OPINION

Climate Change: Confronting Invasive Species - Where to from here?

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Abstract

For the last two decades or so, concerned workers have been investigating the effects of climate change on invasive species and related agronomic issues. As researchers working in this space, we emphasize the importance for current research findings to be translated into practical, real-world management strategies that can be actioned by the end-users. This opinion article is offered as a contribution to this area. It attempts to illustrate the general direction and intensity that research work has taken concerning climate change and its relationship to the problem of invasive species. In addition, we discuss the likely nature of future research in this field. To provide a balanced overview of this activity, we consulted six key scientific Journals, which have consistently offered core articles related to this question. Although we recognized that a considerable amount of laboratory work and field-based research is taking place across the globe on climate change and invasive species, we have settled on 113 articles, which are directly relevant to this discussion.

We note that North American researchers have published most papers in this space since 1979. Several studies have indicated that under anticipated climate change conditions, many invasive species are more likely to grow faster and more extensive than agriculturally important crops, and their reproductive outputs may also significantly increase. If this finding reflects the general case for agronomic weeds of particular concern, then it is clear that extra caution will need to be taken with management strategies. Developmental work and an increased range of stakeholders will be required to reduce the burgeoning impacts of these species on economic, agricultural production. We encourage researchers to communicate more widely on the outcomes of their work and promote more collegiate engagement with the researchers in other parts of the world to share their knowledge and insights into efficient and effective management approaches.

Keywords: climate change; weed science; weeds; invasive species; crops; weed management

Introduction

The United Nations predicts the global human population is expected to reach between 8 and 10 billion by 2050 (Leridon, 2020). This will significantly increase the demand for food. It is anticipated that by 2050 we will need to at least double the current production output.

Consequently, our existing food production systems will come under extreme strain. Exacerbating the food supply problem, agricultural practices, in general, are already increasingly open to a series of concurrent and interacting disturbances. Issues such as deteriorating soil quality, the rising intensity of insect attacks and aggressive weed invasion, together with more frequent and severe flood and drought events, have already raised significant concerns for this essential industry.

Furthermore, in the last decade or so, sharp increases in atmospheric CO_2 levels, which have occasioned associated climate change conditions, have added additional pressure on crop productivity, increasing the vulnerability of farmers, food production systems and food suppliers.

It is essential that to alleviate the effects of the above pressures on the agricultural community, researchers need to provide some consolidated answers to problems facing crop production and management. In this brief Opinion article, we have initially examined research articles published in six key Agricultural Journals, which have addressed invasive pest and weed studies and agricultural issues related to climate change effects.

Whilst we do not intend this opinion piece to be an exhaustive literature review of the above issues, our objectives are: (i) to illustrate the general direction and intensity that research work has recently taken regarding climate change and its relationship to the problem of invasive species, and (ii) to subsequently highlight the nature of future required research.

In addition, we examined the relative publication rates from countries where the research has been conducted, to see if there is a particular focus on this issue.

Invasive species and climate change publications

Publication statistics

To provide a quantitative measure of the current work in this area, we searched six well-established and relevant English language scientific Journals for articles specifically addressing the effects of climate change on invasive plant species. The Journals were: *Weed Science*, *Weed Research, Biological Invasions, Journal of Ecology, Functional Ecology,* and *Oecologia*. The criteria used to determine the suitability of an article for entry into the listing were the paper specifically addressed the effects of climate change parameters on one or more invasive species. We only considered plant species and vegetation communities.

In the research articles examined, we included laboratory and field studies, reviews, computer modelling, or a combination of these investigations. We found a total of 113 relevant articles published in the six journals selected since 1979, with the majority (27) of the articles published in *Functional Ecology* (Figure 1).

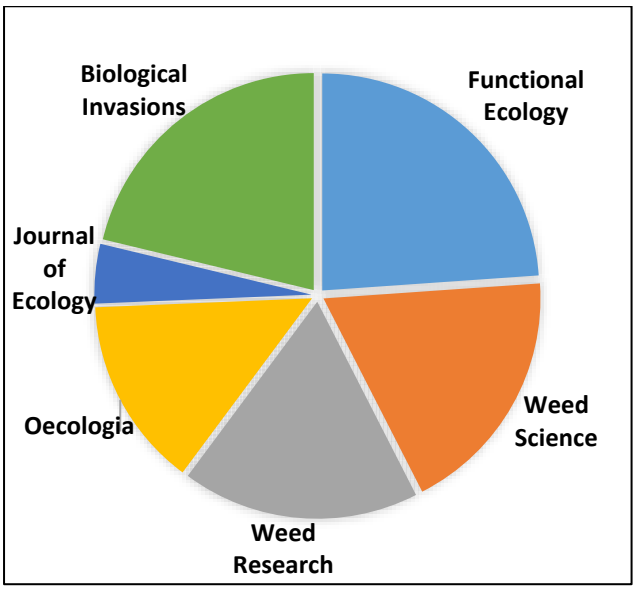

Figure 1. The proportion of articles published in selected journals that address the effect of climate change on invasive plants

Only *Weed Science* and *Oecologia* had published papers addressing this topic before 2000 (Figure 2). However, it is of interest that both *Weed Science* and *Oecologia* have significantly reduced the number of papers regarding the impact of climate change on invasive plants since the 1990s and 2000s. Indeed, *Oecologia* did not publish one relevant article between 2000 and 2009. *Weed Science* has evidenced a notable decline in publications related to climate change effects since 2010 (Figure 2).

We comment that, although global change ecology is listed as one of *Oecologia's* core focus areas, it appears that invasive species' research is not within their primary scope, and this could justify the reduced number of publications in this field.

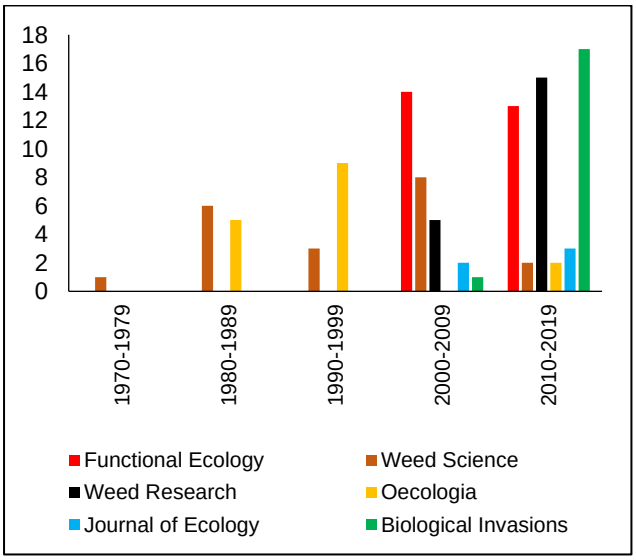

Figure 2. The total number of articles investigating the impacts of climate change on invasive species across each decade since 1971

In contrast, the other four journals have seen a significant increase in publications relevant to the effect of climate change on invasive plant species, particularly since 2000 (Figure 2).

In the last decade, *Biological Invasions* published 17 relevant papers, mainly modelling and simulation-based, addressing potential climate change effects. It is possible that other journals, such as *Weed Science,* are being selective in accepting articles, which may be argued as falling just beyond or outside their specific mandates.

Publication generators

Authors from North America contributed the most significant proportion of literature (59 articles), with the United States providing 56 (Figure 3). Almost all the articles pre-2000 were from North American authors. These studies appeared to have been published at a relatively consistent rate (Figure 4). We have deliberately excluded conference papers and book chapters from this analysis to focus on peer-reviewed material

Overall, approximately three-quarters of the research was conducted in either North America or Europe during the review period, suggesting that research outcomes and findings will be skewed towards invasive plants of the Northern Hemisphere. The most frequently observed studies conducted were those under controlled laboratory conditions (44 articles); however, studies that observed the effects of climate change *in situ* were also prominent (34 articles) (Figure 4).

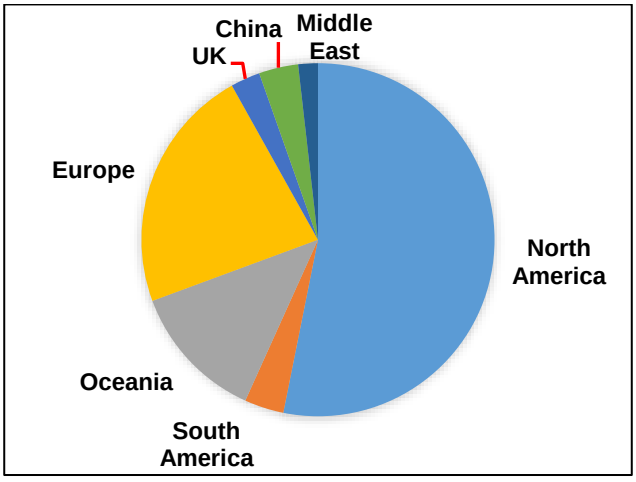

Figure 3. Published articles on Climate Change and invasive species in the six journals shown as a proportion of the originating region. The USA contributed the highest proportion of the research (56 articles)

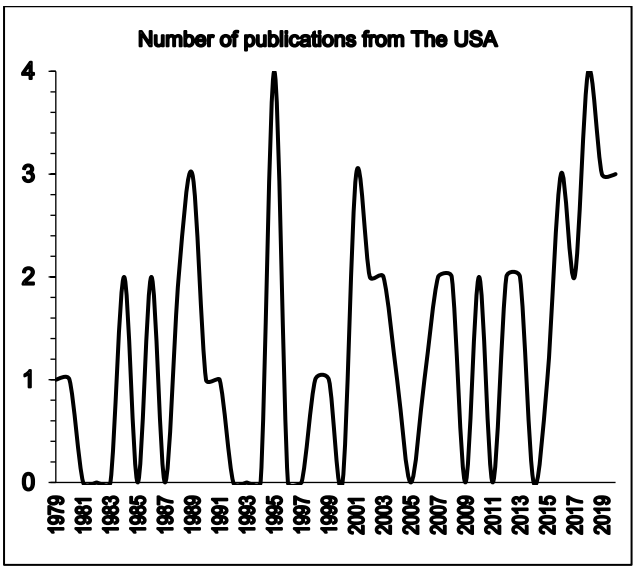

Figure 4. The number of publications produced in the USA was consistent from 1979 to 2020, with an average of 1.3 articles published per year.

Publication foci

Issues dominating these publications suggest that climate change will exacerbate the stresses on agriculture due to increased drought (Chirino et al., 2017). There will be a significant contribution to management difficulties reducing the efficacy of many herbicides when applied to control invasive plants (Waryszak et al., 2018).

It has been established that in many cases, under climate change conditions, exotic species are likely to grow faster and more extensive than crops (Valerio et al., 2013). Their reproductive outputs have also been observed to significantly increase (Bajwa et al., 2019). These changes are the basis of the anticipated increased future threat to agriculture and food security posed by invasive plant species under climate change scenarios. These transformations are also generally threatening ecosystems worldwide (Ziska et al., 2012).

However, given this context, it is surprising that only a relatively small number of studies, published in these leading Journals since the 1970s, specifically explore the effect of climate change on invasive plants.

If the bioclimatic envelopes are known for a target species, with the available preliminary biological research, computer modelling can predict potential changes in spread under different climate change scenarios such as warmer temperatures, drought, or high rainfall. All bioclimatic modelling research appears to have been conducted in Australia and New Zealand. While this method can predict changes in distribution as a response to selected

environmental parameters, it does not consider all climatic variables and their interactions as effectively as laboratory or field-based experiments (Heikkinen et al., 2006).

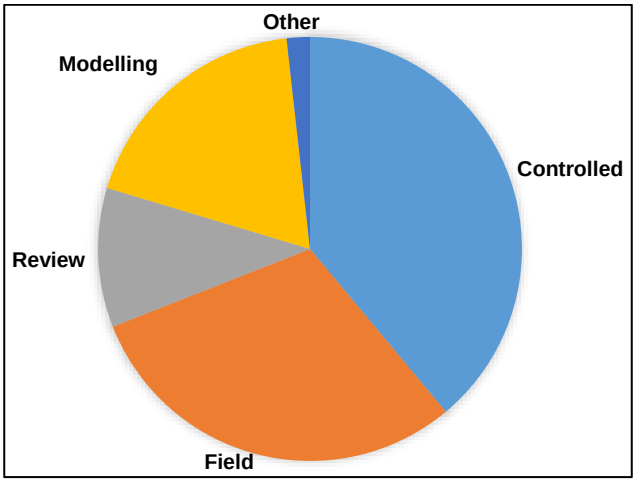

Figure 5. The proportion of the types of research articles published in the journals. The highest number of studies (44 papers) were conducted under controlled laboratory conditions

A reflection on research findings and management implications

Research findings to date suggest that the relationship between climate change effects and invasive plant species' consequences on crop outputs is a complex issue, primarily because of the varying responses of C_3 and C_4 plants to increased CO_2 levels. Publications suggest that under predicted elevated CO_2 levels, C_3 crops, such as soybean (Glycine max L.), rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.), will be favoured with higher photosynthetic rates compared to C_4 weeds (e.g., waterhemp (*Amaranthus rudis* L.), Palmer amaranth (*A. palmeri* S. wats.) and kochia (*Kochia scoparia* L.) (Elmore and Paul, 1983).

However, C_3 weeds (lambsquarters (*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* Medik.), common ragweed (*Ambrosia artemisiifolia* L.) and giant ragweed (*Ambrosia trifda* L.) will also be favoured under elevated CO_2 levels, thus imposing severe competition on C_4 crops, such as corn (*Zea mays* L.), sorghum [*Glycine max* (L.) Merr.] and sugarcane (*Saccharum officinarum* L.) (Varanasi et al., 2016).

As a corollary of these reactions, any expected positive impacts of future climate changes on many C_3 crops are likely to be nullified by increased invasive species competition (Varanasi et al., 2016). In addition to this growth rate factor, weeds are expected to demonstrate improved survival mechanisms under predicted future climatic changes due to their high intraspecific genetic variation and physiological plasticity.

At the same time, the efficacy of commonly used herbicides is being significantly influenced by the predicted climate changes, since environmental factors such as temperature, soil moisture, and precipitation play a significant role in all phases of herbicide activity (Kudsk and Kristensen, 1992; Varanasi et al., 2016; Ziska, 2016). In light of these changes, the current consensus is that weed management strategies for all major crops, as well as general weed management, will have to be significantly altered in the future.

Increasing atmospheric CO_2 levels can either favour the crops or weeds in the same cropping area, depending on whether they are C_3 or C_4 species (Ziska et al., 1999).

In addition, under expected, more frequent and severe drought, deep-rooted (perennial) plants are predicted to be favoured (Storrie and Cook, 2007; Stratonovitch et al., 2012). This suggests that under these climate change parameters, perennial weeds could become a more significant management challenge in annual cropping systems (Rodenburg et al., 2011). Rodenburg et al. (2011) identified at least 26 invasive perennial species that will become a more significant threat to rice fields under projected climate change parameters.

To address the potential adverse effects of climate change on crops in the future, based on research to date, we suggest the implementation of a dual adaptive approach. The selection of crop cultivars with superior survival attributes is one such approach, where drought tolerance, heat-stress tolerance, weed-suppressing ability and allelopathy are key attributes (Varanasi et al., 2016).

For example, in a recent study, a competitive wheat genotype has shown that weed abundance and the amounts of herbicides applied can be reduced up to 50% by improved above-ground weed suppression (Travlos, 2012). Recent research has also focused on stimulating competitive and advanced allelopathy potential in crop weed suppression (Bertholdsson et al., 2012; Worthington and Reberg-Horton, 2013). The introduction of such advanced breeding programs to develop and release improved cultivars to overcome the future effects of climatic changes and weed competition is thus critical.

Again exemplifying the complex nature of this issue, our reading suggests that according to the meta-analysis conducted by Liu et al. (2017), native

plant species will not respond in similar ways to climate changes as compared to invasive species.

The broad discrepancies in data indicate that while some may benefit by expanding their ranges, invasive plant species can also be helped or discouraged under global environmental changes. However, within the general ecological context, invasive plant species may benefit more from elevated temperature and atmospheric CO_2 levels compared to native plant species regardless of their carbon fixation pathway (Liu et al., 2017).

Authors have evaluated 74 and 117 invasive alien and native plants species, respectively, in the attempt to understand if alien plants benefit more from the global environmental change than native species. Liu et al. (2017) reported that elevated temperature and CO_2 enrichment enhanced the growth of invasive alien plants more than native species.

Our reading has indicated that despite the substantial number of research investigations conducted in the review period comparing native and invasive species' responses to a single climate effect, studies evaluating their responses to multiple co-occurring climate effects are scarce (Liu et al., 2017). Therefore, it is clear that future research must focus more on the basic biological studies evaluating the interactive effects of predicted climate changes of invasive species' responses.

Where to from here?

It is commonly agreed that climate change will significantly influence flora dynamics and interactions in both agricultural and native landscapes. It is expected that many invasive weeds, such as *Datura stramonium* L. (Ramesh et al., 2017) and *Cirsium arvense* L. (Ziska et al., 2011) are likely to undergo a more extensive range expansion in comparison to many agricultural weeds or native species (Chauhan et al., 2014). This is most likely because 'weedy' species have high genetic variability, an intensely competitive nature, and physiological plasticity (Wainwright and Cleland 2013).

Despite the current bioclimatic modelling providing helpful information on predicted species distribution, future research and modelling should consider how localized land use will change in response to climate change (Ramesh et al., 2017).

Such information will be critical for the future planning of agricultural and native landscapes. It will assist land managers in adapting and utilizing the most suitable species or cultivars for a given region. Selecting suitable crop species that will withstand or benefit from the driving pressures of climate change will reduce agricultural losses resulting from competing weeds (Bloomfield et al., 2006). To achieve this, however, future research should investigate further how several climate change scenarios, such as drought, elevated atmospheric CO_2 levels, floods and increased temperature, can influence land use and species interactions.

It is generally agreed that invasive plant species management is required to maximize global crop production. Whilst several studies have suggested that herbicide applications are the most common treatments to control invasive weeds around the world (Gianessi, 2013; McErlich and Boydston, 2014), problems are developing with this approach.

Evolution of herbicide resistance in weeds leading to significant economic losses to the sustainability of agriculture. This has now become a significant problem associated with the continuous use of herbicides (Mwendwa et al., 2020; Heap, 2021). Although there are clearly many positives in using herbicides, an increasing number of opinions hold that future research and management should carefully consider the impacts that climate change may have on the efficiency of chemical control.

In this respect, recent research suggests that certain herbicides may become less effective over time due to changing climatic conditions such as elevated atmospheric CO_2 levels, highly variable rainfall and increased temperature (Chauhan et al., 2014; Ziska and McConnell, 2016; Ziska, 2016).

In many cases, this increased tolerance can be attributed to improved metabolic efficiency, allowing the plant to rapidly translocate herbicide away from the treated leaf (Matzarif et al., 2019; Refatti et al., 2019). This increased tolerance has been repeatedly observed in glyphosate, one of the world's most commercially important herbicides, in species such as couch grass [*Elymus repens* (L.) Gould] (Ziska and Teasdale, 2000), barnyard grass [*Echinochloa colona* (L.) Link] (Mollaee et al., 2020) and Canadian fleabane [*Conyza canadensis* (L.) Cronquist] (Matzarif et al., 2019).

Indeed, such changes may result in specific 'modes of action' becoming less effective over time and result in a more substantial number of herbicide-resistant weeds (Loladze, 2014). This strongly suggests that future research should investigate and evaluate how herbicide applications may be altered under predicted climatic scenarios. We also recommend that future research be developed to examine a range of integrated management treatments (such as biological control, fire management and mechanical control) to help reduce

the long-term economic and environmental impact of invasive weeds under predicted climatic scenarios (Bhat and Jan, 2010; Ramesh et al*.,* 2017).

As explored in this article, our view is climate change will exacerbate the stresses on agricultural and native species, thus favouring the domination of invading weeds. This situation clearly increases the pressure on land managers and researchers to develop new and improved approaches to combat what is likely the most challenging environmental topic of our generation. It is surprising that since 1979 only 113 relevant articles have been published in six key international Journals, most conducted in the Northern Hemisphere.

Further, it is also expected that several current management treatments, such as herbicide application, may become less effective over time due to plant mutations and adaptions to changing climatic conditions. In this respect, future research should investigate how changing climatic conditions influence land use and how this change may impact the interaction between agricultural, native and invasive species. This will help formulate a greater understanding of species interactions in response to future climate change and help to develop and maintain long-term sustainable land systems.

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