

Invasive plant impacts on grassland ecosystems: A meta-analysis and its implications for the food-water-energy security

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Abstract. Grassland ecosystems play a crucial role in supporting food, water, and energy security, yet they are highly vulnerable to the invasion of non-native plant species. Grassland ecosystems are vital for maintaining security in food, water, and energy sectors, yet they remain highly susceptible to non-native plant invasions. Although the consequences of these invasions for these security domains are not yet fully established, this research utilizes a meta-analysis of 478 effect sizes derived from 52 field investigations across 19 countries to assess their influence on grassland functions. The study employed log response ratios (lnRR) to estimate effect sizes, with data analyzed using random-effects modeling and meta-regression. The results revealed that plant invasions had the most substantial positive impacts on litter-fuel chemistry (lnRR 0.33) and the nitrogen cycle (lnRR 0.23). These results indicate increased fuel accumulation and nitrogen turnover. However, these changes may influence fire dynamics, nutrient retention, and soil-water interactions under specific ecological contexts. Within the context of the food-water-energy nexus, increases in biomass and nitrogen due to invasions may be interpreted as enhanced productivity, although underlying ecosystem stability may be affected. These findings suggest potential implications for ecosystem stability and, consequently, food, water, and energy security in grassland ecosystems.

1 Introduction

Grasslands encompass over 40% of the terrestrial surface [1]. These ecosystems typically emerge in regions characterized by annual precipitation ranging from 150 to 1,200 mm and average temperature fluctuations between 0 and 25°C. The primary determinants influencing the spatial distribution of grasslands are precipitation and temperature; however, factors such as fire dynamics, soil attributes, and the temporal distribution of precipitation also significantly contribute. Furthermore, selective grazing practices and mowing activities influence the distribution patterns of grasslands. Grasslands are characterized by a

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predominance of grasses and encompass a range of plant species, including grasses, shrubs, succulents, and herbs/forbs. Consequently, these ecosystems provide habitats for a wide array of large herbivorous grazers. The presence of grazing mammals profoundly affects the ecological functioning of grasslands by modulating nutrient cycling, primary productivity, and species composition [1].

Grasslands serve as critical habitats supporting a diverse array of species and are integral to global ecological processes. Numerous species, including large and small mammals, avian species, reptiles, amphibians, insects, and soil microorganisms, play essential roles in grassland ecosystems. These ecosystems provide many ecosystem services, including primary productivity in the form of food production within grazing systems, water regulation, carbon storage, climate regulation, nutrient cycling, soil fertility, and ecosystem stability and resilience to climate variability [1].

Nevertheless, grassland ecosystems are recognized as particularly susceptible to the encroachment of invasive plant species [2]. These ecosystems are characterized by their openness, which allows greater levels of light penetration. Such conditions are particularly conducive to the establishment of invasive species, which typically depend heavily on light availability. Furthermore, recurrent disturbances, such as overgrazing and wildfires, exacerbate the potential for invasion. Moreover, arid and nutrient-deficient environments are advantageous for invasive species with high physiological plasticity, as they can utilize resources more effectively than indigenous species.

Numerous investigations suggest that the repercussions of plant invasions in grasslands depend on both geographic context and specific ecosystem functions. Certain functions may experience transient enhancements, while others may degrade. The challenge in elucidating the ecological mechanisms that underpin systemic transformations resulting from invasions is compounded by this variability. Consequently, the implementation of meta-analytic methodologies is imperative for discerning global trends, identifying the most susceptible ecosystem functions, and comprehending the ramifications of invasions on food, water, and energy security.

2 Methods

This study searched the Scopus database for studies on the impact of invasive plant species on grassland ecosystems. The search used the following keywords: TITLE-ABS-KEY ("savanna" OR "grassland" OR "tropical savanna") AND TITLE-ABS-KEY ("exotic plant" OR "invasive grass" OR "invasive tree" OR "invasive plant species" OR "invasive alien plant species" OR "plant invasion") AND TITLE-ABS-KEY ("impact" OR "effect"). The search was limited to articles and conference proceedings with no date restriction. The search yielded 801 studies from 1966 to 2025. After eliminating 8 duplicate entries, a total of 793 titles and abstracts underwent screening. A total of 498 records were omitted at the title and abstract phase due to their lack of relevance to grassland or associated ecosystems, categorization as review articles, or classification as studies focused solely on modeling. The subsequent evaluation of 295 full-text articles was conducted to ascertain their eligibility. Among these, 243 were discarded owing to inadequate statistical evidence, absence of comparative analysis between invaded and uninvaded conditions, incomplete variance data, or because they were not derived from field-based investigations. In conclusion, 52 studies met all specified inclusion criteria and were incorporated into the meta-analysis. The methodology for study selection adhered to the PRISMA 2020 guidelines (Figure 1).

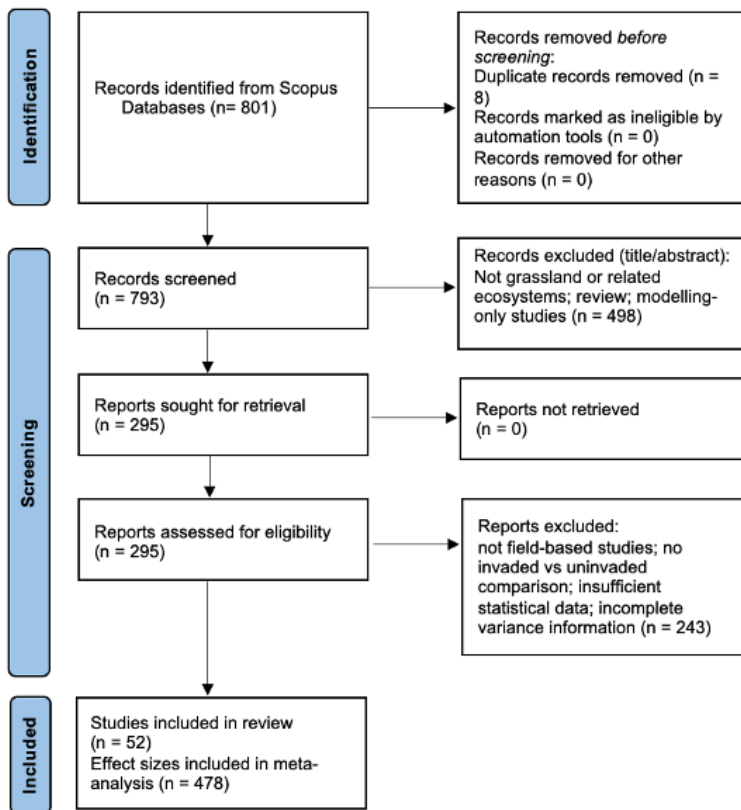


Fig. 1. PRISMA 2020 flow diagram illustrating the study selection process.

Data were extracted from each study, including the following: study ID, year, country, invasive species, ecosystem, variables studied (comparing invaded versus uninvaded conditions), sample size, mean values in control and invaded conditions, and standard error or standard deviation for each condition. This process yielded 478 variables, which were then compared between uninvaded (control) and invaded conditions to estimate the effect size. Effect size computations were conducted utilizing the log response ratio (lnRR) in the R programming environment (R Core Team) employing the metafor package (version 4.8-0). The logarithmic response ratio (lnRR) was determined as $\ln(X_{\text{invaded}} / X_{\text{control}})$, where X denotes the mean value of the variable in both invaded and uninvaded contexts. Each category was analyzed using a random-effects model.

In order to elucidate the data and the effects attributable to each category, invader type, and ecosystem type, meta-regression techniques were employed. Furthermore, we computed heterogeneity statistics (I^2) to characterize the variance structure and used Egger's regression test to evaluate publication bias. Given that multiple effect sizes were extracted from individual studies, potential non-independence was accounted for within the random-effects modelling by treating study identity as a grouping variable. This methodology mitigates potential biases arising from intra-study clustering of effect sizes. Effect sizes are quantitative measures that summarize the magnitude of the difference between uninvaded (control) and invaded conditions in the studied variables. Effect sizes were categorized into 15 functional ecosystem groups. These categories included fauna diversity, greenhouse gas (GHG) flux, litter-fuel chemistry, the nitrogen cycle, plant community structure, plant diversity, seed bank

diversity, soil carbon, soil chemistry, soil minerals, soil nutrients, soil bioactivity, soil physical properties, vegetation productivity, and water.

3 Results and discussion

This study compiled 478 effect sizes from 52 field studies in 19 countries, as shown in Figure 2. There are 55 invasive plant species, with cheatgrass (*Bromus tectorum*) being the most frequently studied species. These species can be categorized into five types based on their habit: grasses, herbs, shrubs, trees, and succulents. There are also 18 types of grassland ecosystems. Analysis using a random-effect model shows that plant invasion results in relatively small but positive aggregate changes in ecosystem function ($\lnRR = 0.10$) compared with uninvaded conditions. However, the exceptionally high heterogeneity value ($I^2 > 99\%$) indicates that the impact of invasion depends heavily on the ecosystem context, invader type, and the observed ecosystem function. This pattern aligns with the latest global synthesis, which emphasizes that plant invasions rarely produce uniform responses across ecosystems but rather trigger highly contextual and function-specific responses [3].

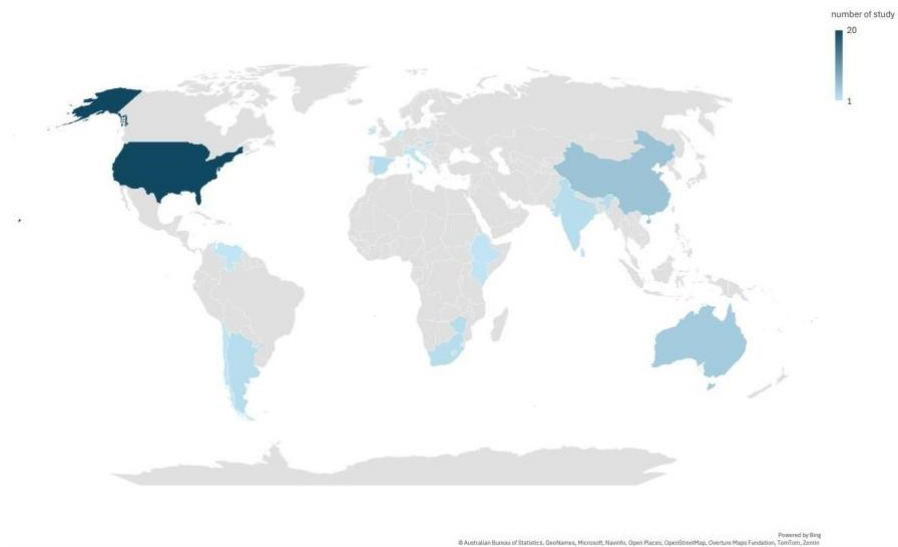


Fig. 2. The distribution of the study countries

The results of the meta-analysis show that plant invasion has the most significant positive impact on two functional ecosystem groups: litter chemistry and the nitrogen cycle. Litter-fuel chemistry is the ecosystem function with the greatest impact from invasion, as indicated by the highest positive effect size (\lnRR 0.33). As shown in Figure 3, the forest plot of litter-fuel chemistry indicates that plant invasion consistently increases the quantity and quality of fuel in grassland ecosystems. This phenomenon is reflected by positive \lnRR values for variables such as litter biomass, litter dry mass, fuel mass, and fire intensity. Grass and shrub-type invaders have high productivity and rapid litter accumulation rates, so the increase in litter biomass is particularly pronounced for these types.

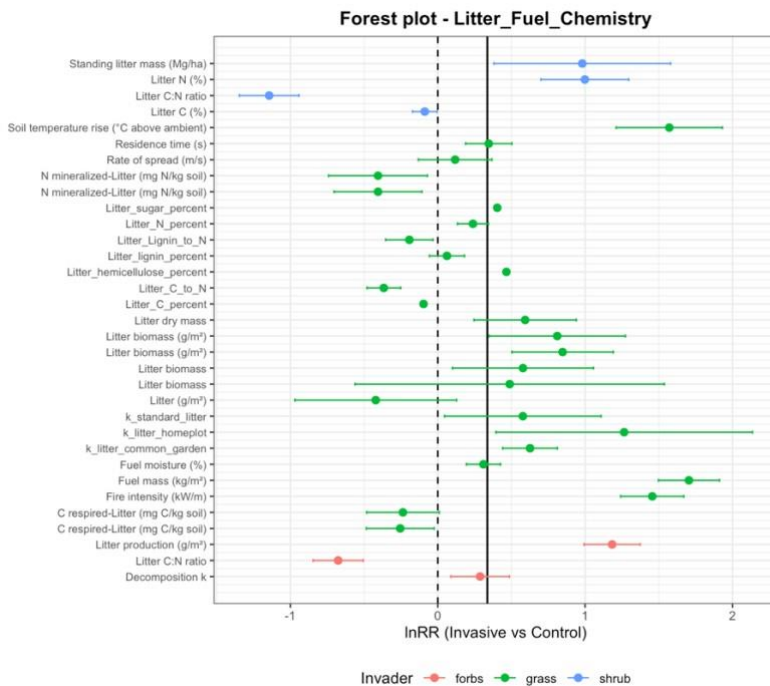


Fig. 3. Forest plot shows that plant invasion in grasslands tends to increase the quality and quantity of litter fuel in grasslands

Additionally, changes in litter quality are characterized by a decrease in the litter C:N ratio and an increase in its nitrogen and lignin content. This combination makes the litter more flammable and biochemically reactive. Changes in litter-fuel chemistry may potentially influence fire regimes, particularly in fire-dependent grassland systems, based on established ecological linkages reported in previous studies. Such changes in fuel properties may create conditions that favor positive feedback between invasion and fire in specific grassland contexts. These findings align with previous studies indicating that invasive plant species strengthen the relationship between invasion and fire regimes in grasslands [3, 4].

The nitrogen cycle group also showed a high positive effect size (lnRR 0.23). The nitrogen cycle forest plot showed a more heterogeneous pattern, but with a strong tendency towards accelerated nitrogen cycling (Figure 4). This indicates that plant invasion consistently accelerates nitrogen cycle processes in grasslands. A recent study by Afzal [5] confirms that plant invasions can have long-lasting effects on soil processes, especially nitrification.

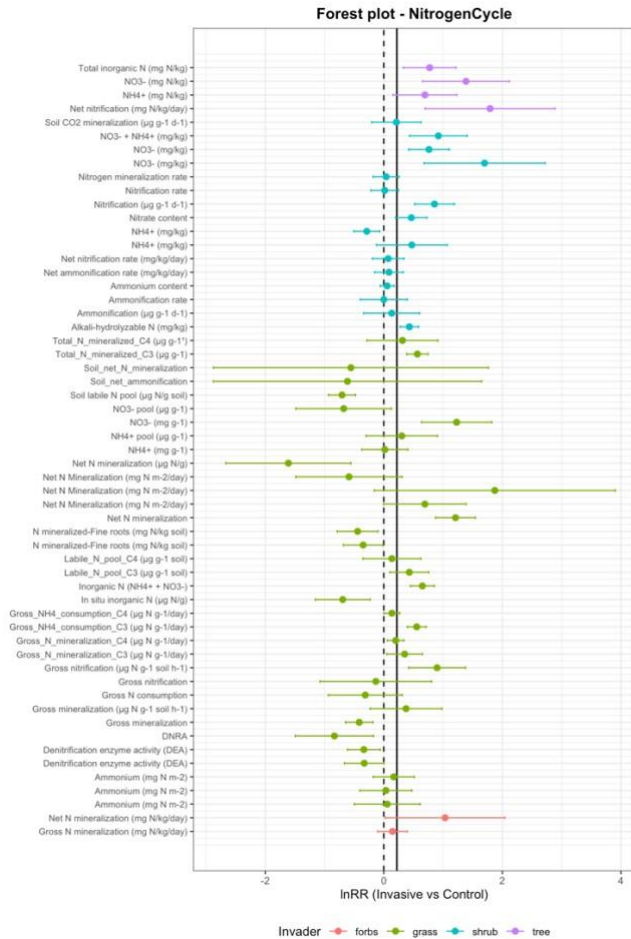


Fig. 4. Forest plot shows that plant invasion in grasslands tends to accelerate the nitrogen cycle ($\ln RR > 0$) with varying responses among invader types

Most variables representing nitrogen availability, such as NO_3^- , NH_4^+ , total inorganic N, and labile N pool, showed positive $\ln RR$. However, net nitrification, gross nitrification, and N mineralisation rate, which were also positive, indicated that invasion accelerated nitrogen turnover. This makes the system more open and more prone to fast-flux, potentially increasing nitrogen losses [6]. Furthermore, variables such as soil net ammonification and denitrification enzyme activity (DEA) show negative or near-zero $\ln RR$ values, indicating weakening of nitrogen retention in the long term. In the context of increased mineralisation rates and inorganic nitrogen availability, this is often associated with increased fertility. However, these results reflect the acceleration of a short-term nutrient cycle. High nitrogen can alter soil properties, including pH, and can decrease or increase dissolved/inorganic nitrogen, potentially disrupting the balance of other nutrients and soil microbes [7]. Therefore, this forest plot suggests that invasion accelerates short-term nutrient turnover, which may be interpreted as increased fertility under specific ecological contexts.

Integrated results from the nitrogen cycle and litter-fuel chemistry demonstrate that plant invasion modifies the function of grassland ecosystems through a series of interconnected mechanisms. Invasive plants accelerate nitrogen cycling and chemically transform plant residues and fuel properties, potentially shifting grasslands from conservative systems toward

less resilient states. These mechanisms suggest potential implications for food, water, and energy security [8], although these dimensions were not directly measured in this study.

Plant invasions in grassland ecosystems have been associated with changes in litter-fuel chemistry, potentially altering fire dynamics in fire-prone systems. In the context of energy security, ecosystem energy may increasingly be stored in combustible biomass rather than being steadily channeled into productivity. This biomass may then be rapidly released through fire events. Consequently, more frequent or intense fires may damage forage vegetation, reduce soil quality, and disrupt hydrological functions in fire-prone systems. Therefore, although invasion may increase biomass, such changes do not necessarily translate into enhanced forage stability and may be associated with greater disturbance risk in specific contexts. A study of a Brazilian grassland found that fires increased surface runoff by about 25% and decreased soil infiltration by about 18% [9].

At the same time, plant invasion increases soil nitrogen levels by altering the nitrogen cycle. However, in the context of food and water security, this increase creates a soil nutrient imbalance. These changes may alter nutrient balance and increase the potential for nutrient loss through leaching under specific environmental conditions. When the acceleration of the nitrogen cycle occurs alongside an increase in litter-fuel chemistry, grasslands may transition toward a pseudo-productive state, potentially reducing long-term system stability related to food, water, and ecosystem energy dynamics.

This study shows that invasive species impact ecosystems by changing litter-fuel chemistry and accelerating the nitrogen cycle. These changes may contribute to nutrient imbalances and increase the potential risk of fire and soil-water degradation under certain ecological conditions. While the impact may appear positive based on numerical indicators alone, these functional shifts may pose potential risks to ecosystem resilience and long-term food, water, and energy stability. Studies of grassland landscapes in Africa and North America show that, while invasive species can maintain or even enhance some ecosystem services, they consistently reduce the supporting and regulating services that underpin system stability [10, 11]. Therefore, invasive species management may play an essential role in supporting the long-term stability of food, water, and energy security, alongside biodiversity conservation.

4 Conclusion

This meta-analysis demonstrates that plant invasions significantly alter key ecosystem functions in grasslands, particularly litter-fuel chemistry and nitrogen cycling. These findings provide quantitative evidence of shifts in biomass accumulation and nutrient dynamics during invasion. While this study did not directly measure fire regime dynamics or food-water-energy security indicators, the observed functional changes suggest potential implications for ecosystem resilience and resource regulation. Therefore, invasive species management should be considered within broader sustainability frameworks, with further research needed to quantify links between invasion-driven functional shifts and food-water-energy outcomes.

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