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REVIEW PAPER

Review: How will climate change impact the 'many little hammers' of ecological weed management?

Sonja Katherine Birthisel | Ruth S. Clements | Eric R. Gallandt

School of Food and Agriculture and Ecology and Environmental Sciences Program, University of Maine, Orono, ME, USA

Correspondence
Eric R. Gallandt, School of Food and Agriculture and Ecology and Environmental Sciences Program, University of Maine, 5722 Deering Hall, Orono, ME 04469-5722, USA.
Email: gallandt@maine.edu

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Abstract

Increasing atmospheric carbon dioxide concentrations [CO_2] and climate change are impacting farming worldwide. Ecological weed management (EWM) principles, including use of diverse tactics already employed by many farmers, may assist in adapting to and mitigating climate change. We systematically reviewed the literature on EWM and climate change and here summarise practical considerations related to changing efficacy and utility of non-chemical EWM practices. Localised changes in precipitation will affect tillage and cultivation. We expect that mulching, transplanting and some weed seedbank management strategies, which add resiliency to a weed management programme, may show increased utility in a future with more extreme and variable weather. Innovations in autonomous robotic weeding technologies and cultivation tool design show promise in helping to overcome challenges related to low and variable cultivation efficacy and traditionally slow working rates. EWM practices that help farmers achieve multiple objectives and provide benefits beyond climate change adaptation, such as financial gains, may be most advantageous, the development of which could be facilitated by interdisciplinary research and outreach efforts. Overall, we conclude that in an increasingly variable climate, farmers will have to employ a greater *diversity* of weed management tactics in order to spread risk and enable climate resilience through farming systems diversification.

KEYWORDS
adaptation, agroecology, global warming, IWM, non-chemical control, organic farming

1 | INTRODUCTION

Ecological weed management (EWM) is the application of ecological principles to weed management decisions (MacLaren et al., 2020). The goal of EWM is to manipulate the relationships between crops, weeds and other agroecosystem components to benefit the crop and limit the growth of weeds, while minimising negative environmental impacts. EWM can reduce the need for pesticide applications (Westerman et al., 2005), improve soil quality (Gallandt et al., 1999) and preserve biodiversity (Benton et al., 2003). Successful EWM typically employs the use of multiple management tactics incorporated into diverse farm rotations, or 'many little hammers' (Liebman and Gallandt, 1997), to stress weeds at multiple sensitive points in their life cycles. Unfortunately, adoption of EWM by farmers has lagged behind our understanding of its benefits, due at least in part to the barrier of increased systems complexity associated with EWM (Bastiaans et al., 2008; Liebman et al., 2016).

Our climate is rapidly changing in response to anthropogenic activities (IPCC, 2014). Climate change will likely affect multiple interconnected aspects of farming systems (IPCC, 2014), with substantial implications for weed management (Figure 1). While it is human nature to discount the risks of large-scale problems like climate change that seem distant or abstract (Jones et al., 2017), farmers in hard-hit areas of the world are already adapting

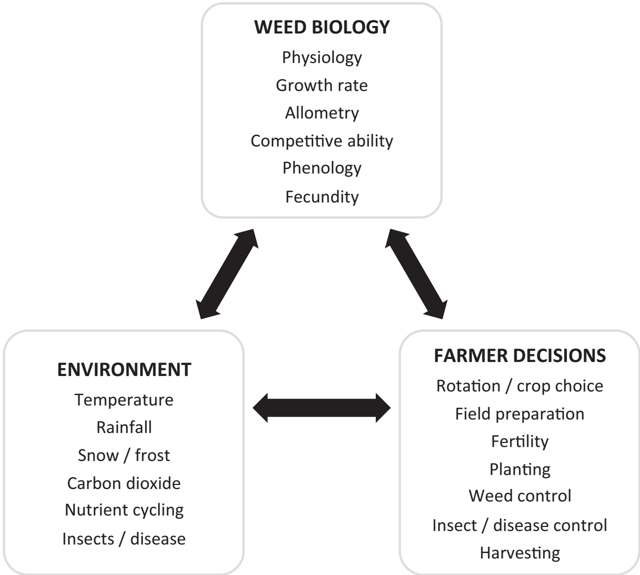

FIGURE 1 Conceptual diagram showing important factors that may interact to influence weed management in a changing climate

to climate change impacts. In response to increasing drought, Bangladeshi farmers reported harvesting rainwater, managing weeds and implementing new cropping strategies (Hossain et al., 2016). The International Panel on Climate Change (IPCC) (2014) warns that mitigation is needed immediately, as 'insufficient responses are already eroding the basis for sustainable development' in some areas of the world. Integration of on-farm adaptation and mitigation strategies (Sivakumar and Stefanski, 2006) into practical and locally applicable farming practices (Johansen et al., 2012) is a pressing need.

The principles of sustainable agriculture have been suggested by the IPCC (2014, 2019) and others (Ngouajio, 2005; Wall and Smit, 2005; Wolfe et al., 2018) as a helpful existing framework for climate change response. EWM fits within this framework (Liebman and Gallandt, 1997) and may be considered analogous to a pre-adaptation: practitioners of EWM already employ diverse rotations that may help spread risk, while minimising greenhouse gas emissions (Hunt et al., 2020) and building soil quality by increasing soil organic matter, all of which are likely to aid in the adaptation to or mitigation of climate change (Bai et al., 2019; Lengnick, 2015). Increased diversity of rotations and integration of non-chemical control tactics are already being advocated and adopted to combat herbicide-resistant weeds (Chauhan et al., 2017; Davis and Frisvold, 2017; Liebman et al., 2016). Thus, the barrier of increased management complexity that has heretofore hindered adoption of EWM (Bastiaans et al., 2008) may be less prohibitive than in the past.

1.1 | Climate change effects on weeds

Patterson (1995) first considered the ramifications of climate change for weed growth, phenology and distribution. Recent reviews, and an excellent book (Ziska and Dukes, 2011), have summarised the literature on potential impacts of rising [CO_2] and climate change on weed biology (Kathiresan and Gualbert, 2016; Ramesh et al., 2017; Roger et al., 2015; Ziska and McConnell, 2016), demography (Bradley et al., 2010; Clements et al., 2014; Peters et al., 2014) and chemical control (Ziska, 2016).

In isolation from other changes, [CO_2] enrichment benefits both crops and weeds, favouring species with C3 photosynthetic pathways over C4 species (Ziska and Dukes, 2011). However, C4 plants are favoured by increasing temperature and water stress, both likely climate change impacts in many regions (IPCC, 2019). From a physiological standpoint, increased [CO_2] typically results in increasing (a) weed biomass, (b) C:N ratio of leaf tissue and (c) root:shoot ratio (Chadha et al., 2020; Torresen et al., 2020; Ziska and Dukes, 2011). How [CO_2] impacts combine with temperature, moisture and other climatic factors to affect future competitive outcomes between crops and weeds existing in real-world communities remains a largely open question (Figure 1; Ziska and McConnell, 2016), though the impact of many factors has been examined individually. Competition studies on the impacts of [CO_2] on crops vs. weeds show mixed results, with weeds favoured in 8 of 15 studies reviewed by Korres et al. (2016).

Increased temperatures can facilitate the spread of invasive weeds (Clements et al., 2014), and high phenotypic plasticity likely pre-adapts many weed species to succeed under increasingly variable temperature and moisture conditions. Moreover, weeds evolve rapidly (Neve et al., 2009), which could contribute to greater range expansion under climate change than predicted with current models (Clements and Ditommaso, 2011).

1.2 | Climate change and weed management

Research on the practical ramifications of climate change for specific weed control practices has predominantly focused on herbicide application and efficacy. Overall, weeds are expected to become more difficult to reliably control with herbicides under increasing [CO_2] and climate change (Ziska, 2016). Glyphosate tolerance can increase in response to [CO_2] (Manea et al., 2011), some grasses can survive pinoxaden under elevated temperatures (Matzrafi et al., 2016), and isoproturon effectiveness can decrease due to soil warming (Bailey, 2004). These effects are necessary to keep in mind for EWM strategies that include limited herbicide use, but EWM typically relies on a suite of tactics integrated with or in lieu of chemical control (Liebman and Gallandt, 1997). Practical implications of climate change for the many non-chemical tactics integral to EWM have not been thoroughly addressed in past reviews (Ziska and Dukes, 2011).

1.3 | Purpose of this review and methods

Ziska (2016) identified as a critical area for future research: 'Identification or synthesis of non-chemical weed management strategies that could strengthen weed management with projected changes in climate and [CO_2]'. We begin to address this knowledge gap via a management-focused synthesis of the literature on EWM and climate change. In the sections below, we (a) summarise likely impacts of climate change on agriculture in the 21st century; (b) consider the implications of these changes for commonly employed non-chemical EWM practices; (c) identify opportunities for the use of EWM in climate change adaptation and mitigation; (d) examine barriers to farmer adoption of climate change responses including EWM; and (e) suggest directions for future research.

We began this review by querying the databases *Web of Science* and *Agricola* with targeted combinations of search terms (Table 1). Two searches were conducted on 3 August 2017, the second of which utilised a broader set of terms than the first. Combined, these searches yielded 41 unique abstracts. A third search using a yet broader set of terms was conducted on 16 August 2017, through which an additional 137 abstracts were identified. A fourth search was conducted on 29 September 2020 using all combinations of terms from previous searches, which yielded 56 new, unique abstracts. Many identified papers are cited herein, though some were omitted due to lack of direct relevance or redundancy with other papers.

2 | CLIMATE CHANGE IMPACTS ON AGRICULTURAL SYSTEMS

Climate change is already impacting agriculture, and according to the most recent IPCC assessment, negative impacts of climate change on crop yields have been more common than positive impacts (IPCC, 2014). This coming century, along with further increases in [CO_2] and mean global temperature, weather patterns are expected to become more variable overall, with likely increased incidence of extreme high temperatures across most regions, and increased incidence of heavy precipitation in many parts of the world (Figure 2).

The ramifications of changes in temperature and atmospheric conditions for plant growth may be more nuanced than is widely appreciated. Minimum winter temperatures, which often limit plant species ranges and form the basis for hardiness zone designations, are expected to increase in the United States at a faster rate than mean winter temperatures this century (Parker and Abatzoglou, 2016). This has obvious implications for poleward expansion of cold-limited species like *Pueraria montana* (Lour.) Merr. var. *lobata* (Willd.) Maesen & S.M. Almeida ex Sanjappa & Predeep (kudzu) (Ziska and Dukes, 2011). Similarly, night-time temperatures in the Northeast United States have increased at a faster rate than daytime temperatures in recent years, a trend which is expected to continue and may

TABLE 1 Summary of systematic abstract review conducted using the databases Web of Science and Agricola

Date	Abstracts (No.)	Search terms (Boolean phrase)		
3 August 2017	41	"ecological weed management"	AND	"climate change"
		"ecological weed management"	AND	"global warming"
		"ecological weed control"	AND	"climate change"
		"ecological weed control"	AND	"global warming"
		"cultural weed management"	AND	"climate change"
		"cultural weed management"	AND	"global warming"
		"cultural weed control"	AND	"climate change"
		"cultural weed control"	AND	"global warming"
		"integrated weed management"	AND	"climate change"
		"integrated weed management"	AND	"global warming"
		"organic weed management"	AND	"climate change"
		"organic weed management"	AND	"global warming"
		"organic weed control"	AND	"climate change"
		"organic weed control"	AND	"global warming"
		"ecological weed management"	AND	climate
		"ecological weed management"	AND	weather
		ecology AND "weed management"	AND	climate
		ecology AND "weed management"	AND	weather
16 August 2017	137	"weed management"	AND	"climate change"
		"weed management"	AND	"global warming"
		"weed control"	AND	"climate change"
		"weed control"	AND	"global warming"
29 September 2020	56	*All of the above search terms used		
TOTAL	234			

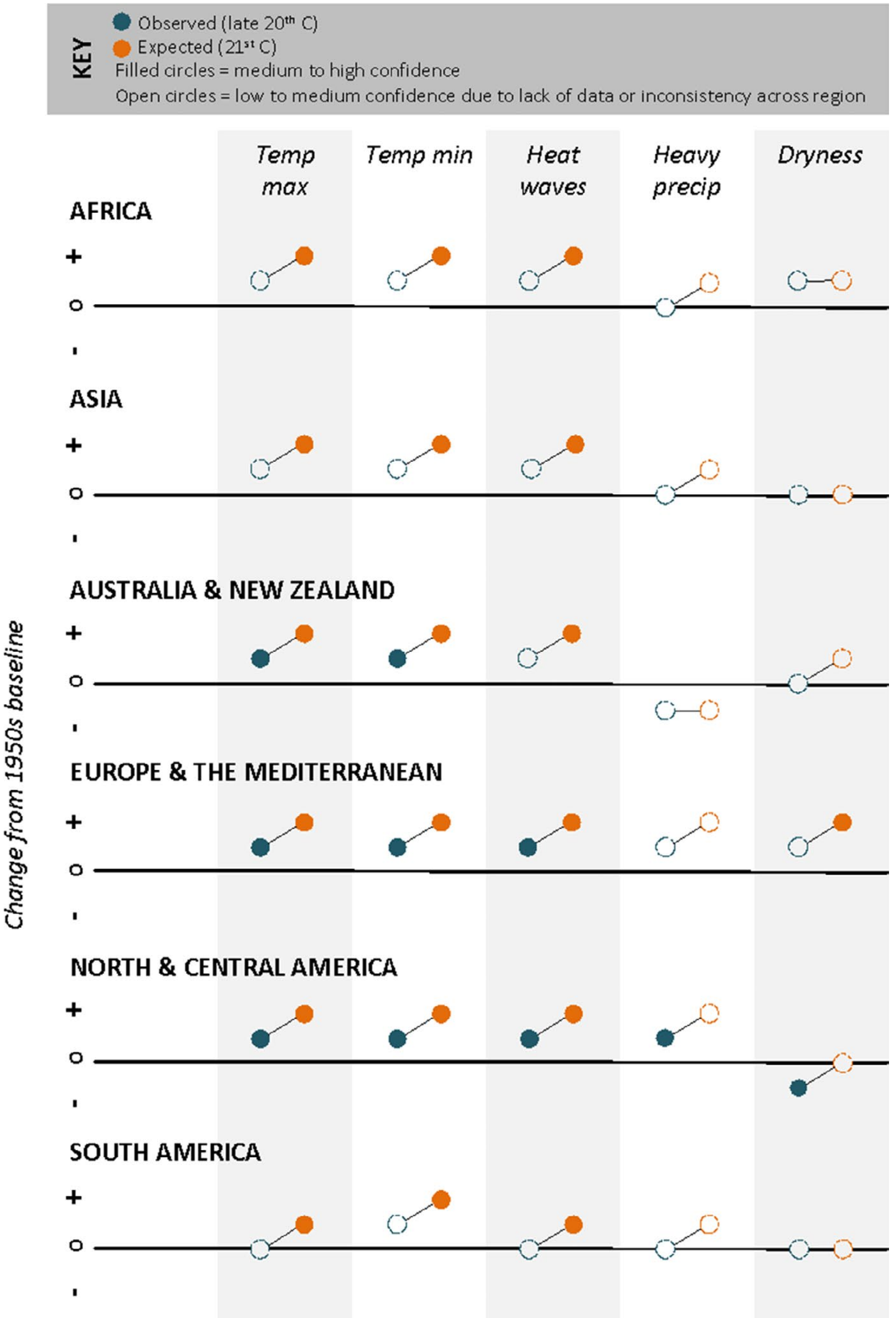

FIGURE 2 Observed and expected future changes in incidence of climate extremes in six major world regions. Location of points above or below 1950s baseline indicates trends towards higher (+) or lower (−) incidence of periods with high maximum temperatures, high (less cold) minimum temperatures, heatwaves, heavy precipitation events and unusual dryness. Trends are summarised from IPCC SREX (Handmer et al., 2012)

increase night respiration, reducing carbohydrate accumulation and crop yields (Wolfe et al., 2018). The greenhouse gas tropospheric ozone (O_3) is likely to increase in parts of Asia throughout this century, with negative effects on plant growth, varying by species and cultivar (Singh et al., 2010).

A recent assessment found drought risk to be most severe in parts of Africa, Europe and Asia (Carrão et al., 2016) and noted that most areas of the planet currently lack sufficient infrastructure (e.g. irrigation) to cope with drought. Drought-affected areas and drought severity are anticipated to increase this century, resulting in significant yield losses to major food crops (Li et al., 2009). Flood risk is likely to increase in some regions of the world while decreasing in others (Kundzewicz et al., 2014). Hirabayashi et al. (2013) projected potential increased flood risk from rivers in much of Central and South America, Africa and Asia and decreased risk in the Middle East, much of Europe and portions of North America.

Future climate change impacts to agriculture are likely to include location-specific changes in the number and timing of ‘field working days’, or days when soils are warm and dry enough to conduct field operations. Increased precipitation can decrease field working days by leaving soils too waterlogged to conduct field operations. Few models have been constructed to predict changes in field working days under climate change (Cooper et al., 1997; Harris and Hossell, 2001; Tomasek et al., 2017; Trnka et al., 2011), and all on fairly limited spatial scales. Such models may offer a window into future risk that could help farmers prioritise strategic equipment and infrastructure investments. Tomasek et al. (2015, 2017) proposed methods to optimise field working day models and projected both increases in growing season length and decreases in field working days during spring planting times for Illinois, USA, by the end of the century.

3 | IMPLICATIONS FOR ECOLOGICAL WEED MANAGEMENT

Fundamental principles of EWM include reducing seedling recruitment, improving crop competitiveness and reducing seedbank size (Bastiaans et al., 2008). Diversifying in-season management to include physical weed control—either in addition to or in lieu of herbicide use—is also a typical component of EWM (Liebman et al., 2016). In a changing climate, the 'many little hammers' (Liebman and Gallandt, 1997) used by growers in implementing EWM will likely be subject to changes in efficacy. Potential implications of rising [CO_2] and climate change for the utility of important EWM practices, encompassing both efficacy and likely co-benefits provided by practices, are discussed below and summarised in Table 2.

3.1 | Reducing seedling recruitment

Practices that limit weed emergence may become increasingly useful, especially mulching strategies, which can contribute multiple benefits likely to increase on-farm climate change resilience (Lee et al., 2019; Lengnick, 2015).

In many vegetable and fruit crops, natural and plastic mulches are expected to remain effective methods of reducing seedling recruitment, while further allowing conservation of soil moisture in dry conditions and reducing damage to soil structure from heavy rain (Kader et al., 2017). Mulches are therefore considered likely to become increasingly beneficial under either increasingly wet or dry conditions (Table 2). Mulches often change the seasonal distribution of a farmer's workload, as they require labour input at application, but can thereafter diminish hand weeding labour (Brown and Gallandt, 2018a). Thus, mulching may reduce risk of worker heat stress, which is expected to increase with climate change (IPCC, 2014), though the warming effect of black plastic could lead some crops to overheat with rising temperatures. Both plastic and natural mulches may improve yields, but in developing nations, plastic may be less available and more expensive than natural materials (Kader et al., 2017). By contributing to increased soil organic matter, natural mulches could result in less nutrient leaching over time (Connor et al., 2011), mitigating an additional challenge posed by increased rainfall.

Weed seedling recruitment may also be reduced by cover crop residues in reduced and no-till systems. Advances in planter technology are allowing some crops, including wheat, to be sown into heavy residue (Kumar et al., 2013) following cover crop termination. Roller-crimping has emerged as a cover crop termination method that allows for creation of a weed suppressive cover crop mulch without the use of herbicides (Diacono et al., 2016). Combined with high-residue cultivators, these practices can facilitate no-till or conservation agriculture (CA), which can result in high water infiltration rates and increased conservation of soil moisture (Syswerda and Robertson, 2014; Thierfelder et al., 2017). Reduced tillage may therefore be a useful adaptation to drier climate conditions (Feiza et al., 2010; Kumar et al., 2018). CA can also reduce erosion (Mafongoya et al., 2016) and may be

TABLE 2 Summary of expected changes in utility of ecological weed management practices under climate change conditions: + indicates positive change, − indicates negative change, ± indicates mixed positive and negative change, and 0 indicates insufficient data

Principles and practices	↑[CO_2]	↑Temp	↑H_2O	↓H_2O
Reducing seedling recruitment				
Plastic mulch	0	±	+	+
Natural mulch	0	+	+	+
Cover crop mulch	0	+	+	+
Tarping	0	+	0	0
Manipulating competition				
Competitive crops and cultivars	0	0	0	±
Increase plant density	0	0	0	±
Alter spatial arrangement	0	0	0	±
Intercropping and living mulch	0	0	+	±
Cover crops	0	0	+	−
Irrigation placement	0	0	−	+
Fertility placement	0	0	−	+
Transplant	+	±	+	+
Seedbank reduction				
Stale seedbed	0	+	±	+
Soil solarisation	0	+	±	±
Harvest weed seed control	±	0	−	+
Short-duration cover crops	±	0	+	0
Summer fallow	0	0	0	+
Seed predation	0	0	0	0
Diverse physical weed control				
Tillage	−	0	−	0
Cultivation	−	−	−	+
Flaming	−	0	±	−
Flooding	0	0	0	0
Mowing	−	0	−	0
Grazing and herbivory	−	±	0	0
Biocontrol	0	0	0	0
Hand weeding	0	−	0	0

adaptive in areas that experience increased incidence of heavy precipitation (Figure 2). Indeed, fields in which pumpkins were being grown under CA lost nine times less soil than conventional plots during a simulated storm event, without sacrificing yields (O'Rourke and Petersen, 2016). No-till practices can also increase soil organic carbon (Lee et al., 2019) and reduce methane emissions compared to conventional tillage, providing potential climate change mitigation benefits (Somasundaram et al., 2020). However, most CA is still heavily dependent on herbicides, and weed management can be a challenge for farmers who either choose to farm organically or lack access to chemical control options (Nichols et al., 2015; Thierfelder et al., 2018). For smallholder farmers, many of whom required more hand hoeing labour after adopting CA in Africa (Mafongoya et al., 2016), improved tools for two-wheel tractors or animal-drawn rippers and seeders may facilitate CA adoption (Johansen et al., 2012; Lee and Thierfelder, 2017).

3.2 | Manipulating competition

Choosing fast-growing species and cultivars, manipulating plant spatial arrangement and increasing plant density are all strategies that have long been used to benefit crop–weed competitive outcomes (Kumar et al., 2013; Liebman and Gallandt, 1997). By allowing more rapid canopy closure, these strategies could potentially reduce evapotranspiration (Connor et al., 2011) and therefore be helpful under conditions in which moisture is limiting. However, intra-specific competition for limited water resources could negatively impact crop yields at increased plant densities (Table 2).

Cover crops provide multiple agronomic benefits (Brennan, 2017; Syswerda and Robertson, 2014), including the potential to contribute to climate change mitigation by increasing soil carbon (Bai et al., 2019; Lee et al., 2019). They can be beneficial for weed control, particularly when termination is timed to pre-empt seed rain (Mirsky et al., 2010). The decision to incorporate cover crops into soil as green manure or leave them on the soil surface as residue also influences their effects (Testani et al., 2020). In the future, cover crops may become less desirable in increasingly dry areas in which crops rely on stored soil moisture as depletion of water resources may limit growth of subsequent crops (Hunt and Kirkegaard, 2011). In areas where increased heavy precipitation is expected, however, cover crops may reduce erosion risk.

Intercropping and living mulches are likely to become less desirable under reduced moisture conditions, due to competition for water resources. There are, however, success stories. Drought-tolerant living mulches decreased weed density without impacting yields in a Japanese asparagus (*Asparagus officinalis* L.) crop (Araki et al., 2012), and some Bangladeshi farmers have responded to recent droughts by intercropping rice (*Oryza* spp.) between mango (*Mangifera indica* L.) and Indian jujube (*Zizyphus mauritiana* Lamarck) (Hossain et al., 2016), diversifying their farm income by incorporating drought-tolerant trees into their rice cropping system. As with mulching and cover crops, intercropping may help protect against erosion in heavy rains.

Where decreased precipitation and soil moisture levels are expected, strategies like drip irrigation and banded fertiliser application may be increasingly effective at providing crops with a competitive advantage against weeds. Conversely, areas that experience increased precipitation and soil moisture levels may see competition for water resources decrease, and fertility may be more likely lost due to leaching (Table 2). More efficient use of water resources is likely to benefit farmers in many regions of the world under climate change (Figure 2), and innovations in irrigation technology may therefore be of great use. The novel 'water pillow' irrigation system, in which water-filled black plastic tubes with drip holes are placed alongside crop rows, showed higher water use efficiency and less weed pressure when compared to a drip irrigation control, while maintaining tomato (*Solanum lycopersicum* L.) yield (Gerçek et al., 2017). Integration of irrigation with traditional mulches is also beneficial: black plastic mulch combined with partial irrigation led to strong weed suppression and increased water use efficiency in wheat, demonstrating the utility of this combination of practices for farmers adapting to dry conditions (Ahmad et al., 2020).

In applicable crops, transplanting may become increasingly beneficial under a range of future conditions (Table 2). Transplanting provides crops with an early competitive advantage against weeds, which may be increasingly important if weed seedling growth rates increase in response to temperature and rising [CO_2] (Peters and Gerowitt, 2014; Ziska and Dukes, 2011). By providing a controlled environment for root system development, transplanting may also reduce mortality at early growth stages that could occur due to moisture extremes in a field setting (Figure 2; Table 2).

Many authors have suggested that breeding programmes aimed at developing climate change-adapted varieties should select for cultivars that exhibit rapid growth rates or enhanced weed suppressiveness (Bajwa et al., 2020; Korres et al., 2016; Kumar et al., 2013; Liebman et al., 2016; Ngouajio, 2005; Robertson et al., 2016). Specific climate-adaptive traits to prioritise may include greater root:shoot ratio, changes in leaf area and arrangement and allelopathic attributes (Korres et al., 2016), as well as increased water use efficiency (Farooq et al., 2019) and growth response to [CO_2]. Older (1920s) varieties of oat (*Avena sativa* L.) had a stronger response to [CO_2] than varieties from the 1990s (Ziska and Blumenthal, 2007), suggesting that past breeding efforts have not necessarily selected plants that are well adapted to rising [CO_2]. Crop varieties with a higher degree of plasticity than has been favoured in the past, including landraces or heritage varieties, may be worth re-considering; though maximum yields in a good year may be reduced, choosing varieties with a moderate likelihood of success under a wide variety of conditions could be increasingly sensible in a more variable climate (IPCC, 2014).

3.3 | Seedbank reduction

Seedbank depletion can lead to a sustained reduction in weed pressure (Gallandt, 2006), which is expected to be increasingly desired as herbicides (Ziska, 2016) and physical weed control measures

(Table 2) exhibit lower or more variable efficacy with climate change. Successful seedbank management requires strategies that maximise seedbank 'debits' and minimise 'credits' (Forcella et al., 1993), primarily by targeting weed germination and seed rain. Methods of weed seedbank management include stale seedbed preparation, soil solarisation, harvesting weed seed control, strategic use of fallow and cover crops and seed predation.

Encouraging germination is the most effective way to debit the weed seedbank (Gallandt, 2006). This is the principle behind creating a stale seedbed: encouraging weed seeds to germinate and then subsequently killing seedlings prior to crop planting or emergence, often with shallow cultivation (Johnson and Mullinix, 2000) or flaming (Rasmussen, 2003). A major trade-off to stale seedbed creation is that it takes time for weeds to germinate, and farmers in regions with short growing seasons may be unwilling to 'waste' growing degree days on this practice. The longer growing seasons expected with continued global temperature rise could therefore lead to wider applicability of this practice (Table 2). Efficacy may be increased by irrigating after tillage to encourage a larger 'flush' of weeds (Benvenuti and Macchia, 2006; Kumar et al., 2013). This suggests that stale seedbeds could become increasingly effective under a climate future with increasing moisture, provided wet soils do not limit field access. Though it seems paradoxical, efficacy could also increase with aridity in some circumstances: at low precipitation, emergence of both *Chenopodium album* L. (common lambsquarters) and *Setaria faberi* Herrm. (giant foxtail) increased with longer intervals between precipitation events, which the authors suggest may be due to those seeds reaching a minimum moisture threshold for germination (Baskin and Baskin, 2014) and being exposed to greater amounts of water in the longer intervals (Robinson and Gross, 2010). However, emergence responses varied under typical precipitation amounts (Robinson and Gross, 2010).

Solarisation is an intensive form of stale seedbed preparation that utilises clear plastic to trap solar energy, heating soils to temperatures hot enough to kill weed seeds or seedlings (Horowitz et al., 1983; Standifer et al., 1984). We recently demonstrated that solarisation can result in mortality of weed seeds (Gallandt et al., 2018) and reduced weed density (Birthisel and Gallandt, 2019) in the Northeast United States, suggesting that its applicability in temperate regions may be greater than previously assumed (Walters and Pinkerton, 2012). Efficacy of this practice generally increases with both ambient air temperature and soil moisture (Mahrer and Shilo, 2012), though it is also strongly affected by light intensity, which is impacted by cloudiness.

Tarping, the practice of covering soil with black plastic silage tarps for several weeks prior to planting, is also very effective in creating a stale seedbed (Gallandt et al., 2018; Lounsbury et al., 2020) and has become popular among small-scale growers of high-value crops in the Northeast United States and Canada (Fortier, 2014). The mechanisms through which tarping reduces seedling recruitment have yet to be fully elucidated. Tarping increases soil surface temperature, changes the gaseous environment in soil, retains moisture and blocks light. This environment may directly kill seeds, but more likely will promote germination while preventing establishment; thus, the practice could become more effective in a warming world (Table 2).

Harvest weed seed control (HWSC) is a collection of methods that target weed seeds during harvesting. HWSC utilises various specialised machinery on a combination to either concentrate chaff in certain areas to later be burned or removed, directly bale chaff during harvest, or pulverise harvested weed seeds before releasing the debris back into the field (Schwartz-Lazaro et al., 2017; Walsh et al., 2013; Walsh et al., 2017). Weed seed retention at harvest is essential for success of HWSC, which could in turn select for plants that mature or shatter seeds earlier in the season (Shergill et al., 2020). Rising [CO_2] is expected to alter flowering dates of many crop and weed species, which may impact future efficacy of HWSC depending on weed–crop combination (Table 2). For example, elevated [CO_2] delayed flowering of *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot (Italian ryegrass) (Cleland et al., 2006) but did not alter flowering of wheat (*Triticum aestivum* L.) (Sæbø and Mortensen, 1996), suggesting that HWSC could become more effective for this weed–crop combination due to increased seed retention at harvest. For a thorough review of [CO_2] effects on flowering time, see Springer and Ward (2007). Of course, [CO_2] does not act in isolation; temperature also affects crop and weed phenology (Torresen et al., 2020; Ziska and Dukes, 2011), while the impacts of altered precipitation regimes (Figure 2) on field working days during the harvest period may increase or restrict the timely use of HWSC (Table 2).

Fallow periods (Gallandt, 2014; Rodenburg et al., 2011) and short-duration cover crops (Mirsky et al., 2010) both rely upon timely disturbance, usually by shallow tillage, to encourage seedbank depletion through germination and subsequent pre-emption of seed rain. As with HWSC, effects of rising [CO_2] (Springer and Ward, 2007) and temperature (Ziska and Dukes, 2011) on flowering time in some weed species may impact the necessary timing or frequency of disturbance. Summer fallow periods also have utility for conserving soil moisture in water-limited areas (Hunt and Kirkegaard, 2011; Manalil and Flower, 2014), suggesting an important co-benefit of this practice for water-limited systems. Short-duration cover crops, however, may become increasingly advantageous in areas with more frequent or heavier precipitation events, as they offer the co-benefits of soil protection and erosion control (Table 2).

Seed predation by invertebrates including carabid beetles could increase locally in a warming climate, since invertebrate activity–density and seed consumption rates often increase with rising temperature (Noroozi et al., 2016; Saska et al., 2010). However, these relationships will be impacted by changing demography of seed predators and the flora and fauna with which they interact, including changing migration patterns of birds (Charmantier and Gienapp, 2014), which can be important seed predators in some systems (Birthisel et al., 2015). Moles and Westoby (2003) found no relationship between seed predation and latitude, suggesting that large-scale trends in seed predation might be relatively unaffected by climate change, and more information is needed before making strong predictions on this topic (Table 2).

Climate change likely has further implications for the longevity and dynamics of not only weed seeds (Long et al., 2015), but other propagules including perennial roots and rhizomes (Torresen et al., 2020). Declining winter snowpack may allow soils to freeze to greater depths (Patel et al., 2018; Tatariw et al., 2017), potentially increasing propagule mortality. Farmers in Japan have employed this mechanism to kill overwintering *Solanum tuberosum* L. (potato) weeds, mechanically removing snow from their fields to increase frost depth (Yanai et al., 2014). Strategic fallowing to bring perennating organs closer to the soil surface, thereby increasing mortality through freezing in winter (Schimming and Messersmith, 1988) or desiccation in summer (Foster, 1989; Liebman et al., 2001) may become increasingly effective with, respectively, decreasing snowpack and increasing aridity.

3.4 | Diverse physical weed control

Physical weed control practices, especially tillage and cultivation, are integral to many EWM systems. Climate change has substantial implications for efficacy of physical weed control as these practices are generally more sensitive to environmental conditions than are herbicide-based controls (Liebman et al., 2001).

Tillage and cultivation efficacy for control of perennial weeds may decrease in future as rising [CO_2] is known to increase root:shoot ratio of several perennial species (Ziska and Dukes, 2011), which could facilitate regrowth from root fragments. Though tillage will likely continue to be an effective means of killing annual weeds, changes in phenology may alter the times of year at which tillage is most helpful. Zahra et al. (2009) reported that all the significant winter annual weeds in Canada are facultative; movement away from fall weed management might therefore encourage current summer annuals to become winter annuals with climate change. Conversely, Tozzi et al. (2014) found that winter warming periods limited the success of *Erigeron canadensis* L. (Canada fleabane) as a winter annual by reducing the survival of rosettes and seedlings, but also promoted earlier flowering, implying that earlier spring tillage or other suitable control measures might be needed in future to pre-empt seed rain for this species.

Efficacy of inter- and intra-row cultivation often improves with dry soil conditions (Cirujeda and Taberner, 2004; Evans et al., 2012); hence, cultivation may be increasingly useful in areas of the world expected to experience increased dryness, but less reliable in areas experiencing increasing soil moisture (Figure 2). Duration of the 'critical weed free' period during which weeds must be controlled to avoid reductions in crop yield is also moisture sensitive. Coble et al. (1981) reported that the critical weed-free period for *A. artemisiifolia* was two weeks in dry years compared to four weeks in wet years. Given that cultivation is most effective on small seedlings (Cirujeda and Taberner, 2004), rising temperatures, which contributed to increased height in certain annual species (Peters and Gerowitt, 2014), could lead to declining efficacy in some circumstances. Studies comparing impacts of rising [CO_2] to growth allocation in annual weeds compared to crops would be useful in predicting ramifications of [CO_2] increase for selectivity, a crucial consideration for in-row cultivation (Kurstjens and Perdok, 2000).

In regions where field working days may become fewer or less predictable, strategies that increase cultivation efficacy and reduce variability may help farmers make best use of time when conditions are suitable for cultivation. Strategically 'stacking' two or three cultivation tools for a single pass resulted in relatively high cultivation efficacy (75%), with evidence of synergistic effects based on the combined modes of action between implements (Brown and Gallandt, 2018b). For some tool combinations, this synergy was maintained across a range of weed sizes and soil moisture conditions (Brown and Gallandt, 2018b), making this a promising practice for a climate future characterised by increased seedling growth rates and precipitation variability. Use of larger tractors and wider cultivation machinery could allow more ground to be covered per cultivation pass, representing another strategy for optimising use of potentially limited field working days. Similarly, camera guidance systems that use hydraulic side-shifting to maintain precise distance between cultivation implements and crop rows (Melander et al., 2015) may improve working rates (Gallandt et al., 2018) and are being adopted for use in vegetable, row and cereal crops. Finally, progress in autonomous robotic technology is rapidly paving the way for further mechanisation of cultivation operations (Bawden et al., 2017; Fennimore et al., 2016; Merfield, 2016). As of early 2021, there are 35 companies with commercially available agricultural robots, many focused on weed control (Future Farming Field Robots Catalog; accessed December 2020). Lightweight autonomous robotic weeders could access fields too muddy for tractor operations, expanding the conditions suitable for cultivation and other physical weed control techniques.

Flaming can be conducted with tractor-drawn equipment, or at small scales with a hand-held torch and backpack-mounted propane cylinder. Although flaming remains effective when soils are moist (Ascard et al., 2007), tractor accessibility will become limited under wet field conditions. On the other hand, in increasingly arid regions, applicability of flaming could be limited due to danger of wildfires (Ziska and Dukes, 2011; Table 2).

Flooding is an effective and commonly used weed control strategy for transplanted rice (Kumar et al., 2013) and may contribute to climate change adaptation in African rice systems (Rodenburg et al., 2011). However, its continued applicability and potential for expansion in a changing climate will be contingent upon future water availability. Irrigation and water-holding infrastructure may be forward-looking investments for some farmers (Kumar et al., 2013), but will only be beneficial if sufficient irrigation water is locally available. Given that projections of future precipitation and water availability are characterised by uncertainty (Kundzewicz et al., 2014; Li et al., 2009), rice growers will likely need a diverse range of weed management strategies to respond to a changing climate (Rodenburg et al., 2011).

Where water is not limiting, increasing [CO_2] could increase plant growth, thereby necessitating more frequent mowing or grazing to control grassland weeds (Ziska and Dukes, 2011). Rotational grazing can be beneficial for weed control (Tozer et al., 2008) and has been cited as a climate change best management practice in Vermont, USA (Helling et al., 2015), but it may not be ideally suited to all regions: grazing with sheep in a Montana dryland cropping system did not reduce global warming potential in comparison to herbicide application (Barsotti et al., 2013). Rising temperatures and changes to the C:N content of weed biomass (e.g. Blumenthal et al., 2016) could impact grazing, herbivory by insects and biological control of weeds. Some biological control agents may be capable of increasing efficacy (Kriticos et al., 2009) by increasing feeding rates or number of generations possible per year (Seastedt, 2014). However, different responses to warming between agent and host may alter phenological synchrony, potentially decreasing efficacy (Seastedt, 2014). Overall, it seems premature to set general expectations for how this might impact EWM.

Hand weeding remains common practice in organic (Baker and Mohler, 2015) and specialty crop systems (Fennimore and Doohan, 2008), as well as among many smallholder farmers worldwide (Gianessi, 2013; Johansen et al., 2012; Thierfelder et al., 2018). The IPCC (2014) indicates increased risk of mortality and morbidity for those working outdoors during periods of extreme heat. Thus, working rates for hand weeding and other manual tasks may decline (Table 2) following the expected increased incidence of extremely warm days and heatwaves around the globe (Figure 2). Timely and effective implementation of more mechanised control tactics, as well as cultural practices and a focus on reducing seedbanks and seedling recruitment, will become increasingly important. Forms of climate-related occupational stress included difficulties with weed control in Southwest Nigeria (Oyekale, 2015), where increasing heatwaves are already impacting farming (Figure 2). Farmers in Bangladesh, however, reported strategic hand hoeing as a climate change adaptation they used to minimise drought impacts (Hossain et al., 2016); farmers simultaneously hoed and closed surface cracks in their soil to minimise water loss. Innovation in and adoption of hand tools that increase working rates with little cost to efficacy (E. Gallandt, unpub. obs.) could benefit small-scale growers under diverse climatic conditions.

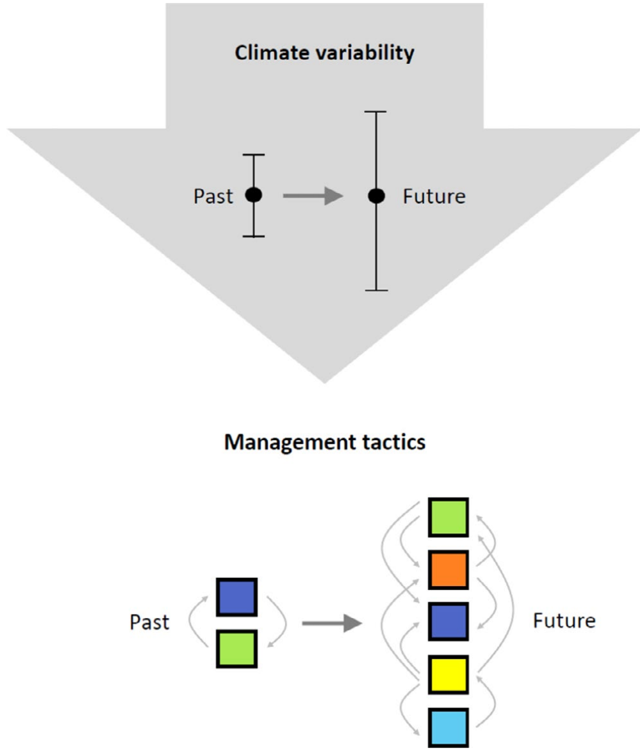

FIGURE 3 Conceptual diagram illustrating the hypothesis that increased variability of future conditions may necessitate increased variety of management tactics. Boxes with different colours represent different weed management tactics, and arrows represent possible combinations of tactics used in sequence

4 | ADOPTION OF DIVERSE VALUE-ADDED EWM PRACTICES

> If you are doing something for just one reason… Stop

The long-time vegetable farmer quoted above expressed the view that every farm management decision should result in multiple benefits (T. Roberts, pers. comm.) IPCC guidance is in concordance, recommending climate adaptation strategies that have co-benefits, including adoption of more environmentally sustainable agricultural practices (IPCC, 2014) that are likely to contribute to improved yields and reduced environmental impacts, including through climate mitigation. As discussed herein, many EWM tactics including mulching, transplanting and situationally appropriate practices to target the weed seedbank could individually gain greater utility with climate change (Table 2), either by increasing efficacy of weed management or conferring co-benefits likely to enhance resilience. However, the most substantial ramifications of EWM for climate resilience must be viewed and understood at a whole-systems level.

First, we expect that in an increasingly variable climate, employing a greater *diversity* of management tactics will become increasingly beneficial (Figure 3). We reason that this diversity of management tactics will effectively spread risk, reducing the likelihood of catastrophic failure due to poor performance by few overly utilised tactics. This hypothesis is an extension of the ecological principle that ability to withstand and recover from stress is among the realisable benefits of enhanced system biodiversity (Cardinale et al., 2012).

Further, if a shift in our dominant weed management paradigm towards increased diversity of tactics occurs alongside a corresponding shift towards increased biological diversity in farming systems—either through adoption of extended rotations or landscape-level features like perennial plantings along field margins—substantive climate mitigation benefits could result. Recent models quantifying the potential carbon sequestration and greenhouse gas mitigation benefits of 'natural climate solutions' in agriculture underscore this point (Fargione et al., 2018; Griscom et al., 2017). Liebman and Schulte (2015) compellingly articulate the mechanisms through which diversification of farm management enables biological diversity. They further demonstrate greatly improved ecosystem function through management diversification in the US maize belt and describe policy mechanisms relevant to increased adoption of diversified practices (Liebman and Schulte, 2015). We understand EWM to be a set of principles and practices synergistic to increased farm system diversity and as such consider it an important existing framework that might help enable transitions to more diverse, sustainable and climate-resilient farming systems.

Given that farmers may underestimate the challenge of climate change (Jones et al., 2017), outreach outcomes (i.e. adoption of climate-resilient EWM practices) might be improved by focusing on co-benefits. Highlighting this point, Li et al. (2017) found that the climate change adaptation behaviour of Hungarian farmers was largely driven by financial and managerial considerations, though experience with extreme weather was also important. Financial considerations are doubly important as anxiety about near-term challenges related to farm survival may override farmers' ability to implement long-term plans (Findlater et al., 2018). In developed nations, the need for increased systems complexity has been a barrier to farmer adoption of EWM practices (Bastiaans et al., 2008). However, complexity of conventionally managed systems is expected to increase regardless: the proliferation of herbicide-resistant weeds and paucity of new herbicide modes of action (Davis and Frisvold, 2017; but see Yan et al., 2018) will likely necessitate application of more diverse tactics (Ziska and McConnell, 2016). Diverse rotations are one such tactic that show promise for reducing dependency on herbicides while maintaining crop yields (Hunt et al., 2019; Liebman and Nichols, 2020) and reducing weed density (Weisberger et al., 2019). Identification of additional diversified management strategies that allow farmers to simultaneously address the co-occurring challenges of herbicide resistance and climate change, coupled with tailored outreach that considers farmer decision-making contexts and economic constraints (Chatrchyan et al., 2017; Liebman et al., 2016), could be of great benefit in our present climate.

4.1 | Directions for future research

The best available science suggests that climate change is already impacting agriculture and will do so increasingly throughout this century (Figure 2; IPCC, 2019). Many questions remain regarding the impacts of climate change and rising [CO_2] on weeds and the control strategies employed in EWM. Table 2 serves to highlight key knowledge gaps, illustrating our limited understanding of the changing utility of many EWM practices in a changing climate. Practices for which knowledge gaps are most evident include the following: use of competitive crops and cultivars, alteration of planting density and spatial arrangement, summer fallow periods, weed seed predation, flooding, biocontrol and hand weeding (Table 2). Below, we further outline several directions for future research that have received relatively little research attention to date, and we consider to be of high priority.

Few studies have examined farmer perceptions and decision-making around EWM (Jabbour et al., 2014a, 2014b; Zwickle et al., 2016; Zwickle et al., 2014), and though there is a growing literature on farmers' perceptions of climate change (e.g. Arshad et al., 2016; Chatrchyan et al., 2017; Li et al., 2017; Niles and Mueller, 2016; Roco et al., 2015), substantial knowledge gaps remain. We are aware of only one study in which weed management and climate change perceptions have been jointly considered (Hossain et al., 2016). More collaboration with social scientists in bridging this gap could provide guidance for designing targeted outreach approaches (Jones et al., 2017; Neve et al., 2018) that can help overcome barriers to adoption of climate-resilient EWM practices (Liebman et al., 2016; Roesch-McNally et al., 2017; Roesch-McNally et al., 2018).

Given that farmers serve as important sources of information for one another (White et al., 2018) and influence the spread of innovative practices within farming communities (Taylor and Bhasme, 2018), case studies that feature farmers, or research farms representative of local farming systems, could help further facilitate adoption of climate-resilient EWM practices. The few existing weed management case studies focusing on opportunities for climate adaptation or mitigation reveal useful insights. For example, the climate-adapted push–pull cropping system in sub-Saharan Africa has been shown to reduce *Strigia* spp. densities by upwards of fivefold and lead to substantial grain yield benefits in comparison to grain monocrops (Khan et al., 2014) and through integrated research and outreach has been adopted by regional growers. Examples of farmers using diverse crop and fallow rotations (Nordell and Nordell, 2009) and cover crops (Groff, 2008) to manage weeds further highlight potential co-benefits of weed management strategies that can also provide resilience to varying soil moisture conditions (Kumar et al., 2020; Lee et al., 2019; Lee and Thierfelder, 2017). Case studies that explicitly illustrate connections between EWM strategies and adapting to or mitigating climate change are needed to provide practical examples for farmers seeking more information on making changes to their own farming systems.

The interface of EWM and climate change is a complex, dynamic system (Figure 1). Simulation models have been extensively used to predict weed demographic shifts under climate change (e.g. Case and Stinson, 2018; Kriticos et al., 2009) and can facilitate the design of cost-effective invasive species management plans (Richter et al., 2013), but we have seen few examples of success in translating such models into user-friendly tools accessible to stakeholders. The Landscape Futures Analysis Tool includes a weed management model and an ability to project climate changes (Summers et al., 2015), and the Climate Smart Farming project has developed several excellent tools, though none as yet related to weed management (CSF Extension Team, 2021). Tools that engage users in learning through virtual trial and error may be useful for outreach on topics like EWM that at the outset can appear complex or abstract (Birthisel, 2018).

Expert opinion holds that, given the magnitude of the challenge, humanity's collective response to climate change has thus far been too slow (IPCC, 2014). Given this, there seems a pressing need to pursue applied solutions that offer both mitigation and adaptation benefits (IPCC, 2014, 2019). Research to reduce variability in efficacy and improve the fossil fuel efficiency of physical weed control, including through innovative tool design (Brown and Gallandt, 2018b), use of 'big data', and strategic employment of robotic weeders (Bawden et al., 2017), is promising areas of inquiry. Given that 72% of the world's farms are less than 1 ha in size (Lowder et al., 2016), we also think it is important to consider what innovations in small-scale tools (Johansen et al., 2012) could enhance the basis for EWM among smallholder farmers. Finally, we believe there is a pressing need for cropping systems research aimed at developing diversified 'value-added' approaches that (a) are profitable and help diversify farm income, (b) consider local farmer opinions and constraints, and (c) utilise ecological pest management to minimise external inputs (Khan et al., 2016; Khan et al., 2014; Kumar et al., 2020). Interdisciplinary teams (Jordan et al., 2016; Liebman et al., 2016; Neve et al., 2018) may facilitate the development of EWM approaches that can be fully integrated into profitable and climate-resilient cropping systems.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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ORCID

Sonja Katherine Birthisel https://orcid.org/0000-0003-2892-8946
Ruth S. Clements https://orcid.org/0000-0002-9565-5653
Eric R. Gallandt https://orcid.org/0000-0001-6684-6250

REFERENCES

Ahmad, S., Raza, M.A.S., Saleem, M.F., Iqbal, R. & Zaheer, M.S. (2020) Significance of partial root zone drying and mulches for water saving and weed suppression in wheat. *Journal of Animal and Plant Sciences*, 30, 154–162.

Araki, H., Sarwar, A.K.M.G., Hirata, T. & Hoshino, Y. (2012) Weed control, carbon storage and yield in asparagus field with living mulch. *Acta Horticulturae*, 950, 189–194.

Arshad, M., Kächele, H., Krupnik, T.J., Amjath-Babu, T.S., Aravindakshan, S., Abbas, A. et al. (2016) Climate variability, farmland value, and farmers' perceptions of climate change: implications for adaptation in rural Pakistan. *International Journal of Sustainable Development & World Ecology*, 24, 532–544.

Ascard, J., Hatcher, P.E., Melander, B. & Upadhyaya, M.K. (2007) Thermal weed control. In: Upadhyaya, M.K. & Blackshaw, R.E. (Eds.) *Non-Chemical Weed Management*. Cambridge, MA: CABI, pp. 155–175.

Bai, X., Huang, Y., Ren, W., Coyne, M., Jacinthe, P.-A., Tao, B. et al. (2019) Responses of soil carbon sequestration to climate-smart agricultural practices: a meta-analysis. *Global Change Biology*, 25, 2591–2606.

Bailey, S.W. (2004) Climate change and decreasing herbicide persistence. *Pest Management Science*, 60, 158–162.

Bajwa, A.A., Farooq, M., Al-Sadi, A.M., Nawaz, A., Jabran, K. & Siddique, K.H.M. (2020) Impact of climate change on biology and management of wheat pests. *Crop Protection*, 137, 105304. https://doi.org/10.1016/j.cropro.2020.105304

Baker, B.P. & Mohler, C.L. (2015) Weed management by upstate New York organic farmers: strategies, techniques and research priorities. *Renewable Agriculture and Food Systems*, 30, 418–427.

Barsotti, J.L., Sainju, U.M., Lenssen, A.W., Montagne, C. & Hatfield, P.G. (2013) Net greenhouse gas emissions affected by sheep grazing in dryland cropping systems. *Soil Science Society of America Journal*, 77, 1012–1025.

Baskin, C.C. & Baskin, J.M. (2014) Ecologically Meaningful Germination Studies. In: *Seeds. Ecology, Biogeography, and Evolution of Dormancy and Germination*. Second Edition. Cambridge, MA: Academic Press. 5–36.

Bastiaans, L., Paolini, R. & Baumann, D.T. (2008) Focus on ecological weed management: what is hindering adoption? *Weed Research*, 48, 481–491.

Bawden, O., Kulk, J., Russell, R., Mccool, C., English, A., Dayoub, F. et al. (2017) Robot for weed species plant-specific management. *Journal of Field Robotics*, 34, 1179–1199.

Benton, T.G., Vickery, J.A. & Wilson, J.D. (2003) Farmland biodiversity: is habitat heterogeneity the key? *Trends in Ecology & Evolution*, 18, 182–188.

Benvenuti, S. & Macchia, M. (2006) Seedbank reduction after different stale seedbed techniques in organic agricultural systems. *Italian Journal of Agronomy*, 1, 11–21.

Birthisel, S. (2018) *Multi-tactic ecological weed management in a changing climate*. PhD thesis, University of Maine, Orono, USA.

Birthisel, S. & Gallandt, E.R. (2019) Trials evaluating solarization and tarping for improved stale seedbed preparation in the Northeast USA. *Organic Farming*, 5, 52–65.

Birthisel, S.K., Gallandt, E.R., Jabbour, R. & Drummond, F.A. (2015) Habitat and time are more important predictors of weed seed predation than space in a Maine USA mixed vegetable agroecosystem. *Weed Science*, 63, 916–927.

Blumenthal, D.M., Kray, J.A., Ortmans, W., Ziska, L.H. & Pendall, E. (2016) Cheatgrass is favored by warming but not CO_2 enrichment in a semi-arid grassland. *Global Change Biology*, 22, 3026–3038.

Bradley, B.A., Blumenthal, D.M., Wilcove, D.S. & Ziska, L.H. (2010) Predicting plant invasions in an era of global change. *Trends in Ecology & Evolution*, 25, 310–318.

Brennan, E.B. (2017) Can we grow organic or conventional vegetables sustainably without cover crops? *HortTechnology*, 27, 151–161.

Brown, B. & Gallandt, E.R. (2018b) Evidence of synergy with 'stacked' intrarow cultivation tools. *Weed Research*, 58, 284–291.

Brown, B. & Gallandt, E.R. (2018a) A systems comparison of contrasting organic weed management strategies. *Weed Science*, 66, 109–120.

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P. et al. (2012) Biodiversity loss and its impact on humanity. *Nature*, 486, 59–67.

Carrão, H., Naumann, G. & Barbosa, P. (2016) Mapping global patterns of drought risk: an empirical framework based on sub-national estimates of hazard, exposure and vulnerability. *Global Environmental Change*, 39, 108–124.

Case, M.J. & Stinson, K.A. (2018) Climate change impacts on the distribution of the allergenic plant, common ragweed (*Ambrosia artemisiifolia*) in the eastern United States. *PLoS One*, 13, e0205677. https://doi.org/10.1371/journal.pone.0205677

Chadha, A., Florentine, S., Javaid, M., Welgama, A. & Turville, C. (2020) Influence of elements of climate change on the growth and fecundity of *Datura stramonium*. *Environmental Science and Pollution Research*, 27, 35859–35869. https://doi.org/10.1007/s11356-020-10251-y

Charmantier, A. & Gienapp, P. (2014) Climate change and timing of avian breeding and migration: evolutionary versus plastic changes. *Evolutionary Applications*, 7, 15–28.

Chatrchyan, A.M., Erlebacher, R.C., Chaopricha, N.T., Chan, J., Tobin, D. & Allred, S.B. (2017) United States agricultural stakeholder views and decisions on climate change. *WIREs Climate Change*, 8, e467. https://doi.org/10.1002/wcc.469

Chauhan, B.S., Matloob, A., Mahajan, G., Aslam, F., Florentine, S.K. & Jha, P. (2017) Emerging challenges and opportunities for education and research in weed science. *Frontiers in Plant Science*, 8, 1–13.

Cirujeda, A. & Taberner, A. (2004) Defining optimal conditions for weed harrowing in winter cereals on *Papaver rhoeas* L. and other dicotyledoneous weeds. In: *Proceedings of the 6th EWRS Workshop on Physical and Cultural Weed Control* (Lillehammer, Norway), pp. 101–105.

Cleland, E.E., Chiariello, N.R., Loarie, S.R., Mooney, H.A. & Field, C.B. (2006) Diverse responses of phenology to global changes in a grassland ecosystem. *Proceedings of the National Academy of Sciences*, 103, 13740–13744.

Clements, D.R. & Ditommaso, A. (2011) Climate change and weed adaptation: can evolution of invasive plants lead to greater range expansion than forecasted? *Weed Research*, 51, 227–240.

Clements, D.R., DiTommaso, A. & Hyvönen, T. (2014) Ecology and management of weeds in a changing climate. In: Chauhan, B.S. & Gulshan, M. (Eds.) *Recent Advances in Weed Management*. New York, NY: Springer, pp. 13–37.

Coble, H.D., Williams, F.M. & Ritter, R.L. (1981) Common ragweed (*Ambrosia artemisiifolia*) interference in soybeans (*Glycine max*). *Weed Science*, 29, 339–342.

Connor, D.J., Loomis, R.S. & Cassman, K.G. (2011) *Crop Ecology: Productivity and Management in Agricultural Systems*, 2nd edition. Cambridge, NY: Cambridge University Press.

Cooper, G., McGechan, M.B. & Vinten, A.J.A. (1997) The influence of a changed climate on soil workability and available workdays in Scotland. *Journal of Agricultural Engineering Research*, 68, 253–269.

CSF Extension Team. (2021) Climate smart farming tools. Available at: http://climatesmartfarming.org/tools/ [Accessed 11 January 2021].

Davis, A.S. & Frisvold, G.B. (2017) Are herbicides a once in a century method of weed control? *Pest Management Science*, 73, 2209–2220.

Diacono, M., Fiore, A., Farina, R., Canali, S., Di Bene, C., Testani, E. et al. (2016) Combined agro-ecological strategies for adaptation of organic horticultural systems to climate change in Mediterranean environment. *Italian Journal of Agronomy*, 11(730), 85–91.

Evans, G.J., Bellinder, R.R. & Hahn, R.R. (2012) An evaluation of two novel cultivation tools. *Weed Technology*, 26, 316–325.

Fargione, J.E., Bassett, S., Boucher, T., Bridgham, S.D., Conant, R.T., Cook-Patton, S.C. et al. (2018) Natural climate solutions for the United States. *Science Advances*, 4, eaat1869.

Farooq, M., Hussain, M., Ul-Allah, S. & Siddique, K.H.M. (2019) Physiological and agronomic approaches for improving water-use efficiency in crop plants. *Agricultural Water Management*, 219, 95–108. https://doi.org/10.1016/j.agwat.2019.04.010

Feiza, V., Feiziene, D., Auskalnis, A. & Kadziene, G. (2010) Longterm, sustainable tillage: results from cambisol, field experiments on. *Zemdirbyste-Agriculture*, 97, 3–14.

Fennimore, S.A. & Doohan, D.J. (2008) The challenges of specialty crop weed control, future directions. *Weed Technology*, 22, 364–372.

Fennimore, S.A., Slaughter, D.C., Siemens, M.C., Leon, R.G. & Saber, M.N. (2016) Technology for automation of weed control in specialty crops. *Weed Technology*, 30, 823–837.

Findlater, K.M., Satterfield, T., Kandlikar, M. & Donner, S.D. (2018) Six languages for a risky climate: how farmers react to weather and climate change. *Climatic Change*, 148, 451–465.

Forcella, F., Eradat-Oskoui, K. & Wagner, S.W. (1993) Application of weed seedbank ecology to low-input crop management. *Ecological Applications*, 3, 74–83.

Fortier, J.-M. (2014) *The Market Gardener*. Vancouver, BC: New Society.

Foster, L. (1989) The biology and non-chemical control of dock species *Rumex obtusifolia* and *R. crispus*. *Biological Agriculture and Horticulture*, 6, 11–25.

Gallandt, E.R. (2006) How can we target the weed seedbank? *Weed Science*, 54, 588–596.

Gallandt, E. (2014) Weed management in organic farming. In: Chauhan, B. & Mahajan, G. (Eds.) *Recent Advances in Weed Management*. New York, NY: Springer, pp. 63–85.

Gallandt, E.R., Birthisel, S.K., Brown, B.J., McCollough, M. & Pickoff, M. (2018) Organic farming and sustainable weed control. In: Korres, N.E. (Ed.) *Weed Control: Sustainability, Hazards, and Risks in Cropping Systems Worldwide*. Boca Raton, FL: CRC Press, pp. 628–655.

Gallandt, E.R., Brainard, D. & Brown, B. (2018) Developments in physical weed control. In: Zimdahl, R.L. (Ed.) *Integrated Weed Management for Sustainable Agriculture*. Cambridge: Burleigh Dodds Science Publishing, pp. 261–283.

Gallandt, E.R., Liebman, M. & Huggins, D.R. (1999) Improving soil quality: implications for weed management. *Journal of Crop Production*, 2, 95–121.

Gerçek, S., Demirkaya, M. & Işik, D. (2017) Water pillow irrigation versus drip irrigation with regard to growth and yield of tomato grown under greenhouse conditions in a semi-arid region. *Agricultural Water Management*, 180, 172–177.

Gianessi, L.P. (2013) The increasing importance of herbicides in worldwide crop production. *Pest Management Science*, 69, 1099–1105.

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A. et al (2017) Natural climate solutions. *Proceedings of the National Academy of Sciences*, 114, 11645–11650.

Groff, S. (2008) Mixtures and cocktails: Soil is meant to be covered. *Journal of Soil and Water Conservation*, 63, 110A–111A.

Handmer, J., Honda, Y., Kundzewicz, Z.W., Arnell, N., Benito, G., Hatfield, J., et al. (2012) Changes in impacts of climate extremes: Human systems and ecosystems. In: Field, C.B., Barros, V., Stocker, T.F. et al. (Eds.) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation – Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press, pp. 231–290.

Harris, D. & Hossell, J.E. (2001) *Weed Management Constraints Under Climate Change*. In: Proceedings 2001 BCPC International Conference on Weeds (12–15 November, Brighton, UK). Farnham, Surrey: British Crop Protection Council, pp. 91–96.

Helling, A., Conner, D., Heiss, S. & Berlin, L. (2015) Economic analysis of climate change best management practices in Vermont agriculture. *Agriculture*, 5, 879–900.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S. et al. (2013) Global flood risk under climate change. *Nature Climate Change*, 3, 816–821.

Horowitz, M., Regev, Y. & Herzlinger, G. (1983) Solarization for weed control. *Weed Science*, 31, 170–179.

Hossain, M.N., Chowdhury, S. & Paul, S.K. (2016) Farmer-level adaptation to climate change and agricultural drought: empirical evidences from the Barind region of Bangladesh. *Natural Hazards*, 83, 1007–1026.

Hunt, J.R. & Kirkegaard, J.A. (2011) Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. *Crop & Pasture Science*, 62, 915–929.

Hunt, N.D., Hill, J.D. & Liebman, M. (2019) Cropping system diversity effects on discharge, soil erosion, and agronomic performance. *Environmental Science & Technology*, 53, 1344–1352.

Hunt, N.D., Liebman, M., Thakrar, S.K. & Hill, J.D. (2020) Fossil energy use, climate change impacts, and air quality-related human health damages of conventional and diversified cropping systems in Iowa, USA. *Environmental Science & Technology*, 54, 11002–11014.

IPCC. (2014) Summary for policymakers. In: Field, C.B., Barros, V.R., Dokken, D.J. et al. (Eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, NY: IPCC, pp. 1–32.

IPCC. (2019) Summary for policymakers. In: Shukla, P.R., Skea, J. & Calvo Buendia, E. (Eds.) *Climate Change and Land: An IPCC. Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Geneva, Switzerland: IPCC, pp. 1–41.

Jabbour, R., Gallandt, E.R., Zwickle, S., Wilson, R.S. & Doohan, D. (2014a) Organic farmer knowledge and perceptions are associated with on-farm weed seedbank densities in Northern New England. *Weed Science*, 62, 338–349.

Jabbour, R., Zwickle, S., Gallandt, E.R., McPhee, K.E., Wilson, R.S. & Doohan, D. (2014b) Mental models of organic weed management: comparison of New England US farmer and expert models. *Renewable Agriculture and Food Systems*, 29, 319–333.

Johansen, C., Haque, M.E., Bell, R.W., Thierfelder, C. & Esdaile, R.J. (2012) Conservation agriculture for small holder rainfed farming: opportunities and constraints of new mechanized seeding systems. *Field Crops Research*, 132, 18–32.

Johnson, W.C. & Mullinix, B.G. (2000) Evaluation of tillage implements for stale seedbed tillage in peanut (*Arachis hypogaea*). *Weed Technology*, 14, 519–523.

Jones, C., Hine, D.W. & Marks, A.D.G. (2017) The future is now: reducing psychological distance to increase public engagement with climate change. *Risk Analysis*, 37, 331–341.

Jordan, N., Schut, M., Graham, S., Barney, J.N., Childs, D.Z., Christensen, S. et al. (2016) Transdisciplinary weed research: new leverage on challenging weed problems? *Weed Research*, 56, 345–358.

Kader, M.A., Senge, M., Mojid, M.A. & Ito, K. (2017) Recent advances in mulching materials and methods for modifying soil environment. *Soil and Tillage Research*, 168, 155–166.

Kathiresan, R. & Gualbert, G. (2016) Impact of climate change on the invasive traits of weeds. *Weed Biology and Management*, 16, 59–66.

Khan, Z., Midega, C.A.O., Hooper, A. & Pickett, J. (2016) Push-pull: chemical ecology-based integrated pest management technology. *Journal of Chemical Ecology*, 42, 689–697.

Khan, Z.R., Midega, C.A.O., Pittchar, J.O., Murage, A.W., Birkett, M.A., Bruce, T.J.A. et al. (2014) Achieving food security for one million sub-Saharan African poor through push-pull innovation by 2020. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 369, 20120284. https://doi.org/10.1098/rstb.2012.0284

Korres, N.E., Norsworthy, J.K., Tehranchian, P., Gitsopoulos, T.K., Loka, D.A., Oosterhuis, D.M. et al. (2016) Cultivars to face climate change effects on crops and weeds: a review. *Agronomy for Sustainable Development*, 36, 1–22.

Kriticos, D.J., Watt, M.S., Withers, T.M., Leriche, A. & Watson, M.C. (2009) A process-based population dynamics model to explore target and non-target impacts of a biological control agent. *Ecological Modelling*, 220, 2035–2050.

Kumar, V., Jat, H.S., Sharma, P.C., Balwinder-Singh, Gathala, M.K., Malik, R.K. et al. (2018) Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. *Agriculture Ecosystems & Environment*, 252, 132–147. https://doi.org/10.1016/j.agee.2017.10.006

Kumar, V., Obour, A.K., Jha, P., Liu, R., Manuchehri, M.R., Dille, J.A. et al. (2020) Integrating cover crops for weed management in the semiarid U.S. Great Plains: opportunities and challenges. *Weed Science*, 68, 311–323. https://doi.org/10.1017/wsc.2020.29

Kumar, V., Singh, S., Chhokar, R.S., Malik, R.K., Brainard, D.C. & Ladha, J.K. (2013) Weed management strategies to reduce herbicide use in zero-till rice-wheat cropping systems of the indo-gangetic plains. *Weed Technology*, 27, 241–254.

Kundzewicz, Z.W., Kanae, S., Seneviratne, S.I., Handmer, J., Nicholls, N., Peduzzi, P. et al. (2014) Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal*, 59, 1–28.

Kurstjens, D.A.G. & Perdok, U.D. (2000) The selective soil covering mechanism of weed harrows on sandy soil. *Soil and Tillage Research*, 55, 193–206.

Lee, H., Lautenbach, S., Nieto, A.P.G., Bondeau, A., Cramer, W. & Geijzendorffer, I.R. (2019) The impact of conservation farming practices on Mediterranean agro-ecosystem services provisioning-a meta-analysis. *Regional Environmental Change*, 19, 2187–2202. https://doi.org/10.1007/s10113-018-1447-y

Lee, N. & Thierfelder, C. (2017) Weed control under conservation agriculture in dryland smallholder farming systems of southern Africa. A review. *Agronomy for Sustainable Development*, 37, 48. https://doi.org/10.1007/s13593-017-0453-7

Lengnick, L. (2015) *Resilient Agriculture*. Vancouver, BC: New Society.

Li, S., Juhasz-Horvath, L., Harrison, P.A., Pinter, L. & Rounsevell, M.D.A. (2017) Relating farmer's perceptions of climate change risk to adaptation behaviour in Hungary. *Journal of Environmental Management*, 185, 21–30.

Li, Y., Ye, W., Wang, M. & Yan, X. (2009) Climate change and drought: a risk assessment of crop-yield impacts. *Climate Research*, 39, 31–46.

Liebman, M., Baraibar, B., Buckley, Y., Childs, D., Christensen, S., Cousens, R. et al. (2016) Ecologically sustainable weed management: how do we get from proof-of-concept to adoption? *Ecological Applications*, 26, 1352–1369.

Liebman, M. & Gallandt, E.R. (1997) Many little hammers: ecological approaches for management of crop-weed interactions. In: Jackson, L.E. (Ed.) *Ecology in Agriculture*. San Diego, CA: Academic Press, pp. 291–330.

Liebman, M., Mohler, C. & Staver, C. (2001) *Ecological Management of Agricultural Weeds*. Cambridge, MA: University Press.

Liebman, M. & Nichols, V.A. (2020) Cropping system redesign for improved weed management: a modeling approach illustrated with giant ragweed (*Ambrosia trifida*). *Agronomy*, 10, 262. https://doi.org/10.3390/agronomy10020262

Liebman, M. & Schulte, L.A. (2015) Enhancing agroecosystem performance and resilience through increased diversification of landscapes and cropping systems. *Elements: Science of the Anthropocene*, 3, 41.

Long, R.L., Gorecki, M.J., Renton, M., Scott, J.K., Colville, L., Goggin, D.E. et al. (2015) The ecophysiology of seed persistence: a mechanistic view of the journey to germination or demise. *Biological Reviews of the Cambridge Philosophical Society*, 90, 31–59.

Lounsbury, N., Warren, N., Wolfe, S. & Smith, R. (2020) Investigating tarps to facilitate organic no-till cabbage production with high-residue cover crops. *Renewable Agriculture and Food Systems*, 35, 227–233. https://doi.org/10.1017/S1742170518000509

Lowder, S.K., Skoet, J. & Raney, T. (2016) The number, size, and distribution of farms, smallholder farms, and family farms worldwide. *World Development*, 87, 16–29.

MacLaren, C., Storkey, J., Menegat, A., Metcalfe, H. & Dehnen-Schmutz, K. (2020) An ecological future for weed science to sustain crop production and the environment. A review. *Agronomy for Sustainable Development*, 40, 24.

Mafongoya, P., Rusinamhodzi, L., Siziba, S., Thierfelder, C., Mvumi, B.M., Nhau, B. et al. (2016) Maize productivity and profitability in conservation agriculture systems across agro-ecological regions in Zimbabwe: a review of knowledge and practice. *Agriculture, Ecosystems & Environment*, 220, 211–225.

Mahrer, Y. & Shilo, E. (2012) Physical principles of solar heating of soils. In: Gamliel, A. & Katan, J. (Eds.) *Soil Solarization: Theory and Practice*. St. Paul, MN: American Phytopathological Society, pp. 147–152.

Manalil, S. & Flower, K. (2014) Soil water conservation and nitrous oxide emissions from different crop sequences and fallow under Mediterranean conditions. *Soil & Tillage Research*, 143, 123–129.

Manea, A., Leishman, M.R. & Downey, P.O. (2011) Exotic C4 grasses have increased tolerance to glyphosate under elevated carbon dioxide. *Weed Science*, 59, 28–36.

Matzrafi, M., Seiwert, B., Reemtsma, T., Rubin, B. & Peleg, Z. (2016) Climate change increases the risk of herbicide-resistant weeds due to enhanced detoxification. *Planta*, 244, 1217–1227.

Melander, B., Lattanzi, B. & Pannacci, E. (2015) Intelligent versus non-intelligent mechanical intra-row weed control in transplanted onion and cabbage. *Crop Protection*, 72, 1–8.

Merfield, C.N. (2016) Robotic weeding's false dawn? Ten requirements for fully autonomous mechanical weed management. *Weed Research*, 56, 340–344.

Mirsky, S.B., Gallandt, E.R., Mortensen, D.A., Curran, W.S. & Shumway, D.L. (2010) Reducing the germinable weed seedbank with soil disturbance and cover crops. *Weed Research*, 50, 341–352.

Moles, A.T. & Westoby, M. (2003) Latitude, seed predation and seed mass. *Journal of Biogeography*, 30, 105–128.

Neve, P., Barney, J.N., Buckley, Y., Cousens, R.D., Graham, S., Jordan, N.R. et al. (2018) Reviewing research priorities in weed ecology, evolution and management: a horizon scan. *Weed Research*, 58, 250–258. https://doi.org/10.1111/wre.12304

Neve, P., Vila-Aiub, M. & Roux, F. (2009) Evolutionary-thinking in agricultural weed management. *New Phytologist*, 184, 783–793.

Ngouajio, M. (2005) Historical perspective on weed control and pest management in horticultural crops. *HortTechnology*, 15, 508–510.

Nichols, V., Verhulst, N., Cox, R. & Govaerts, B. (2015) Weed dynamics and conservation agriculture principles: a review. *Field Crops Research*, 183, 56–68.

Niles, M.T. & Mueller, N.D. (2016) Farmer perceptions of climate change: associations with observed temperature and precipitation trends, irrigation, and climate beliefs. *Global Environmental Change*, 39, 133–142.

Nordell, A. & Nordell, E. (2009) Weed the soil, not the crop. *ACRES*, 40, 1–6.

Noroozi, S., Alizadeh, H. & Mashhadi, H.R. (2016) Temperature influences postdispersal predation of weed seeds. *Weed Biology and Management*, 16, 24–33.

O'Rourke, M.E. & Petersen, J. (2016) Reduced tillage impacts on pumpkin yield, weed pressure, soil moisture, and soil erosion. *HortScience*, 51, 1524–1528.

Oyekale, A.S. (2015) Climate change induced occupational stress and reported morbidity among cocoa farmers in South-Western Nigeria. *Annals of Agricultural and Environmental Medicine*, 22, 357–361.

Parker, L.E. & Abatzoglou, J.T. (2016) Projected changes in cold hardiness zones and suitable overwinter ranges of perennial crops over the United States. *Environmental Research Letters*, 11, 1–8. https://doi.org/10.1088/1748-9326/11/3/034001

Patel, K.F., Tatariw, C., MacRae, J.D., Ohno, T., Nelson, S.J. & Fernandez, I.J. (2018) Soil carbon and nitrogen responses to snow removal and concrete frost in a northern coniferous forest. *Canadian Journal of Soil Science*, 12, 1–12.

Patterson, D.T. (1995) Weeds in a changing climate. *Weed Science*, 43, 685–701.

Peters, K., Breitsameter, L. & Gerowitt, B. (2014) Impact of climate change on weeds in agriculture: a review. *Agronomy for Sustainable Development*, 34, 707–721.

Peters, K. & Gerowitt, B. (2014) Important maize weeds profit in growth and reproduction from climate change conditions represented by higher temperatures and reduced humidity. *Journal of Applied Botany and Food Quality*, 87, 234–242.

Ramesh, K., Matloob, A., Aslam, F., Florentine, S.K. & Chauhan, B.S. (2017) Weeds in a changing climate: vulnerabilities, consequences, and implications for future weed management. *Frontiers in Plant Science*, 8, 1–12.

Rasmussen, J. (2003) Punch planting, flame weeding and stale seedbed for weed control in row crops. *Weed Research*, 43, 393–403.

Richter, R., Dullinger, S., Essl, F., Leitner, M. & Vogl, G. (2013) How to account for habitat suitability in weed management programmes? *Biological Invasions*, 15, 657–669.

Robertson, M., Kirkegaard, J., Rebetzke, G., Llewellyn, R. & Wark, T. (2016) Prospects for yield improvement in the Australian wheat industry: a perspective. *Food and Energy Security*, 5, 107–122.

Robinson, T.M.P. & Gross, K.L. (2010) The impact of altered precipitation variability on annual weed species. *American Journal of Botany*, 97, 1625–1629.

Roco, L., Engler, A., Bravo-Ureta, B.E. & Jara-Rojas, R. (2015) Farmers' perception of climate change in mediterranean Chile. *Regional Environmental Change*, 15, 867–879.

Rodenburg, J., Meinke, H. & Johnson, D.E. (2011) Challenges for weed management in African rice systems in a changing climate. *Journal of Agricultural Science*, 149, 427–435.

Roesch-McNally, G.E., Gordon Arbuckle, J. & Tyndall, J.C. (2017) What would farmers do? Adaptation intentions under a Corn Belt climate change scenario. *Agriculture and Human Values*, 34, 333–346.

Roesch-McNally, G.E., Arbuckle, J.G. & Tyndall, J.C. (2018) Barriers to implementing climate resilient agricultural strategies: the case of crop diversification in the U.S. Corn Belt. *Global Environmental Change*, 48, 206–215.

Roger, E., Duursma, D.E., Downey, P.O., Gallagher, R.V., Hughes, L., Steel, J. et al. (2015) A tool to assess potential for alien plant establishment and expansion under climate change. *Journal of Environmental Management*, 159, 121–127.

Sæbø, A. & Mortensen, L.M. (1996) Growth, morphology and yield of wheat, barley and oats grown at elevated atmospheric CO_2 concentration in a cool, maritime climate. *Agriculture, Ecosystems & Environment*, 57, 9–15.

Saska, P., Martinkova, Z. & Honek, A. (2010) Temperature and rate of seed consumption by ground beetles (Carabidae). *Biological Control*, 52, 91–95.

Schimming, W.K. & Messersmith, C.G. (1988) Freezing resistance of overwintering buds of four perennial weeds. *Weed Science*, 36, 568–573.

Schwartz-Lazaro, L.M., Norsworthy, J.K., Walsh, M.J. & Bagavathiannan, M.V. (2017) Efficacy of the integrated Harrington seed destructor on weeds of soybean and rice production systems in the southern United States. *Crop Science*, 57, 2812–2818.

Seastedt, T. (2014) Biological control of invasive plant species: a reassessment for the Anthropocene. *New Phytologist*, 205, 490–502.

Shergill, L.S., Schwartz-Lazaro, L.M., Leon, R., Ackroyd, V.J., Flessner, M.L., Bagavathiannan, M. et al. (2020) Current outlook and future research needs for harvest weed seed control in North American cropping systems. *Pest Management Science*, 76, 3887–3895.

Singh, E., Tiwari, S. & Agrawal, M. (2010) Variability in antioxidant and metabolite levels, growth and yield of two soybean varieties: an assessment of anticipated yield losses under projected elevation of ozone. *Agriculture, Ecosystems & Environment*, 135, 168–177.

Sivakumar, M. & Stefanski, R. (2006) Climate change mitigation, adaptation, and sustainability in agriculture. In: *Proceedings of the 14th Session of the WorldMeteorologicalOrganization on Climate Risks in Vulnerable Areas – Agrometeorological Monitoring and Coping Strategies* (New Delhi, India), pp. 89–102.

Somasundaram, J., Sinha, N.K., Dalal, R.C., Lal, R., Mohanty, M., Naorem, A.K. et al. (2020) No-till farming and conservation agriculture in South Asia – issues, challenges, prospects and benefits. *Critical Reviews in Plant Sciences*, 39, 236–279. https://doi.org/10.1080/07352689.2020.1782069

Springer, C.J. & Ward, J.K. (2007) Flowering time and elevated atmospheric CO2. *The New Phytologist*, 176, 243–255.

Standifer, L.C., Wilson, P.W. & Porche-Sorbet, R. (1984) Effects of solarization on soil weed seed populations. *Weed Science*, 32, 569–573.

Summers, D.M., Bryan, B.A., Meyer, W.S., Lyle, G., Wells, S., McLean, J. et al. (2015) Simple models for managing complex social–ecological systems: the landscape futures analysis tool (LFAT). *Environmental Modelling & Software*, 63, 217–229.

Syswerda, S.P. & Robertson, G.P. (2014) Ecosystem services along a management gradient in Michigan (USA) cropping systems. *Agriculture, Ecosystems & Environment*, 189, 28–35.

Tatariw, C., Patel, K., MacRae, J.D. & Fernandez, I.J. (2017) Snowpack loss promotes soil freezing and concrete frost formation in a northeastern temperate softwoods stand. *Northeastern Naturalist*, 24, B42–B54.

Taylor, M. & Bhasme, S. (2018) Model farmers, extension networks and the politics of agricultural knowledge transfer. *Journal of Rural Studies*, 64, 1–10. https://doi.org/10.1016/j.jrurstud.2018.09.015

Testani, E., Montemurro, F., Ciaccia, C. & Diacono, M. (2020) Agroecological practices for organic lettuce: effects on yield, nitrogen status and nitrogen utilisation efficiency. *Biological Agriculture & Horticulture*, 36, 84–95. https://doi.org/10.1080/01448765.2019.1689531

Thierfelder, C., Baudron, F., Setimela, P., Nyagumbo, I., Mupangwa, W., Mhlanga, B. et al. (2018) Complementary practices supporting conservation agriculture in southern Africa. A review. *Agronomy for Sustainable Development*, 38, 16. https://doi.org/10.1007/s13593-018-0492-8

Thierfelder, C., Chivenge, P., Mupangwa, W., Rosenstock, T.S., Lamanna, C. & Eyre, J.X. (2017) How climate-smart is conservation agriculture (CA)? – its potential to deliver on adaptation, mitigation and productivity on smallholder farms in southern Africa. *Food Security*, 9, 537–560.

Tomasek, B.J., Williams, M.M. & Davis, A.S. (2015) Optimization of agricultural field workability predictions for improved risk management. *Agronomy Journal*, 107, 627–633.

Tomasek, B.J., Williams, M.M. & Davis, A.S. (2017) Changes in field workability and drought risk from projected climate change drive spatially variable risks in Illinois cropping systems. *PLoS One*, 12, 1–15.

Torresen, K.S., Fykse, H., Rafoss, T. & Gerowitt, B. (2020) Autumn growth of three perennial weeds at high latitude benefits from climate change. *Global Change Biology*, 26, 2561–2572. https://doi.org/10.1111/gcb.14976

Tozer, K.N., Chapman, D.F., Quigley, P.E., Dowling, P.M., Cousens, R.D., Kearney, G.A. et al. (2008) Controlling invasive annual grasses in grazed pastures: population dynamics and critical gap sizes. *Journal of Applied Ecology*, 45, 1152–1159.

Tozzi, E., Lyons, E.M. & Van Acker, R.C. (2014) The effect of simulated winter warming spells on Canada fleabane [*Conyza canadensis* (L.) Cronq. var. canadensis] seeds and plants. *Canadian Journal of Plant Science*, 94, 963–969.

Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvåg, A.O., Eitzinger, J., Seguin, B. et al. (2011) Agroclimatic conditions in Europe under climate change. *Global Change Biology*, 17, 2298–2318.

Wall, E. & Smit, B. (2005) Climate change adaptation in light of sustainable agriculture. *Journal of Sustainable Agriculture*, 27, 113–123.

Walsh, M., Newman, P. & Powles, S. (2013) Targeting weed seed in-crop: a new weed control paradigm for global agriculture. *Weed Technology*, 27, 431–436.

Walsh, M., Ouzman, J., Newman, P., Powles, S. & Llewellyn, R. (2017) High levels of adoption indicate that harvest weed seed control is now an established weed control practice in Australian cropping. *Weed Technology*, 31, 341–347. https://doi.org/10.1017/wet.2017.9

Walters, T.W. & Pinkerton, J.N. (2012) Soil solarization: a perspective from cool northern regions. In: Gamliel, A. & Katan, J. (Eds.) *Soil Solarization: Theory and Practice*. St. Paul, MN: American Phytopathological Society, pp. 199–205.

Weisberger, D., Nichols, V. & Liebman, M. (2019) Does diversifying crop rotations suppress weeds? A meta-analysis. *PLoS One*, 14, e0219847. https://doi.org/10.1371/journal.pone.0219847

Westerman, P.R., Liebman, M., Menalled, F.D., Heggenstaller, A.H., Hartzler, R.G. & Dixon, P.M. (2005) Are many little hammers effective? Velvetleaf (*Abutilon theophrasti*) population dynamics in two- and four-year crop rotation systems. *Weed Science*, 53, 382–392.

White, A., Faulkner, J., Simis, S., Tucker, P. & Weatherhogg, K. (2018) *Report of the 2017–2018 New England Adaptation Survey for Vegetable and Fruit Growers*. Burlington, VT: Department of Plant and Soil Science, University of Vermont.

Wolfe, D.W., DeGaetano, A.T., Peck, G.M., Carey, M., Ziska, L.H., Lea-Cox, J. et al. (2018) Unique challenges and opportunities for Northeastern U.S. crop production in a changing climate. *Climatic Change*, 146, 231–245.

Yan, Y., Liu, Q., Zang, X., Yuan, S., Bat-Erdene, U., Nguyen, C. et al. (2018) Resistance-gene-directed discovery of a natural-product herbicide with a new mode of action. *Nature*, 559, 414–419.

Yanai, Y., Hirota, T., Iwata, Y., Nemoto, M., Koga, N., Nagata, O. et al. (2014) Snow cover manipulation in agricultural fields: as an option for mitigating greenhouse gas emissions. *Ecological Research*, 29, 535–545.

Zahra, S., Cici, H. & Van Acker, R.C. (2009) A review of the recruitment biology of winter annual weeds in Canada. *Canadian Journal of Plant Science*, 89, 575–589.

Ziska, L.H. (2016) The role of climate change and increasing atmospheric carbon dioxide on weed management: herbicide efficacy. *Agriculture, Ecosystems & Environment*, 231, 304–309.

Ziska, L.H. & Blumenthal, D.M. (2007) Empirical selection of cultivated oat in response to rising atmospheric carbon dioxide. *Crop Science*, 47, 1547–1552.

Ziska, L.H. & Dukes, J.S. (2011) *Weed Biology and Climate Change*. Ames, IA: Wiley-Blackwell.

Ziska, L.H. & McConnell, L.L. (2016) Climate change, carbon dioxide, and pest biology: monitor, mitigate, manage. *Journal of Agricultural and Food Chemistry*, 64, 6–12.

Zwickle, S., Wilson, R., Bessette, D., Herms, C. & Doohan, D. (2016) Facilitating ecological weed management decisions by assessing risk-benefit tradeoffs. *Agroecology and Sustainable Food Systems*, 40, 635–659.

Zwickle, S., Wilson, R. & Doohan, D. (2014) Identifying the challenges of promoting ecological weed management (EWM) in organic agroecosystems through the lens of behavioral decision making. *Agriculture and Human Values*, 31, 355–370.

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