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Understanding the combined impacts of weeds and climate change on crops

Montserrat Vilà[1,2,*], **Evelyn M Beaury**[3], **Dana M Blumenthal**[4], **Bethany A Bradley**[3,5], **Regan Early**[6], **Brittany B Laginhas**[3], **Alejandro Trillo**[1], **Jeffrey S Dukes**[7], **Cascade J B Sorte**[8] **and Inés Ibáñez**[9]

1 Estación Biológica de Doñana (EBD-CSIC), Av. Américo Vespucio 26, Isla de la Cartuja, 41092 Sevilla, Spain
2 Department of Plant Biology and Ecology, University of Sevilla, Sevilla 41012, Spain
3 Organismic and Evolutionary Biology Graduate Program, University of Massachusetts, Amherst, MA 01003, United States of America
4 Rangeland Resources & Systems Research Unit, USDA Agricultural Research Service, Fort Collins, CO 80526, United States of America
5 Department of Environmental Conservation, University of Massachusetts, Amherst, MA 01003, United States of America
6 Centre for Ecology and Conservation, University of Exeter, Penryn Campus, Penryn TR109 9FE, United Kingdom
7 Department of Forestry and Natural Resources, Department of Biological Sciences, Purdue Climate Change Research Center, Purdue University, West Lafayette, IN 47907, United States of America
8 Department of Ecology and Evolutionary Biology, University of California, Irvine, CA 92697, United States of America
9 School for Environment and Sustainability, University of Michigan, Ann Arbor, MI 48109, United States of America
* Author to whom any correspondence should be addressed.

E-mail: montse.vila@ebd.csic.es

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Supplementary material for this article is available online

Abstract

Crops worldwide are simultaneously affected by weeds, which reduce yield, and by climate change, which can negatively or positively affect both crop and weed species. While the individual effects of environmental change and of weeds on crop yield have been assessed, the combined effects have not been broadly characterized. To explore the simultaneous impacts of weeds with changes in climate-related environmental conditions on future food production, we conducted a meta-analysis of 171 observations measuring the individual and combined effects of weeds and elevated CO_2, drought or warming on 23 crop species. The combined effect of weeds and environmental change tended to be additive. On average, weeds reduced crop yield by 28%, a value that was not significantly different from the simultaneous effect of weeds and environmental change (27%), due to increased variability when acting together. The negative effect of weeds on crop yield was mitigated by elevated CO_2 and warming, but added to the negative effect of drought. The impact of weeds with environmental change was also dependent on the photosynthetic pathway of the weed/crop pair and on crop identity. Native and non-native weeds had similarly negative effects on yield, with or without environmental change. Weed impact with environmental change was also independent of whether the crop was infested with a single or multiple weed species. Since weed impacts remain negative under environmental change, our results highlight the need to evaluate the efficacy of different weed management practices under climate change. Understanding that the effects of environmental change and weeds are, on average, additive brings us closer to developing useful forecasts of future crop performance.

1. Introduction

As the human population grows, global demand for food production is increasing. Concurrently, factors affecting food supply are changing. The spread of weed species and the prevalence of herbicide-resistant weeds is increasing. Weeds already cause greater global crop losses than either insect pests or pathogens (Oerke 2006, Fried *et al* 2017); yield losses to non-native weeds can amount to 42% of crop production (Vilà *et al* 2004). Weed control costs farmers over €150 million per year in the UK (Williamson 2002) and $3 billion per year in the U.S. (Pimentel *et al* 2005). Simultaneously, changes in Earth's climate and atmosphere are directly affecting growing conditions for plants; colder regions are experiencing longer growing seasons (Mueller *et al* 2015), drought conditions are increasing in many regions (Naumann *et al* 2018), and rising atmospheric CO_2 is affecting plant growth worldwide (Zhu *et al* 2016). Some of these changes are causing widespread yield losses in crops (Porter *et al* 2014). For example, in South Asian smallholder farms, drought and other water constraints cause yield losses that average 9.1% in wheat, rice, sorghum and chickpea crops (Li *et al* 2011). Furthermore, a recent meta-analysis of studies modeling climate warming impacts on crops found that models project yield losses of wheat, rice and maize to increase in tropical and temperate regions in the second half of the century (Challinor *et al* 2014). However, most predictions of future crop yields are based solely on crop performance under forecasted climates without accounting for changes in weed competition.

Combined effects of climate change and weeds on crop production have not been broadly synthesized, but have important implications for future crop management practices (Thomson *et al* 2010). A primary question is whether the combined effect of weeds and climate change is additive (individual effects sum together), synergistic (effects amplify each other) or antagonistic (effects offset each other) (Crain *et al* 2008, Darling and Côté 2008, Jackson 2015). Some studies that have tested multiple abiotic global change factors have found additive effects (Dieleman *et al* 2012). However, many of these effects are not additive (16) and interactions between abiotic and biotic global factors can be complex (Tylianakis *et al* 2008). If non-additive effects of climate and weeds are common, predictions of future crop yields will have to include them to be realistic (Tubiello *et al* 2007, Ramesh *et al* 2017).

In agricultural systems, both crops and weeds are influenced by multiple climate-related environmental conditions (Korres *et al* 2016). Changes in atmospheric CO_2, temperature and precipitation influence weed and crop species' metabolic rates, phenology and performance (Bunce and Ziska 2000). However, weeds and crops may respond to these changes differently because they have been subjected to distinct selective pressures (Korres *et al* 2016). Further, research on biological invasions suggests that the interaction between environmental change and weed effects could depend on the functional traits of the species involved, the origin of the weeds, and whether one or more weeds are present. For example, the impact of weeds on crops often depends on the plants' functional traits, such as their photosynthetic pathways (Ziska 2003, Fried *et al* 2017). Everything else being equal, increased atmospheric CO_2 increases primary production and water-use efficiency in C3 plants, while C4 plants are less likely to benefit from CO_2 enhancement. In contrast, C4 plants are more likely than C3 plants to thrive under warm and dry conditions (Ainsworth and Long 2005, Prior *et al* 2011). Thus, the competitive outcome between C3 and C4 plants could depend on the specific environmental component of climate change under consideration (Korres *et al* 2016). Since both crops and weeds include C3 and C4 plants, we expect that impacts on crop yield will depend on interactions between photosynthetic pathway and environmental change (Ainsworth and Rogers 2007).

Effects of weeds on crops might also depend on weed origin (native vs. non-native). Non-native plants have left behind natural enemies that keep their populations in check in their native ranges (Maron and Vilà 2001). Release from natural enemies can allow non-native plants to allocate more resources to growth and reproduction in the new regions, and become more competitive (Blossey and Notzold 1995). Many successful non-native plant species also have broad environmental tolerances, high phenotypic plasticity or the ability to evolve more rapidly than native plants (Davidson *et al* 2011, Simberloff *et al* 2012) potentially allowing them to benefit more from global environmental change than native plants (Davidson *et al* 2011). Thus, with environmental change, we expect non-native weeds to have greater impacts on crop yield than native weeds.

The magnitude of weed impacts on crops under environmental change might also depend on whether a crop is infested by one or multiple weed species. Most crops contain diverse communities of weeds, which respond to environmental change through shifts in relative abundance (Booth and Swanton 2002). Ecological theory and empirical evidence suggest that a community of multiple species could be more resilient to environmental change than poor species communities (Tilman *et al* 2014, van der Plas 2019). Thus, in agricultural systems, we expect infestation by multiple weed species to have greater impacts on crop yield under environmental change.

Understanding the interactive effects of climate and weeds requires empirical studies that compare crop yields under different environmental conditions in the presence of weeds (Parmesan *et al* 2018). Some experiments have tested these effects, but these studies have yet to be synthesized quantitatively. As a result, we do not have clear expectations for how climate change and weeds will affect crops, simultaneously. To test the above hypotheses and identify the contexts in which crop yield is most vulnerable to the simultaneous effects of weeds and environmental change, we conducted a systematic review and meta-analysis. Specifically, we analyzed results from experiments addressing the combined and direct effects of weeds and elevated CO_2, drought or warming on the yield-related variables of 23 crop species, and asked the following questions: (a) is the effect of weeds on crop yield altered by environmental change? (b) Are the combined effects of weeds and environmental change on crops additive, synergistic or antagonistic? (c) Do the combined effects of weeds and environmental change depend on the photosynthetic pathway (C3 vs. C4) of the crop/weed species pair, (d) on the origin of the weed (native vs. non-native), or (e) on whether single or multiple weed species are competing with the crop? Finally, (f) how might the main crop species around the world be affected by weeds under environmental change?

2. Materials and methods

2.1. Literature search and data selection criteria

Our database development was based on a systematic literature search protocol, paper selection criteria and data extraction protocol (Pullin and Stewart 2006). For quality control, at each step, we trained data collectors using an example subset of the data and discussed eligibility of all included data.

To identify studies that experimentally tested the interactive effects of weeds and climate changes (elevated CO_2, warming or drought), we searched the Web of Science core collection for all records until 25/07/2018 using the following keywords: (a) 'crop AND (weed control OR herbicide OR weed competition OR weed management) AND weed AND (Warm* OR heat* Or thermal OR temperature increase OR temperature manipulation* OR climate change)'; (b): 'crop AND (weed control OR herbicide OR weed competition OR weed management) AND weed AND (CO_2 OR carbon dioxide) AND (increase* OR enhance* OR enrich* OR elev*)'; and (c) 'crop AND (weed control OR herbicide OR weed competition OR weed management) AND weed AND (Drought OR water stress* OR rainout OR rain out OR rain-out OR precipitation exclusion* OR rain exclusion* OR precipitation removal*)'.

This search retrieved 1436 publications. By reviewing titles and abstracts, we identified studies for which the following criteria for data inclusion were met: (a) the study independently tested the effects on crop performance of both the weed and environmental change; (b) the study tested the combined effects of the weed and environmental change either through experimental manipulation of both factors, or by experimentally manipulating one factor across a gradient of the other factor (e.g. a weed removal experiment across an irrigation gradient); (c) the study included control treatments (no weed and no environmental change); and finally; (d) the response variables were measured simultaneously in all treatments. These criteria for inclusion yielded a set of 57 publications (SI references, figure S1, available online at stacks.iop.org/ERL/16/034043/mmedia).

A single publication could include results of multiple observations. If the publication reported results fitting our criteria for data inclusion for multiple weed and/or crop species, we considered each weed-crop combination to be a unique observation. If several varieties of the same crop were tested independently, we also considered these to be unique observations. If an article included observations conducted on the same crop but located in two or more regions or sites, we considered the studies as independent. Similarly, if the treatments were conducted several times, or the crop was planted at different times, each treatment was used as an independent observation. When the observation incorporated information on more than one control treatment (e.g. different herbicides used to suppress weeds), we included them as independent observations. Following the same reasoning, when the article incorporated information on more than one experimental method for the same environmental change variable (e.g. CO_2 enrichment conducted in both growth chambers and a field experiment), we considered each separately. When more than two treatment levels were examined (e.g. different weed densities, different CO_2 concentrations), only the most extreme treatment was included. Thus, if the degree of weed infestation varied, we compared the effects of the lowest ('control') vs. highest ('treatment') level of infestation.

Studies reported different crop response variables (e.g. plant biomass, seed production, plant height, leaf area, etc). We considered the response variable most associated to the specific crop yield (crop yield hereafter). If the response variables were measured several times, we provided the average value of the time series. If the time series was not provided, we included the measure that we considered ecologically most representative (e.g. the last one in the time series; spring measurement of an annual series during season of maximum activity; measurement closest to maximum crop yield).

For every unique observation, we recorded the weed species and the location of the observation, using this information to determine whether the weed was native or non-native to the study region based on range information provided in several information sources (e.g. CABI Invasive Species Compendium). We also recorded whether the observation focused on a single weed or a mixture of weeds. Crop and weed species were also classified by their photosynthetic pathway (C3 vs. C4).

The analysis included field, greenhouse and chamber experiments. Weed treatments were rather heterogeneous. Weed treatments used included: planting weeds at different densities, removing weeds manually or mechanically, use of herbicides or combinations of these removal methods. In field conditions, drought has mostly tested by different irrigation treatments or by comparing wet and dry seasons or years. Similarly, the effect of warming was tested in experiments that elevated soil or air temperature but also in studies that compared years with different mean temperature but similar precipitation. The effect of increased CO_2 included similar numbers of studies in outdoor open-top chambers as in indoor chambers.

2.2. Data analysis

We examined the effect of weeds and environmental change using standard meta-analytical models (Koricheva *et al* 2013). For each observation, we extracted data on the number of replicates, mean and variability around the mean (e.g. standard deviation or standard error) for controls, individual treatments, and interactive weed and environmental change treatments. We used the WebPlotDigitizer online application (http://arohatgi.info/WebPlotDigitizer/app/) to extract values from figures in the papers. When empirical data were not presented, or were presented only in summarized format, we emailed corresponding authors to request raw data and included any raw data received in the analysis. A description of the flowchart for the publication selection process following Moher *et al* (2009) can be found in figure S1.

2.2.1. Effect size calculation

We compared treatment effects across cases by estimating effect size (ES) as: *ln(Treatment mean/Control mean)*. We used simulations (1000 iterations) to estimate ES mean and SD, ES for each observation was drawn from normal distributions with reported means and SDs (see supplemental information for code). ES was estimated at each iteration and from that output (1000 values) we estimated ES mean and SD (SI text S1). Sample size was also considered in these estimations by weighing reported variances by sample size (Gurevitch and Hedges 2001). We used simulations to estimate ES, instead of standard metrics (e.g. Hedges' g) because a large proportion of observations did not report a measure of variability associated with the mean (57%). We included these observations by estimating the variance around their ES as a latent variable.

Although there is a lack of consistency about how to handle missing variance data (Wiebe *et al* 2006), there are three common methods of dealing with this: an algebraic calculation which requires parametric summary statistics, trial-level imputation (averaging, or running regressions, across observations with known variances), and no imputation (excluding observations with no variance) (Batson and Burton 2016). We did not want to bias our results by excluding such a large proportion of the data, as a result, in our analyses, we opted for the most conservative, lowest bias, imputation method. We estimated the missing variances as a function of the largest ES variance calculated from observations with reported variances. We sampled from normal distributions (limited to be positive) with estimated largest variance as the mean and a SD of 1. There were also nine observations that did not report sample size. For these observations, we followed the most conservative approach and assigned them a sample size $N = 1$.

We calculated the expected additive effect of weeds plus environmental change by summing the individual experimental results (weed + environmental change) and compared the expected additive effect to the measured combined effect reported in each observation (weed and environmental change). We followed Jackson (2015) to estimate the mean and pooled SD of the additive effect (see ES4 in table 1).

To address our specific research questions, we calculated several ESs, all based on crop performance under different treatments, C: control, W: with weeds, EC: under environmental change, and W and EC: with weeds and under environmental change (table 1, SI text S1).

2.2.2. Analysis of ESs

Individual values of ES were then analyzed to assess effects of weeds and environmental change factors on crop production. ESs were analyzed using mixed effects models with publication as a random effect. This accounted for the lack of independence among observations from the same study. By using study random effects in our analyses, individual observations were nested within each study, thus the study random effect is a 'combined' mean, as in Ponisio *et al* (2015). Given the low number of studies considering the combined effects of weeds and environmental change on crops, including other potential random effects (e.g. for crop and weed species) was not feasible. For each ES calculation the effect of different environmental change factors (elevated CO_2, drought or warming) were estimated. Since we were using latent estimates of ES variability (for those observations with missing variance), we used a hierarchical Bayesian approach in this analysis; parameters were all estimated from non-informative prior distributions except for the missing variances (see description of methods above). All the prior distributions for the ES were: ES* ~ Normal (0,100), and all the precision terms prior distributions were: 1/variance ~ Gamma (0.001, 0.001).

We ran similar analyses, using ES1-effect of weeds alone and ES3-weed effect under environmental change, for each combination of crop/weed photosynthetic pathway (C3 and C4), for each crop species, for each type of weed origin (native and non-native), and for single vs. multiple weed species systems. Due to the low number of data points for some of the subgroups, this second analysis was done without publication random effects. ES calculations and analyses were carried out in OpenBUGS (Thomas *et al* 2006; see SI text S1 for analysis code). ES posterior estimates that did not include zero in their 95% credible intervals were considered statistically significant. ESs with 95% credible intervals that did not overlap were considered significantly different from each other.

2.2.3. Publication bias

Meta-analysis results may be distorted by publication bias, that is, the selective publication of articles finding significant effects over those that find

Table 1. Calculations of effect size (ES) estimates to assess the combined effects of environmental change and weeds on crop performance. C: control, crop performance without weeds and without environmental change; W: crop performance under weed treatment and without environmental change; EC: crop performance under environmental change and without weeds; W and EC: observed crop performance with weeds and environmental change; W + EC: expected additive performance (i.e. sum of the individual experimental results) with weeds and environmental change.

Effect size	Comparison	Calculation
ES1	Weed effect on crops under current climatic conditions	ln(W/C)
ES2	Environmental Change (elevated CO_2, drought or warming) effect on crops	ln(EC/C)
ES3	Observed weed effect under Environmental Change	ln(W and EC/EC)
ES4	Additive expectation relative to the observed combined effect	ln(W + EC/W and EC)

non-significant effects (Rothstein 2008). In our case, this bias in publication could lead to an overestimate of the effects of weeds and environmental change variables on crop yield. We visually checked for potential bias using funnel plots (see figure S2; although see Tang and Liu 2000, Lau *et al* 2006).

3. Results and discussion

Our final database contained 171 observations from 57 publications (table S1) on the effect of more than 47 weed species on 23 crop species. Most observations were conducted in North America (72) and Asia (44), followed by Europe (figure 1), with a clear lack of observations conducted in Africa, South America, and Australasia. The majority of observations (84) were on the effect of drought, with 49 on the effect of elevated CO_2 and 31 on the effect of increased temperature. The most frequently studied crops were rice (42 observations), mostly in Eastern Asia, followed by soybean (31), tomato (30) and corn (12). Wheat, the most widely grown crop in the world and second most important food source in low-income countries, was represented in only seven observations, none of them testing the effects of elevated CO_2. Nine crop species were represented by a single observation (figure 1).

3.1. Is the effect of weeds on crop yield altered by environmental change?

Weeds alone significantly reduced crop performance by 27.99% on average (figure 2, table S3). Elevated CO_2 increased crop performance by 45.90% while drought decreased it by 29.85%; warming did not have a significant effect due to its large variation across studies (figure 2, table S3). Elevated levels of atmospheric CO_2 often increase growth and water use efficiency of crop species that translate to increased crop production (Ainsworth and Rogers 2007). On the contrary, drought can have devastating effects to crop yields especially in non-irrigated systems (Li *et al* 2011). The effect of warming is more context-dependent. Warming can accelerate and improve growing conditions in temperate regions by lengthening growing seasons and periods of time with optimal temperature but can also increases the risk of exposure to damaging heat (Tubiello *et al* 2007).

We assessed whether the negative effects of weeds were likely to change with environmental change by comparing ES1 (weed effect under current environmental conditions) and ES3 (weed effect under environmental change). Overall, the simultaneous effect of weeds and environmental change reduced crop performance by 26.64% a value that was not significantly different from the single effect of weeds without environmental change. Crop yield became more variable with warming, such that there was no significant effect under increased temperature (figure 2). ES3 was dependent on the biome (SI text S1, table S2). The effect of the weeds under drought was most negative in Mediterranean, arid or semiarid climates, intermediate in temperate climates and the lowest in tropical and subtropical climates. This indicates that the impact of weeds on major crops might be exacerbated in dry regions such as the Mediterranean biome where models predict decreasing precipitation with climate change (Rojas *et al* 2019). In contrast, the effect of the weeds under warming was negative in tropical climates but not significant in temperate climates.

These results shed some light on how the simultaneous effects of environmental change on crop and weed species may alter their interaction. Weed species tend to have a strong, positive response to elevated atmospheric CO_2 (Ziska 2003), and weed presence counteracted any benefits of elevated CO_2 to crops. In the case of drought, the lack of change in overall weed impact suggests that reduced water availability has a similar negative effect on both crops and weeds, despite the fact that that the impact is larger in water stressed regions. In the case of warming, ES3 was highly variable. A correlation analysis between the magnitude of the change and ES3 indicated an increase in the ES with increasing temperature differences (SI figure S3). Both crops and weeds are likely to benefit from warming, leading to both positive and negative outcomes on the impact of weeds. Overall, our results suggest more variable effects of weeds on crops under environmental change, and a need to adapt weed management practices where weed impacts increase (Peters *et al* 2014).

3.2. Is the combined effect of weeds and environmental change on crops additive, synergistic or antagonistic?

To answer this question, we compared the additive expectation against the observed combined effect

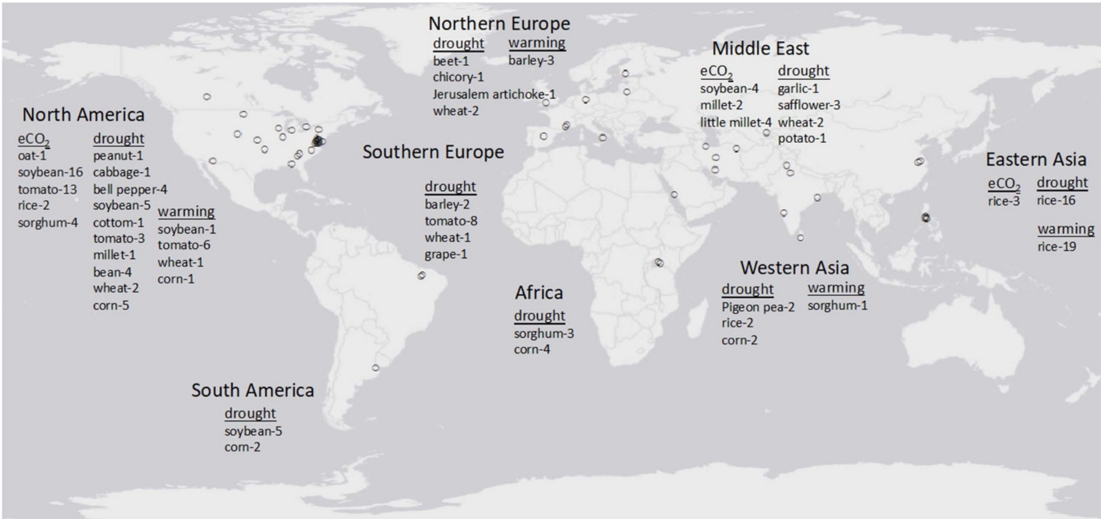

Figure 1. Geographic distribution of study sites used in the analysis. Tables show crop species studied and environmental factor considered. Numbers indicate number of observations included in the meta-analyses (see table S1 for more information).

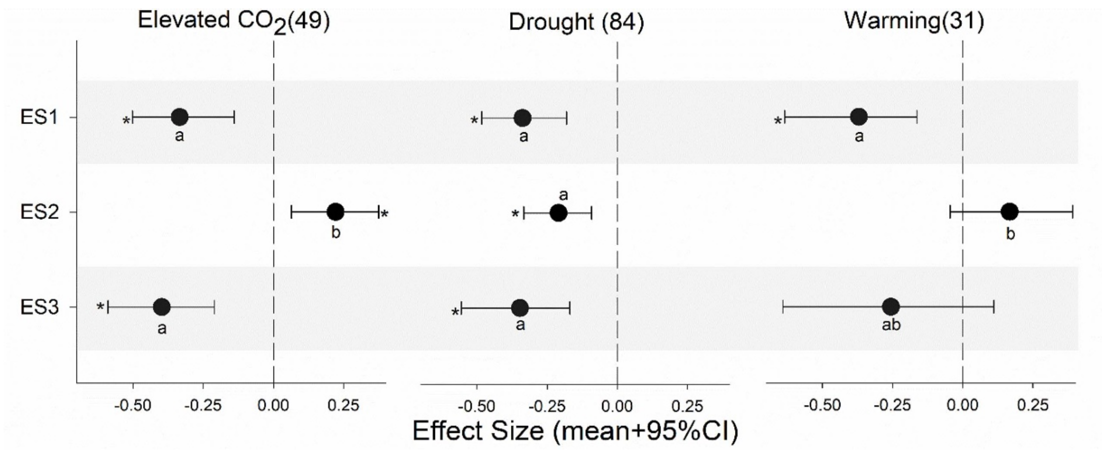

Figure 2. Effect size (ES) estimates comparing crop performance under current environment conditions and without weeds (control) with weeds (ES1), with environmental change (ES2), and the effect of weeds under environmental change (ES3). Credible intervals (95%CI) that do not include zero are considered statistically significant (indicated by an asterisk). Within each environmental change factor, different letters indicate that credible intervals are statistically different from each other. Numbers indicate sample sizes. See table S2 for parameter values.

of weeds and environmental change (ES4). There is wide variation among observations (figure 3). A correlation analysis between the magnitude of the change and ES4 indicated a trend towards synergistic effects with increasing temperature differences (SI figure S4). However, the combined effects of environmental change and weeds are on average additive. The effects of weeds are similar in present and predicted future environmental conditions, even though environmental change can dramatically alter competitive interactions among weeds and crops within particular cropping systems (Tylianakis *et al* 2008, Ziska and Dukes 2011). This result is in line with the additive effects found between other global change drivers (Wu *et al* 2011), but see Dieleman *et al* 2012). To realistically assess future crop production and inform management, we need to consider these combined effects of environmental change and weeds. As it stands, most experimental and synthetic work aimed at predicting crop yield only accounts for one of these two factors. Understanding that the effects of environmental change and weeds are, on average, additive brings us closer to developing useful forecasts of future crop performance.

3.3. Does the combined effect of weeds and environmental change depend on the photosynthetic pathway (C3 vs. C4) of the crop/weed species pair?

We addressed this question by comparing estimates between ES1 and ES3 for the four potential combinations of crop/weed photosynthetic pathway, C3/C3, C3/C4, C4/C3, and C4/C4 (SI table S2). We

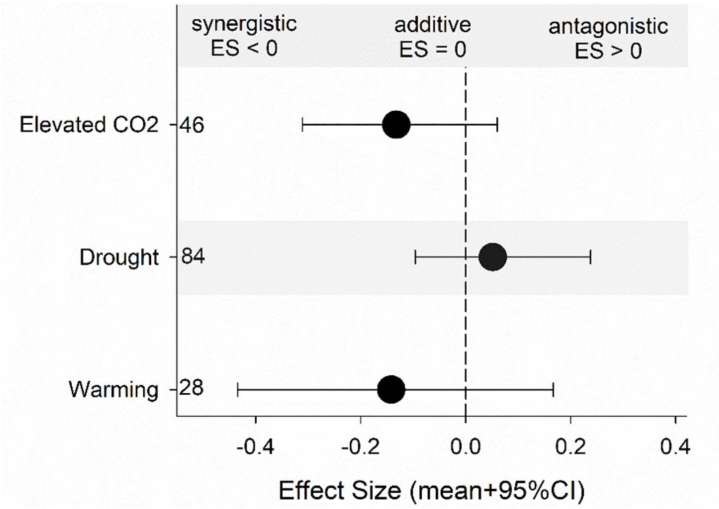

Figure 3. Effect size (ES4: W + EC/W and EC) estimates to test if the combined effect of environmental change factors (EC) and weeds (W) on crop yield are additive, synergistic or antagonistic. We consider effects with credible intervals (95%) overlapping zero to be additive. Numbers are sample sizes. See table S2 for parameter values.

found that the impact of weeds on crops grown under environmental change conditions depended on the species' respective photosynthetic pathways and on the environmental change component under consideration (figure 4).

Elevated CO_2 increased the effect of the weeds on crops if they had the same photosynthetic pathway, decreased the effect of C4 weeds on C3 crops, and was not significant in C4 crop/C3 weed pairs. Thus, under elevated CO_2, weeds might increase their performance and be more competitive than crops if they are of the same photosynthetic pathway. In contrast, a greater responsiveness of C3 crops to CO_2 would benefit them when competing with C4 weeds (e.g. Patterson 1995) such as in rice crops (C3) invaded by C4 weeds (Rodenburg *et al* 2011).

Drought increased the impact of the weeds in mixed pairs, decreased it in the C3/C3 pairs and was not significant in the C4/C4 pairs. Surprisingly, warming decreased the impact of C4 weeds on C3 crops but did not significantly affect C3 weeds' impacts on C3 crops; this combination had a small sample size (only three observations) and large variation. Warmer or drier conditions have been hypothesized to benefit C4 over C3 species (Patterson 1995). However, this pattern was not supported by our meta-analysis, indicating that other functional traits beside photosynthetic pathway might be more important to determine competitive superiority under climate change.

3.4. Does the combined effect of weeds and environmental change depend on the weed origin?

We addressed this question by comparing estimates between ES1 and ES3 for native and non-native weeds (SI table S2). We did not find differences between the impact of native and non-native weeds on crops under current climatic conditions (figure 5). This supports other research findings that non-native plants are not more competitive than common native plants (Zhang and van Kleunen 2019). Contrary to our expectations, environmental change did not increase the impact of non-native weeds relative to native weeds. Indeed, due to large variation across observations, non-native weeds did not consistently reduce crop performance with drought or warming. Rather, the non-native weed effects remained non-significant with environmental change (figure 5). This result does not align with differences found between native and non-native plant performance (i.e. survival, growth and fecundity) with climate change in natural ecosystems (Sorte *et al* 2013, Liu *et al* 2017).

3.5. Is the combined effect of weeds and environmental change on crops similar when there is a single weed species vs. multiple weed species?

We addressed this question by comparing estimates between ES1 and ES3 for single weed species vs. mixtures of weeds (SI table S2). We expected that multiple weed species would have stronger impacts on crops, and the impacts would be less affected by environmental change than single weed species. However, the impact of weeds did not differ depending on the number of weeds present, and the impact of multiple weeds was not modified by environmental change (figure 6). Our results suggest that the potential for diffuse competition among plant species in the community reduces the impacts on a particular species within the community (Goldberg 1987). It is possible that competition among weed species limits their impact on the crop (Lohrer and Whitlatch 2002).

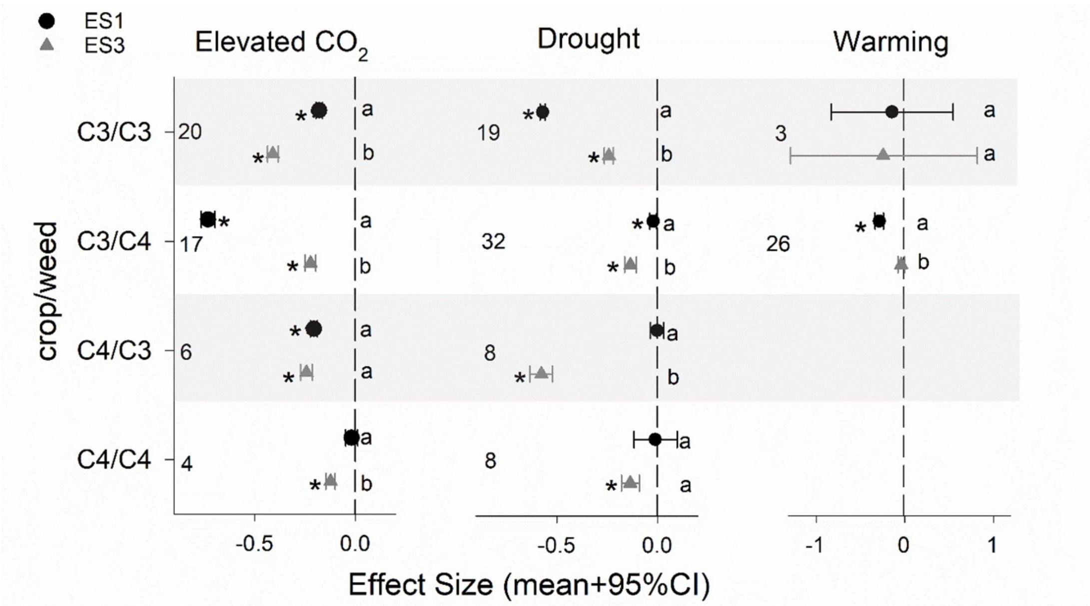

Figure 4. Effect size (ES) estimates of the effect of weeds, both under current environmental conditions (ES1) and with environmental change (ES3), categorized by weed and crop photosynthetic pathways (C3 or C4). Credible intervals (95%) that do not include zero are considered statistically significant (indicated by asterisks). For each photosynthetic pathway and environmental change factor combination, different letters indicate that the effect of the weeds is significantly different between current and changing environmental conditions (credible intervals do not overlap). There are no data to test for the effect of weeds under warming for C4/C3 and C4/C4 pairs. Numbers indicate sample sizes. See table S2 for parameter values.

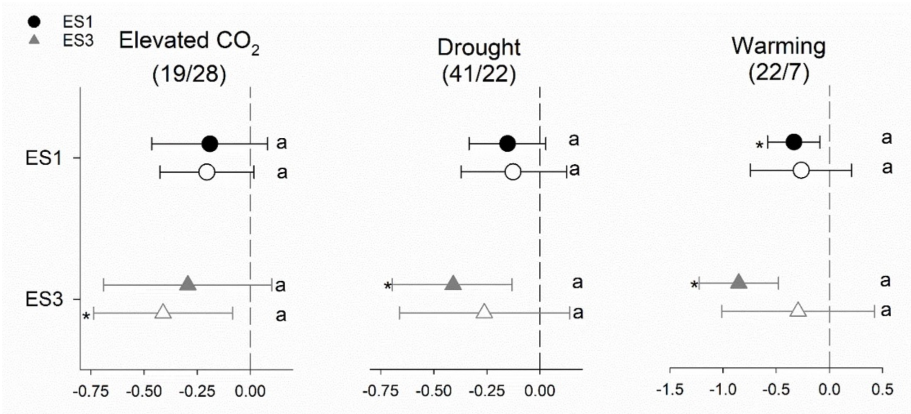

Figure 5. Effect size (ES) estimates of weeds under current environmental conditions (ES1) vs. weeds with environmental change (ES3) relative to weed origin (native-solid symbols or non-native-white symbols). Credible intervals (95%) that do not include zero are considered statistically significant (indicated by asterisks). Within each panel, different letters indicate that the effects are statistically different from each other (credible intervals do not overlap). Numbers indicate sample sizes (native/non-native). See table S2 for parameter values.

We also note that variability in the impacts of weed mixtures was much greater than for single weeds, particularly in the environmental change treatments.

While our results do not support the hypothesis that multiple weed species would have stronger impacts than a single weed, and that multiple weed species become more problematic for crops under environmental change, our sample sizes were too low to confidently reject these hypotheses, particularly under the environmental change treatments. Some studies have indeed found the reverse, that more diverse weed communities are less competitive with the crop than poor weed communities (Storkey and Neve 2018).

3.6. Is the effect of weeds under environmental change similar among major crop species?

Ultimately, in order to effectively inform crop selection and management, we need predictions of individual crop species performance under the combined effects of weeds and environmental change. Despite the general effects of weeds and environmental change on crops (figure 2), individual crop species showed differing responses to environmental change (figure 7).

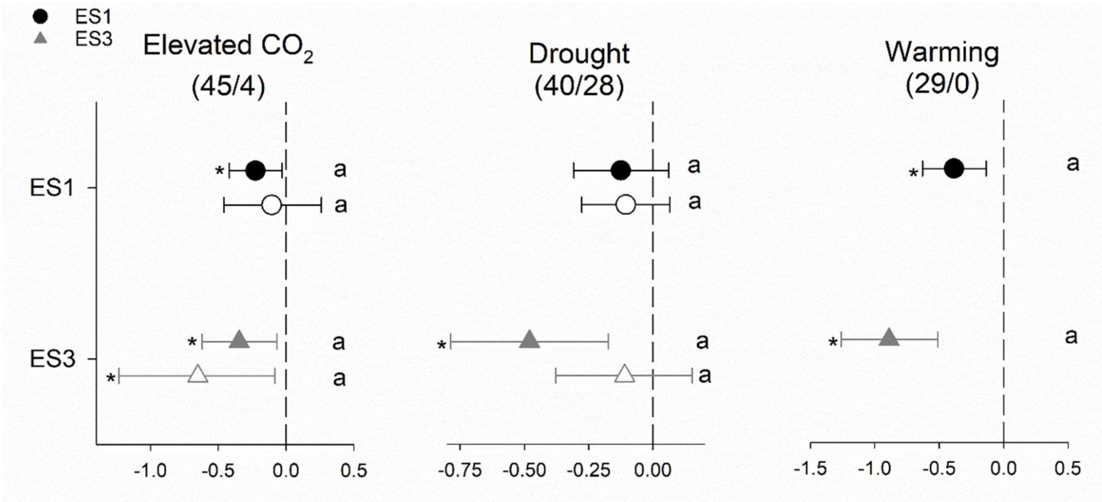

Figure 6. Effect size (ES) estimates of weeds under current environmental (ES1) vs. weeds with environmental change (ES3) for studies with single weed species (solid symbols) vs. multiple weeds (white symbols). Credible intervals (95%) that do not include zero are considered statistically significant (indicated by an asterisk). Within each panel, different letters indicate that the effects are statistically different from each other (credible intervals do not overlap). Numbers indicate sample sizes (single/multiple). See table S2 for parameter values.

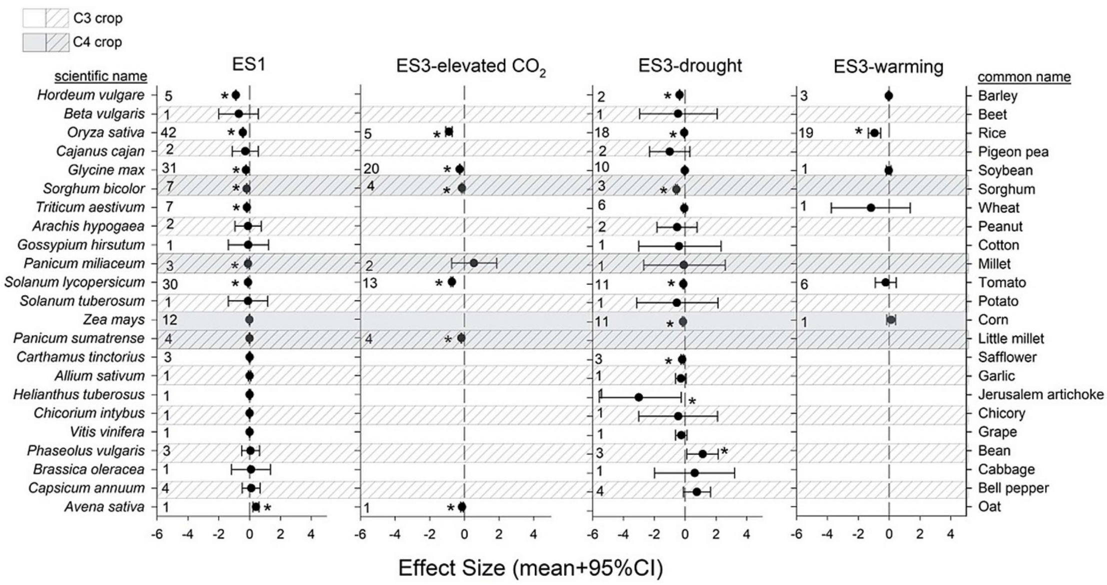

Figure 7. Effect size (ES) estimates of weeds, either under current environmental (ES1) or with environmental change (ES3), for studies of particular crop species. Credible intervals (95%) that do not include zero are considered statistically significant (indicated by an asterisk). Numbers indicate sample sizes. See table S2 for parameter values.

Surprisingly, without environmental change, crop yield was significantly reduced in only seven species, with the performance of only one crop, oat, showing an increase in yield with weeds (figure 7, ES1). Data were available to assess the effect of weeds under elevated CO_2 for seven crops. Elevated CO_2 reversed the negative effect of weeds in millet, a C4 plant, and increased the negative effects of weeds in little millet (C4) and oat (C3).

The impact of weeds under drought conditions become more detrimental for corn (C4), Jerusalem artichoke (C3) and safflower (C3), and were less detrimental (non-significant) in soybean (C3), wheat (C3) and millet (C4); for common beans (C3), the effect of weeds became positive with drought. Under warming, the impact of weeds remained negative for rice and decreased for barley, soybean, wheat and tomato becoming non-significant.

Differences among crop species should be interpreted with caution due to the uneven taxonomic and geographical distribution of the studies (figure 1) and the small number of observations on the combined effects of weeds under environmental change for many crops. More than half of the observations used rice, soybean and tomato crops, while nine crop species were represented by a single observation (figure 7). We should also be aware that differences in weed composition and densities across observations might influence their impact (Vilà *et al* 2004, Zimdahl 2004).

4. Conclusions and the way forward

Understanding how global change will affect crop yield is critical for projecting future food production. For this reason, many studies have quantified the effects of two major factors affecting crop yields: climate change and weeds. However, most studies have examined these factors in isolation (Juroszek and Von Tiedemann 2013), leaving uncertainty about the validity of extrapolations (Ward *et al* 2014). Studies that simultaneously address the effects of environmental conditions related to climate change and weeds on crops are not common, and surprisingly, many have experimental design limitations that precluded their inclusion in meta-analysis (Gurevitch *et al* 1992). Many studies did not explore the single and interactive effects of weeds and environmental change under the same experimental conditions or on the same crop varieties. Other studies lacked control treatments, had no replication, or did not present variance data. This information is often missing in agronomic studies of competition (Vilà *et al* 2004), which limited the dataset of studies available for synthesis. To present a comprehensive dataset, we included studies where the primary aim was not to test for the effect of climate change, but which provided proxies (i.e. contrasting environmental differences) to test for the effect of environmental change on crops with and without (or with low levels of) weeds. To better assess how climate change affects weed constraints on crops, future research should implement replicated well designed experiments with controls that provide full statistics and that explicitly test realistic environmental changes in field conditions. Future studies should also evaluate the effects of multiple environmental change components on crops with and without weeds (Peters *et al* 2014).

Of all pests, weeds have the greatest potential to reduce worldwide crop yields (Oerke 2006). Moreover, our meta-analysis indicates that the effects of weeds alone can be more detrimental on crop yield than environmental change alone. Our results also suggest that weeds will reduce crop yield under climate change by a similar magnitude to their effects under current climatic conditions. Therefore, weed management will remain a critically important activity climatic change. Weed management is facing major challenges such as the increasing rates of weed dispersal through global trade and climate change, the environmental damage caused by weed control, and weed resistance to herbicides (Liebman *et al* 2016). Because our results indicate that under forecasted climate change, the negative effects of weeds will persist to similar magnitude, we propose the following priority research areas: (a) comparing the effects of different weed management practices (e.g. chemical vs. mechanical) to minimize crop yield losses and costs under climate change (Peters *et al* 2014); (b) focusing on rarely studied subsistence crops (e.g. vegetables) that depend on manual labor for weed management and on farming systems that cannot compensate for drought with irrigation (Altieri 2019); (c) exploring differences among crop varieties (e.g. weed-suppressive crop genotypes) in the impact of weeds and climate change (Korres *et al* 2016), (d) conducting research in regions where there are few studies, such as in the southern hemisphere, especially on weed effects with warming and (e) exploring if there are thresholds of environmental change that might cause non-additive effects with weeds.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files, stacks.iop.org/ERL/16/034043/mmedia).

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Author contributions

Author contributions: M V and I I designed research; M V, E B, D B, B A B, R E, B B L and A T performed research; I I and M V analyzed data; M V and I I wrote the paper; E B, D B, B A B, R E, B B L, A T, J D and C J B S commented several versions of the manuscript.

ORCID iDs

Montserrat Vilà https://orcid.org/0000-0003-3171-8261
Evelyn M Beaury https://orcid.org/0000-0002-7971-3593
Dana M Blumenthal https://orcid.org/0000-0001-7496-0766
Bethany A Bradley https://orcid.org/0000-0003-4912-4971

Regan Early https://orcid.org/0000-0003-4108-5904
Alejandro Trillo https://orcid.org/0000-0002-6944-0923
Jeffrey S Dukes https://orcid.org/0000-0001-9482-7743
Cascade J B Sorte https://orcid.org/0000-0003-0952-951X
Inés Ibáñez https://orcid.org/0000-0002-1054-0727

References

Ainsworth E A and Long S P 2005 What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2 *New Phytol.* **165** 351–72

Ainsworth E A and Rogers A 2007 The response of photosynthesis and stomatal conductance to rising [CO_2]: mechanisms and environmental interactions *Plant Cell Environ.* **30** 258–70

Altieri M A 2019 *Crop Protection Strategies for Subsistence Farmers* (Boca Raton, FL: CRC Press)

Batson S and Burton H 2016 A systematic review of methods for handling missing variance data in meta-analyses of interventions in type 2 diabetes mellitus *PLoS One* **11** e0164827

Blossey B and Notzold R 1995 Evolution of increased competitive ability in invasive nonindigenous plants: a hypothesis *J. Ecol.* **83** 887–9

Booth B D and Swanton C J 2002 Assembly theory applied to weed communities *Weed Sci.* **50** 2–13

Bunce J A and Ziska L H 2000 Crop ecosystem responses to climatic change: crop/weed interactions *Climate Change and Global Crop Productivity* ed K R Reddy and H F Hodges (Egham: CABI) pp 333–48

Challinor A J, Watson J, Lobell D B, Howden S M, Smith D R and Chhetri N 2014 A meta-analysis of crop yield under climate change and adaptation *Nat. Clim. Change* **4** 287–91

Crain C M, Kroeker K and Halpern B S 2008 Interactive and cumulative effects of multiple human stressors in marine systems *Ecol. Lett.* **11** 1304–15

Darling E S and Côté I M 2008 Quantifying the evidence for ecological synergies *Ecol. Lett.* **11** 1278–86

Davidson A M, Jennions M and Nicotra A B 2011 Do invasive species show higher phenotypic plasticity than native species and, if so, is it adaptive? A meta-analysis *Ecol. Lett.* **14** 419–31

Dieleman W I *et al* 2012 Simple additive effects are rare: a quantitative review of plant biomass and soil process responses to combined manipulations of CO_2 and temperature *Glob. Change Biol.* **18** 2681–93

Fried G, Chauvel B, Reynaud P and Sache I 2017 Decreases in crop production by non-native weeds, pests, and pathogens *Impact of Biological Invasions on Ecosystem Services* ed M Vilà and P E Hulme (Berlin: Springer) pp 83–101

Goldberg D E 1987 Neighborhood competition in an old-field plant community *Ecology* **68** 1211–23

Gurevitch J and Hedges L V 2001 Meta-analysis: combining the results of independent experiments *Design and Analysis of Ecological Experiments* ed S M Scheiner and J Gurevitch (Oxford : Oxford University Press)

Gurevitch J, Morrow L L, Wallace A and Walsh J S 1992 A meta-analysis of competition in field experiments *Am. Nat.* **140** 539–72

Jackson M C 2015 Interactions among multiple invasive animals *Ecology* **96** 2035–41

Juroszek P and Von Tiedemann A 2013 Plant pathogens, insect pests and weeds in a changing global climate: a review of approaches, challenges, research gaps, key studies and concepts *J. Agric. Sci.* **151** 163–88

Koricheva J, Gurevitch J and Mengersen K 2013 *Handbook of Meta-analysis in Ecology and Evolution* (Princeton, NJ: Princeton University Press)

Korres N E *et al* 2016 Cultivars to face climate change effects on crops and weeds: a review *Agron. Sustain. Dev.* **36** 12

Lau J, Ioannidis J P, Terrin N, Schmid C H and Olkin I 2006 The case of the misleading funnel plot *Br. Med. J.* **333** 597–600

Li X, Waddington S R, Dixon J, Joshi A K and de Vicente M C 2011 The relative importance of drought and other water-related constraints for major food crops in South Asian farming systems *Food Secur.* **3** 19–33

Liebman M *et al* 2016 Ecologically sustainable weed management: how do we get from proof-of-concept to adoption? *Ecol. Appl.* **26** 1352–69

Liu Y, Oduor A M, Zhang Z, Manea A, Tooth I M, Leishman M R, Xu X and Van Kleunen M 2017 Do invasive alien plants benefit more from global environmental change than native plants? *Glob. Change Biol.* **23** 3363–70

Lohrer A M and Whitlatch R B 2002 Interactions among aliens: apparent replacement of one exotic species by another *Ecology* **83** 719–32

Maron J L and Vilà M 2001 When do herbivores affect plant invasion? Evidence for the natural enemies and biotic resistance hypotheses *Oikos* **95** 361–73

Moher D, Liberati A, Tetzlaff J and Altman D G The PRISMA Group 2009 Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement *PLoS Med.* **6** e1000097

Mueller B, Hauser M, Iles C, Rimi R H, Zwiers F W and Wan H 2015 Lengthening of the growing season in wheat and maize producing regions *Weather Clim. Extremes* **9** 47–56

Naumann G, Alfieri L, Wyser K, Mentaschi L, Betts R A, Carrao H, Spinoni J, Vogt J and Feyen L 2018 Global changes in drought conditions under different levels of warming *Geophys. Res. Lett.* **45** 3285–96

Oerke E C 2006 Crop losses to pests *J. Agric. Sci.* **144** 31–43

Parmesan C, Hanley M E and Singer M C 2018 Model vs. experiment to predict crop losses *Science* **362** 1122

Patterson D T 1995 Weeds in a changing climate *Weed Sci.* **43** 685–700

Peters K, Breitsameter L and Gerowitt B 2014 Impact of climate change on weeds in agriculture: a review *Agron. Sustain. Dev.* **34** 707–21

Pimentel D, Zuniga R and Morrison D 2005 Update on the environmental and economic costs associated with alien-invasive species in the United States *Ecol. Econ.* **52** 273–88

Ponisio L C, M'Gonigle L K, Mace K C, Palomino J, De Valpine P and Kremen C 2015 Diversification practices reduce organic to conventional yield gap *Proc. R. Soc.* B **282** 20141396

Porter J R, Xie L, Challinor A J, Cochrane K, Howden S M, Iqbal M M, Lobell D B and Travasso M I 2014 Food security and food production systems *Climate Change 2014: Impacts, Adaptation, and Vulnerability* ed C B Field *et al* (Cambridge: Cambridge University Press) pp 485–533

Prior S A, Runion G B, Marble S C, Rogers H H, Gilliam C H and Torbert H A 2011 A review of elevated atmospheric CO_2 effects on plant growth and water relations: implications for horticulture *HortScience* **46** 158–62

Pullin A S and Stewart G B 2006 Guidelines for systematic review in conservation and environmental management *Conserv. Biol.* **20** 1647–56

Ramesh K, Matloob A, Aslam F, Florentine S K and Chauhan B S 2017 Weeds in a changing climate: vulnerabilities, consequences, and implications for future weed management *Front. Plant Sci.* **8** 95

Rodenburg J, Meinke H and Johnson D E 2011 Challenges for weed management in African rice systems in a changing climate *J. Agric. Sci.* **149** 427–35

Rojas M, Lambert F, Ramirez-Villegas J and Challinor A J 2019 Emergence of robust precipitation changes across crop

production areas in the 21st century *Proc. Natl Acad. Sci.* **116** 6673–8
Rothstein H R 2008 Publication bias as a threat to the validity of meta-analytic results *J. Exp. Criminol.* **4** 61–81
Simberloff D, Souza L, Nuñez M A, Barrios-Garcia M N and Bunn W 2012 The natives are restless, but not often and mostly when disturbed *Ecology* **93** 598–607
Sorte C J *et al* 2013 Poised to prosper? A cross-system comparison of climate change effects on native and non-native species performance *Ecol. Lett.* **16** 261–70
Storkey J and Neve P 2018 What good is weed diversity? *Weed Res.* **58** 239–43
Tang J-L and Liu J L 2000 Misleading funnel plot for detection of bias in meta-analysis *J. Clin. Epidemiol.* **53** 477–84
Thomas A, O'Hara B, Ligges U and Sturtz S 2006 Making BUGS open *R News* **6** 12–17
Thomson L J, Macfadyen S and Hoffmann A A 2010 Predicting the effects of climate change on natural enemies of agricultural pests *Biol. Control* **52** 296–306
Tilman D, Isbell F and Cowles J M 2014 Biodiversity and ecosystem functioning *Annu. Rev. Ecol. Evol. Syst.* **45** 471–93
Tubiello F N, Soussana J F and Howden S M 2007 Crop and pasture response to climate change *Proc. Natl Acad. Sci. USA* **140** 19686–90
Tylianakis J M, Didham R K, Bascompte J and Wardle D A 2008 Global change and species interactions in terrestrial ecosystems *Ecol. Lett.* **11** 1351–63
van der Plas F 2019 Biodiversity and ecosystem functioning in naturally assembled communities *Biol. Rev.* **94** 1220–45
Vilà M, Williamson M and Lonsdale M 2004 Competition experiments on alien weeds with crops: lessons for measuring plant invasion impact? *Biol. Invasions* **6** 59–69
Ward S M *et al* 2014 Agricultural weed research: a critique and two proposals *Weed Sci.* **62** 672–8
Wiebe N, Vandermeer B, Platt R W, Klassen T P, Moher D and Barrowman N J 2006 A systematic review identifies a lack of standardization in methods for handling missing variance data *J. Clin. Epidemiol.* **59** 342–53
Williamson M 2002 Alien plants in the British Isles *Biological Invasions: Economic and Environmental Costs of Alien Plant, Animal and Microbe Species* ed D Pimentel (Boca Raton, FL: CRC Press) pp 91–112
Wu Z, Dijkstra P, Koch G W, Peñuelas J and Hungate B A 2011 Responses of terrestrial ecosystems to temperature and precipitation change: a meta-analysis of experimental manipulation *Glob. Change Biol.* **17** 927–42
Zhang Z and van Kleunen M 2019 Common alien plants are more competitive than rare natives but not than common natives *Ecol. Lett.* **22** 1378–86
Zhu Z *et al* 2016 Greening of the Earth and its drivers *Nat. Clim. Change* **6** 791–5
Zimdahl R L 2004 *Weed-crop Competition: A Review* 2nd edn (Oxford: Blackwell Publishing)
Ziska L H 2003 Evaluation of the growth response of six invasive species to past, present and future atmospheric carbon dioxide *J. Exp. Bot.* **54** 395–404
Ziska L H and Dukes J 2011 *Weed Biology and Climate Change* (New York: Wiley)