Connolly, 2013) and empirical studies (Xu et al., 2018; Valencia et al., 2020) report. For example, decreased rare species under global changes decreased community species richness significantly but had a minor effect on community evenness and functional diversity (Hautier and Van Der Plas, 2022; Jiang and Xu, 2022), and thus the impact of species richness on community stability could be replaced by community evenness and functional traits under different numbers of GCFs.

Additionally, the SEM analyses showed that biotic factors play a greater role than abiotic factors in determining grassland stability (Valencia et al., 2020; Fig. S6). The number of GCFs similar to those found in single- or multi-site experiments (Zhang et al., 2016; Hautier et al., 2020) reduced community stability through decreasing richness-mediated asynchrony while enhancing the positive effect of species stability. Meanwhile, the number of GCFs may increase the abundance/biomass of stable species by altering the community composition (Valencia et al., 2020), which in turn stabilized the communities.

Most interestingly, the contribution of species asynchrony to community stability becomes remarkably important as more GCFs are introduced, especially under the three GCFs. Similar to recent global report that species asynchrony is a key factor in stabilizing plant community at the global scale (Valencia et al., 2020), especially in the face of multiple global changes. Specifically, single GCF reduced the number of stable species with dissimilar ecological characteristics in species-rich communities and thus weakened community stability (Hautier and Van Der Plas, 2022). Alternatively, single GCF weakened the asynchronous dynamics of species (Fig. 2c) probably by weakening interspecific interactions (Gross et al., 2014; Xu et al., 2021) and causing a consistent response of species to environmental fluctuations. Previous study has shown that considering species richness alone and ignoring species identity often cannot capture the impact of global change on communities (Hillebrand et al., 2018). Similarly, our SEM results for two GCFs impact community stability confirmed that the negative effect of increasing GCFs on community stability may be modified by other community attributes (i.e., species identity, species abundance, and species turnover) rather than species richness. In addition, the stronger environmental filtering effects was found under more GCFs, the

potential tipping points for most species in grassland communities may shift under multiple GCFs (Polst et al., 2022), which may lead to the stability of species independent of less GCFs but closely related to grassland types or climate conditions, thus community stability was caused by asynchronous dynamics of tolerant species rather than its stability. Furthermore, community stability is calculated as the ratio of the temporal mean productivity to its SD, which suggests increasing GCFs weakened community stability via reducing temporal mean productivity or increasing SD of productivity (Hautier et al., 2014). We found that the decrease in community stability is mainly caused by the increase in SD of productivity as GCFs increase. Overall, increased GCF number reduces community stability by weakening species asynchrony and thus increasing SD of productivity (Hautier et al., 2014).

4.3. Abiotic factors regulate the effects of GCF numbers on community stability

Previous global synthetic analyses (Komatsu et al., 2019; Berdugo et al., 2020), and several manipulative studies (Niu et al., 2018; Quan et al., 2021; Wagg et al., 2022) have shown that community dynamics are modified by experimental duration, aridity index, and experimental intensity. In this study, the aridity index regulated the effects of GCF numbers on community stability, which can be explained from two perspectives. On the one hand, changes in the aridity index usually reflect shifts in climate and soil conditions, as well as plant and microbial properties, these changes may moderate the effects of GCF numbers on community stability (Wang et al., 2014; Maestre et al., 2015; Berdugo et al., 2020; Hu et al., 2021). On the other hand, the identity of GCF differentially moderates the effects of the aridity index on community stability (Fig. S5a), and the stochastic combination patterns of GCF may shape the relationship between aridity index and community stability. Similar to previous reports (Komatsu et al., 2019; Seabloom et al., 2020), we observed that community stability increased with the increasing experimental duration under different patterns of a number of GCFs, and even if this effect is only significant under single GCFs. Global changes can significantly impact environmental conditions and plant communities, plants may have become more adaptable to global change over time, thereby stabilizing community productivity (Hong et al., 2022). However, we did not find evidence that treatment intensity modifies the effect of the number of GCFs. This lack of effect may be due to regional differences in grassland ecosystem types, climate, and soil conditions that affect the sensitivity of local plant communities to the various identities of GCF and their treatment intensity (Yue et al., 2017b; Gilbert et al., 2020). In addition, the inconsistency in experimental treatment design may also hinder our ability to detect the mediating effect of treatment intensity.

5. Conclusions

Our research has comprehensively synthesized the effects of multiple GCFs on community stability in global grasslands. Our findings show that the response of community stability to types and combinatorial patterns of GCFs varied, with the number of GCFs having a significant negative impact on community stability when ignoring the identity of GCF. Moreover, we discovered that the relationship between community stability and biotic factors was altered by increasing GCF numbers and that aridity, treatment intensity, and experimental duration under different GCF numbers all played a regulatory role in community stability. Notably, our research underscored the crucial importance of species asynchrony in maintaining community stability responses to increasing global change numbers. While our research has contributed important insights, there are several limitations worth noting. Firstly, we did not specifically analyze the effects of different GCF combinations on community stability. Secondly, we acknowledge that the scarcity of experimental data on the three factors in our meta-analysis may have limited our understanding of the effects of the three-factor interaction on community stability. Finally, we recognize that the inherent differences in experimental conditions may have affected the results of our analysis. Therefore, we recommend undertaking more multifactorial experiments to better understand how the combined effects of multiple factors influence the pathways that maintain community stability.

CRediT authorship contribution statement

Fund acquisition: Chao Wang. Data collection and extraction: Zhaobin Song, Chao Wang. Data analysis: Chao Wang. Manuscript writing and revisions: Zhaobin Song, Chao Wang, Yann Hautier.

Declaration of competing interest

All authors declare no conflict of interests to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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