



# Climate change and the geography of weed damage: Analysis of U.S. maize systems suggests the potential for significant range transformations

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## ABSTRACT

By the end of the century, climate change projections under a “business-as-usual” emissions scenario suggest a globally averaged warming of 2.4–6.4 °C. If these forecasts are realized, cropping systems are likely to experience significant geographic range transformations among damaging endemic weed species and new vulnerabilities to exotic weed invasions. To anticipate these changes and to devise management strategies for proactively addressing them, it is necessary to characterize the environmental conditions that make specific weed species abundant, competitive, and therefore damaging the production of particular crops (i.e. defining the *damage niche*). In this study, U.S. maize is used as a model system to explore the implications of climate change on the distribution of damaging agricultural weeds. To accomplish this, we couple ensemble climate change projections of annual temperature and precipitation with survey data of troublesome weed species in maize. At the state scale, space-for-time substitution techniques are used to suggest the potential magnitude of change among damaging weed communities. To explore how the geography of damage for specific species may evolve over the next century, bioclimatic range rules were derived for two weed species that are pervasive in the Northern (*Abutilon theophrasti* Medicus, ABUTH) and Southern (*Sorghum halepense* (L.) Pers., SORHA) U.S. Results from both analyses suggest that the composition of damaging weed communities may be fundamentally altered by climate change. In some states, potential changes in the coming decades are commensurate to those possible by the end of the century. Regions such as the Northeastern U.S. may prove particularly vulnerable with emerging climate conditions favoring few weed species of present-day significance. In contrast, regions like the mid-South are likely to experience fewer shifts even with a similar magnitude in climate change. By the end of the century in the U.S. Corn Belt, cold-tolerant species like *A. theophrasti* may be of minor importance whereas *S. halepense*, a predominantly Southern U.S. weed species at present, may become common and damaging to maize production with its damage niche advancing 200–600 km north of its present-day distribution.

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## 1. Introduction

### 1.1. Climate change and agricultural weeds

Under a ‘business-as-usual’ greenhouse gas (GHG) emission scenario, ensemble climate forecasts project a globally averaged warming of 2.4–6.4 °C (IPCC, 2007) by the end of the century. Model projections also suggest that temperature increases by mid-century will be only modestly affected by future trends in GHG emissions. With increasing certainty that the Earth’s climate is changing and that significant warming is inevitable regardless of future emission reductions, it has become progressively more

important to identify potential vulnerabilities and adaptive responses in managed ecosystems (Howden et al., 2007).

Climate change impacts on cropping systems have been assessed with increasing levels of sophistication for more than 30 years (Tubiello et al., 2007). For crop-weed competition, many experiments characterize the effects of elevated ambient CO<sub>2</sub> on comparative physiology and growth (e.g. Saebo and Mortensen, 1998; O’Donnell and Adkins, 2001; Ziska, 2000, 2001, 2002, 2003), including interactions with factors such as soil nitrogen status (Zhu et al., 2008). Other efforts quantify the role of environmental drivers like temperature and water stress on patterns of crop yield loss from competition (Patterson and Flint, 1979; Patterson et al., 1988; McDonald et al., 2004; Tungate et al., 2007). Indirect impacts of global change may also prove important, with some evidence demonstrating that herbicide efficacy can be reduced at elevated CO<sub>2</sub> (Harris and Hossell, 2001; Ziska and Teasdale, 2000; Ziska et al., 2004). Despite the considerable breadth of research

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dedicated to understanding potential climate change impacts in cropping systems, comparatively little attention has been given to potential effects on the geographic range of agricultural weeds.

Ecological niche theory holds that potential geographic distribution is governed by the basic environmental requirements of a species (see Guisan and Thuiller, 2005). This idea is also termed the conservatism hypothesis: that is, species follow a consistent set of rules in their geographic distribution (Peterson et al., 2003). This concept defines what is referred to as the bioclimatic niche (or envelope) and establishes the environmental conditions under which a species can persist. Environmental factors generally operate within a (partially) nested hierarchy with different factors relevant at different spatial scales (Pearson and Dawson, 2003). Fossil records and present-day correlative studies demonstrate that climate is the principal determinant of vegetation distribution at regional to global scales (Woodward, 1987, 1988; Patterson, 1995). In general, the climate requirements of a species must be satisfied before lower order factors such as topography and landuse influence spatial distribution (Fig. 1). Potential distribution as delimited by the bioclimatic niche is not equivalent to the actual distribution. Dispersal, disturbance, and competition processes determine which areas encompassed by the bioclimatic niche are actually occupied by a species.

Application of these concepts in cropping systems is not simply theoretical. In the U.S., Stoller (1973) found that the northern range limits of two Cyperaceae weed species corresponded to distinct winter temperature minima. Across a north–south transect of cereal systems in Europe, Glemnitz et al. (2000) found that *Lapsana communis* L. was found exclusively in the north whereas species such as *Lolium multiflorum* Lam. were restricted to the warmer conditions of Southern Europe. These types of data strongly suggest that geographic range transformations for agricultural weeds are highly probable outcomes from global climate change (Patterson, 1995; Fuhrer, 2003). If climate change forecasts are realized, cropping systems are likely to experience a significant change in the geographic distribution of endemics and, in some regions, an increased vulnerability to invasion by exotic weed species.

### 1.2. The ‘damage niche’ concept for agroecosystems

Bioclimatic niche concepts are useful for understanding weed demography in agroecosystems, but they must be defined more narrowly when management considerations are the primary

objective of a study. Agricultural weed species are typically of concern in areas where they are strong competitors rather than simply persisting at low densities without causing significant crop yield losses. The subjective concept of *troublesome* integrates environment, production, and competition factors to determine geographic areas where specific weed species tend to be abundant and damaging to crop yield. We introduce the term *damage niche* to refer to the suite of factors under which specific weed species are judged troublesome to the production of specific crops.

Fig. 2 illustrates how the damage niche concept in agroecosystems relates to the bioclimatic niche. *Chenopodium album* L. is a summer-annual weed that is naturalized across most of North America. For the U.S. and Canada, the observed range of *C. album* is represented in grey in Fig. 2. Despite the considerable geographic extent of its bioclimatic niche, this species is only considered troublesome to maize in 11 of 38 U.S. states with surveyed maize production systems (black circles, Fig. 2). From the clustered spatial distribution of these states, it is apparent that precipitation and temperature are both likely candidates for defining the boundaries of the damage niche for this species in maize. In general, *C. album* is not judged troublesome to maize under the warmer conditions of the Southern U.S. or the drier conditions of the western U.S.

### 1.3. Projecting weed distributions in a changing climate

The most widely used analytical approaches for predicting future species distributions with climate change are bioclimatic niche models (BNM). These biogeographic tools apply statistical or machine-learning methods for quantifying associations between surveyed species distributions and environmental factors. Examples include CLIMEX (Sutherst and Maywald, 1985), GARP (Stockwell and Peters, 1999), SPECIES (Pearson et al., 2002), BIOMAPPER (Hirzel et al., 2002), and BIOMOD (Thuiller, 2003). BNM may provide a robust methodology for quantifying the damage niche for agricultural weeds (see Section 1.2). At present, however, surveys of troublesome weeds in cropping systems are limited with respect to geographic coverage and spatial resolution. For the U.S., Bridges (1992) canvassed expert judgment to compile lists of troublesome weed species for major crops in each state. To run a BNM model like GARP, a minimum of 15–20 species occurrence points are required, and this standard does not include data for model validation (Raimundo et al., 2007). With states

## Bioclimatic Niche

resource ‘rules’ that govern potential geographic distribution

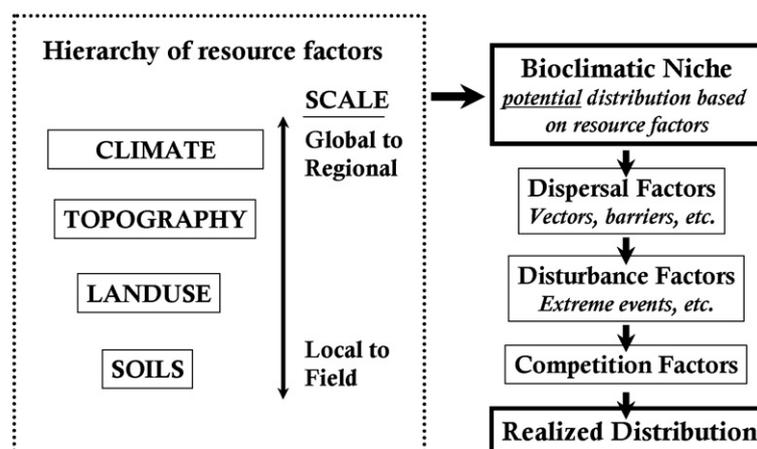
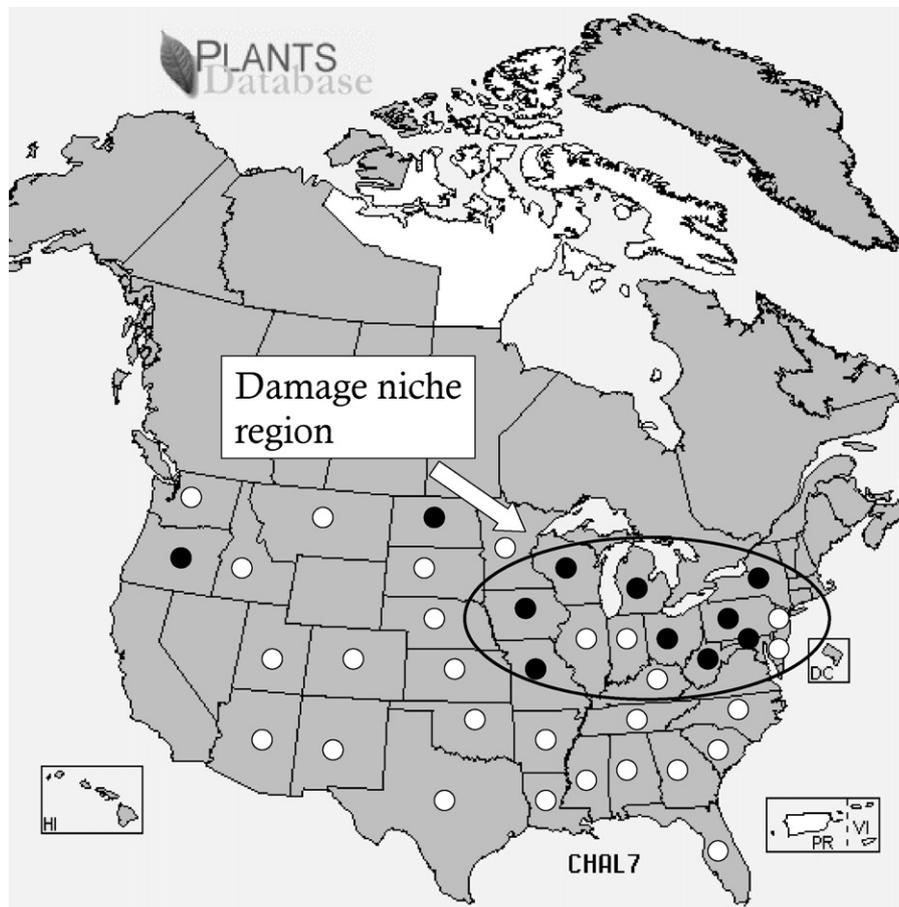


Fig. 1. Hierarchy of resource factors that determine the bioclimatic niche. The bioclimatic niche establishes the potential geographic range for a species. The realized range of a species is influenced by factors such as dispersal, disturbance, and competition processes.



**Fig. 2.** The geographic range for *C. album* includes almost all regions of the U.S. and Canada (grey shaded areas of the map). Within the U.S., states with maize production that were surveyed for troublesome weed species by Bridges (1992) are indicated with circles. Despite its extensive geographic range, *C. album* was only judged troublesome to maize production in states with black circles. This map illustrates that the damage niche for *C. album* in maize is much narrower than its bioclimatic niche which governs overall geographic range. (Distribution map for *C. album* adopted from USDA's PLANTS database, <http://plants.usda.gov/>.)

treated as 'points', this minimum requirement is met for only one of the more than 60 species identified by Bridges (1992) as troublesome to maize production.

In the absence of higher-resolution weed survey data than provided by Bridges (1992), this project uses space-for-time (SFT) substitution and maize as a model system to explore how troublesome weed communities in different U.S. states may evolve with projected changes in mean annual temperature and precipitation. For global change research, SFT identifies present-day analogues for projected climate conditions in order to characterize potential ecosystem responses (Ziska, 2003; Carreiro and Tripler, 2005). In other words, SFT infers the impacts of climate change from current biogeographical patterns in the landscape. For this project, estimates of mean annual precipitation and temperature were projected for two 30-year periods: 2030 (i.e. 2016–2045, 'coming decades') and 2084 (i.e. 2070–2099, 'end of century'). To assess how the geography of damage for individual weed species may be altered by climate change, we also derive simple climate-based range rules that define the damage niche for the two species (*Abutilon theophrasti*, *Sorghum halepense*) that are the most prevalent troublesome species in Northern and Southern U.S. maize systems, respectively.

## 2. Materials and methods

### 2.1. Weed survey data

In the early 1990s, Bridges (1992) canvassed expert judgment to compile lists of the 10 most troublesome weed species in major

cropping systems for each U.S. state. The concept of troublesome integrates both weed abundance and capacity to cause substantial crop yield losses. With this methodology, weed species are also assigned a numerical rank from most (1) to least troublesome (10). In the Bridges (1992) survey, troublesome weed communities in maize were assessed in 38 U.S. states. The number of weed species characterized as troublesome was capped at 10, but fewer than 10 species were reported for some states. Bayer codes (now referred to as EPPO codes, see <http://eppt.eppo.org>) are used by Bridges (1992) to identify species. For several genera (*Amaranthus*, *Cenchrus*, *Cyperus*, *Digitaria*, *Ipomoea*, *Rubus*, *Setaria*, and *Solanum*), species were not differentiated in all states. To facilitate cross-state comparisons in this study, species-level distinctions were not considered for these genera.

### 2.2. Climate data

Hayhoe et al. (2008) have developed statistically downscaled U.S. climate projections at a spatial resolution  $1/8^\circ$  (ca.  $140 \text{ km}^2$ ). These projections are based on several atmosphere-ocean global circulation model (AOGCM) forecasts under the IPCC's SRES high (A1fi), mid-high (A2) and low (B1) greenhouse gas emission scenarios (Nakićenović et al., 2000). Different greenhouse gas emission scenarios reflect diverse development pathways with respect to several socio-economic factors including population growth and technological change. From a current atmospheric concentration of approximately 385 ppm,  $\text{CO}_2$  concentrations are projected to reach 550 and 970 ppm under the low (B1) and high

(A1fi) emission scenarios, respectively, by the end of the century. Global temperature projections for different emission scenarios are similar until approximately 2050 (IPCC, 2007), suggesting that some changes in climate are inevitable regardless of efforts to reduce GHG emissions.

For this study, we use the A1fi scenario, commonly referred to as 'business-as-usual' GHG emissions, to forecast climate changes until the end of the century. Monthly temperature and precipitation projections were derived from three different AOGCMs: GFDL CM2.1 (Delworth et al., 2006), HadCM3 (Pope et al., 2000), and PCM1 (Washington et al., 2000). An ensemble forecast of mean annual temperature and precipitation was then computed by simple averaging of AOGCM output. From the ensemble forecast, future climatology (i.e. 30-year weather averages) centered on 2030 (i.e. 2016–2045, 'coming decades') and 2084 (i.e. 2070–2099, 'end of century') was predicted. Historical climatology (1961–1990) for annual precipitation and temperature was based on monthly observations from the United States Historical Climatology Network gridded to the same 1/8° spatial resolution as the AOGCM projections (see Hayhoe et al., 2008). For future and historical climatology, area-wide mean values for annual precipitation and temperature were calculated for each U.S. state. Based on these calculations, we identified close historical analogues for projections of future climatology (i.e. precipitation difference  $\leq 10$  cm with temperature difference  $\leq 0.6$  °C).

### 2.3. Weed community comparisons

Within the space-for-time substitution and climate analogue approach, the Bray-Curtis (BC) dissimilarity metric for multivariate data was used to make pair-wise comparisons of troublesome weed communities between U.S. states. For this purpose, species were inversely weighted by their Bridges (1992) ranking from the most troublesome species (10) to the least (1). Species that were not judged troublesome in a state were assigned a value of zero. BC is well suited for multivariate comparisons when the objects (e.g. U.S. states) have many zero values among the variables (e.g. species) (Mac Nally, 1989; Quinn and Keough, 2002). The BC metric varies from 0 to 1, with 1 indicating 100% dissimilarity between objects.

To simultaneously contrast weed community composition across all 38 states that have weed survey data for maize, a BC dissimilarity matrix for the full dataset was subjected to principal coordinate analysis (PCoA). PCoA translates multivariate dissimilarities between objects into Euclidean distances (Quinn and Keough, 2002). To aggregate the state-based weed communities into mega-groups, agglomerative hierarchical cluster analysis was performed with the first two coordinates of the PCoA. The final partition was constrained by the pre-analysis specification of four clusters, a number suggested by visual evaluation of PCoA output. Linear discriminant analysis with cross-validation was used to quantify the association between state-based climate parameters and membership in the different groups.

The Bray-Curtis dissimilarity and PCoA analyses were conducted with the PAST software package (<http://folk.uio.no/ohammer/past/>), and Minitab 15 was used for cluster and discriminant analyses.

### 2.4. Developing bioclimatic envelopes (i.e. range rules) for the damage niche

Climate-based range rules for the damage niche were derived for *S. halepense* and *A. theophrasti* by identifying maximum and minimum values of annual temperature and precipitation among U.S. states where these species are characterized as troublesome to maize production by Bridges (1992). Since crop water availability

could not be quantified for states dominated by irrigated production practices (i.e. operationally defined as >50% of maize acreage as reported in NASS, 1992), these states were excluded from our analysis. For *S. halepense*, climate data were used from the following 15 states: AL, AR, FL, GA, IL, IN, KY, LA, MD, MS, MO, NC, SC, TN, and WV. For *A. theophrasti*, climate data were used from the following 10 states: IN, IA, MI, MO, NJ, NY, OH, PA, WV, and WI. Neither species is damaging to maize production in the drier western states in the absence of irrigation. Damage niche range boundaries for temperature act in opposite directions, with *S. halepense* limited by the cooler conditions in the Northern U.S. and *A. theophrasti* limited by the warmer conditions in the south. Two different criteria were used to establish range rules from state-based historical climatology. In the limiting direction (e.g. cooler temperatures for *S. halepense*), the mean climate value for the state at the extreme was used. For example, the state with the coolest mean annual temperature where *S. halepense* is damaging to maize production is West Virginia (WV) and the lower limit of the range rule was set at the mean annual temperature for WV. In the other direction, where there is no apparent climate limitation in the conterminous U.S. (e.g. warm states for *S. halepense*), the range rule was set at the maximum (or minimum) climate value in the state at the extreme (e.g. warmest region in the warmest state for *S. halepense*). Following the climate envelope method developed by Nix (1986), all values that fall between the maximum and minimum are encompassed by the range rules. Due to the aforementioned limitations of state-scale weed survey data, the predictive accuracy of these rules could not be assessed.

Range rules were projected on a map of historical (1961–1990) U.S. climatology at the scale of the climate grids (i.e. 140 km<sup>2</sup>) to establish the contemporary geographic extent of the damage niche using ArcGIS<sup>®</sup> 9 geoprocessing software. To assess how the geography of the damage niche may evolve with forecasted climate changes under the 'business-as-usual' emissions scenario, range rules were subsequently projected onto maps of future U.S. climatology centered on 2030 (i.e. 2016–2045, 'coming decades') and 2084 (i.e. 2070–2099, 'end of century'). Since no effort is made to modify these rules with soil, terrain, or other non-climate criteria, they should be interpreted as coarse-scale (i.e. regional) indicators of potential geographic distribution.

## 3. Results

### 3.1. Assessing the potential for weed community change with climate analogues and SFT substitution

We identified nine U.S. states (AL, DE, IN, KY, MI, NJ, NY, PA, and SC) with present-day analogues to projected climate changes that also have weed survey data for maize (Table 1). Table 2 lists weed species that are currently considered damaging and contrasts them with species judged damaging in states that are analogues to climate projections centered on 2030 (2016–2045) and 2084 (2070–2099) under 'business-as-usual' GHG emissions. Species that are likely to remain damaging to maize are highlighted in bold with the total number of original species retained in each timeframe reported at the bottom of the columns.

Our results suggest that the types of weed community changes in maize are unlikely to be similar across all states. For example, in New York (NY) none of the species currently considered damaging to maize are damaging in Kentucky (KY), the state that New York's annual climate is projected to resemble in 2084. Conversely, in South Carolina (SC) 7 of 10 species now considered damaging to maize are also damaging in Florida (FL), the state that SC is expected to resemble towards the end of the century. Elsewhere, expected changes fall between these extremes. For Kentucky, *S. halepense* is considered the most damaging weed species in maize

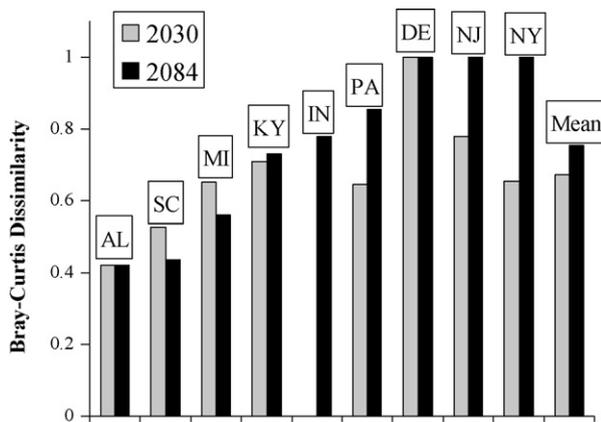
**Table 1**

Recent and projected climatology for selected U.S. states under a 'business-as-usual' emissions scenario. These states have survey data for troublesome weed species in maize and also historical analogues for projected changes to climate (right side of table). A list of state abbreviations is published by the U.S. Postal Service ([http://www.usps.com/nsc/lookups/usps\\_abbreviations.html](http://www.usps.com/nsc/lookups/usps_abbreviations.html)).

Historical and projected annual climatology (A1fi – 'business-as-usual' emissions scenario)				Historical analogues (for projected climatology)		
State	Period	Temperature (°C)	Precipitation (cm)	State	Temperature (°C)	Precipitation (cm)
AL	1961–1990	16.9	138	–	–	–
	2016–2045	18.5	147	LA	18.9	141
	2070–2099	22	142	FL	21.5	136
DE	1961–1990	13.1	110	–	–	–
	2016–2045	14.6	119	NC	14.9	122
	2070–2099	17.9	125	GA	17.5	125
IN	1961–1990	10.8	100	–	–	–
	2016–2045	12.7	107	VA	12.9	108
	2070–2099	16.5	115	SC	17	118
KY	1961–1990	12.9	119	–	–	–
	2016–2045	14.6	128	NC	14.9	122
	2070–2099	18.3	137	LA	18.3	137
MI	1961–1990	6.9	81	–	–	–
	2016–2045	8.7	83	IA	8.9	83
	2070–2099	12.4	90	MO	12.5	100
NJ	1961–1990	11.3	115	–	–	–
	2016–2045	12.9	126	KY	12.9	119
	2070–2099	16.4	132	AL	16.9	138
NY	1961–1990	7.1	102	–	–	–
	2016–2045	8.8	110	PA	8.9	106
	2070–2099	12.5	115	KY	12.9	119
PA	1961–1990	8.9	106	–	–	–
	2016–2045	10.7	113	WV	10.5	111
	2070–2099	14.3	120	NC	14.9	122
SC	1961–1990	17	118	–	–	–
	2016–2045	18.5	131	LA	18.9	141
	2070–2099	21.7	135	FL	21.5	136

at present and is also the most damaging species in the states that Kentucky may resemble in 2030 (NC) and 2084 (LA). However, none of the other species currently considered damaging in Kentucky are likely to remain so by the end of the century.

A measure of multivariate dissimilarity (Bray-Curtis) between the current weed community in a state and that of its projected climate analogues for 2030 and 2084 is presented in Fig. 3. With this measure, a value of 1 indicates 100% dissimilarity between weed communities. Three results are noteworthy when considering trends among the states. First, potential changes in coming decades for several states (i.e. AL, SC, MI, KY, and DE) are similar to



**Fig. 3.** For maize systems in selected U.S. states, Bray-Curtis dissimilarity between current communities of troublesome weed species and communities that are projected to be favored by climate conditions in 2030 and 2084. A value of 1 indicates complete dissimilarity between weed communities.

those possible by the end of the century. Second, there are strong regional differences with states in the Northeastern U.S. (i.e. NY, NJ, DE, and PA) predicted to experience more extensive changes in their damaging weed communities than states in the Southern U.S. (i.e. AL, SC). Differences between geographic regions are not related to a greater degree of climate change (see Table 1). Rather, states in the Northeastern U.S. are projected to cross a climate transition zone that separates weed communities with substantially different compositions whereas states like Alabama (AL) and South Carolina (SC) are not expected to cross any major transition zones (see Section 3.2). Lastly, in some regions large weed community changes are likely by the end of the century with states like NY, NJ, PA, and DE projected to have climate conditions that will favor an entirely different suite of troublesome weed species than at present (i.e.  $BC > 0.85$ ).

To evaluate the reliability of this SFT approach for predicting future weed community composition based on state-scale climate factors, we identified six pairs of states that are contemporary climate analogous and compared their troublesome weed communities by computing the Bray-Curtis dissimilarity metric for each pair. Excluding one case which was an outlier (KY and DE), the mean BC value for these comparisons was 0.53 ( $SE \pm 0.05$ ) and the pairs share, on average, 5 species in common with a range from 4 to 6. This indicates that our approach provides a reasonable, but not perfect, methodology for predicting future weed community composition when applied at the scale of U.S. states.

### 3.2. Weed community mega-groups and associations with climate

In order to explore how troublesome weed communities vary across all 38 U.S. states surveyed by Bridges (1992), BC

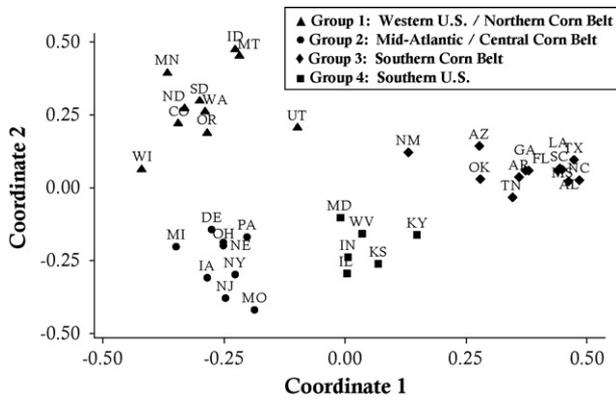
**Table 2**

For U.S. states, weed species (EPPO codes) that are currently considered damaging to maize production contrasted to those judged damaging in states that are close analogues to projected changes to climate centered on 2030 (2016–2045) and 2084 (2070–2099). Species that are expected to remain climatically favored are highlighted in bold. Full scientific names for EPPO codes can be accessed at <http://eppt.eppo.org/>.

Alabama (AL)	Present (AL historical)	2030 (LA historical)	2084 (FL historical)
Weed rank			
1	<b>SORHA</b>	<b>SORHA</b>	<b>PANTE</b>
2	<b>PANTE</b>	ROOEX	DEDTO
3	<b>BRAPP</b>	<b>BRAPP</b>	<b>CASOB</b>
4	<b>IPO sp.</b>	<b>IPO sp.</b>	<b>SORHA</b>
5	PANDI		XANST
6	<b>CASOB</b>		<b>IPO sp.</b>
7	<b>AMA sp.</b>		ACNHI
8	<b>CYP sp.</b>		<b>CYP sp.</b>
9			<b>AMA sp.</b>
10			DIG sp.
	RETAINED:	3/8	6/8
Delaware (DE)	Present (DE historical)	2030 (NC historical)	2084 (GA historical)
Weed rank			
1	CIRAR	SORHA	PANTE
2	PANDI	PANTE	IPO sp.
3	APCCA	BRAPP	XANST
4	SET sp.	CASOB	CASOB
5	AMA sp.	IPO sp.	CASOC
6		CYP sp.	SORHA
7		SIYAN	
8		SOL sp.	
9		ABUTH	
10		CYNDA	
	RETAINED:	0/5	0/5
Kentucky (KY)	Present (KY historical)	2030 (NC historical)	2084 (LA historical)
Weed rank			
1	<b>SORHA</b>	<b>SORHA</b>	<b>SORHA</b>
2	SORVU	PANTE	ROOEX
3	AMBTR	BRAPP	BRAPP
4	AMPAL	CASOB	<b>IPO sp.</b>
5	PANDI	<b>IPO sp.</b>	
6	<b>SIYAN</b>	CYP sp.	
7	CMIRA	<b>SIYAN</b>	
8	CONAR	SOL sp.	
9	<b>IPO sp.</b>	ABUTH	
10	XANST	CYNDA	
	RETAINED:	3/10	2/10
Indiana (IN)	Present (IN historical)	2030 (VA historical)	2084 (SC historical)
Weed rank			
1	ABUTH	No data	CYNDA
2	AMBTR		PANTE
3	<b>SORHA</b>		BRAPP
4	CIRAR		<b>SORHA</b>
5	<b>XANST</b>		<b>IPO sp.</b>
6	SET sp.		CYP sp.
7	<b>IPO sp.</b>		CASOB
8	SIYAN		PANDI
9	APCCA		AMA sp.
10	DATST		<b>XANST</b>
	RETAINED:	–	3/10
Michigan (MI)	Present (MI historical)	2030 (IA historical)	2084 (MO historical)
Weed rank			
1	<b>ABUTH</b>	<b>SET sp.</b>	<b>ABUTH</b>
2	<b>PANDI</b>	<b>ABUTH</b>	SORVU

**Table 2 (Continued)**

Michigan (MI)	Present (MI historical)	2030 (IA historical)	2084 (MO historical)
3	<b>AGRRE</b>	AMA sp.	<b>SET sp.</b>
4	<b>CHEAL</b>	<b>CHEAL</b>	AMA sp.
5	CIRAR	XANST	<b>PANDI</b>
6	<b>APCCA</b>	POLPY	ASCSY
7	CONAR	HELAN	<b>APCCA</b>
8	DIG sp.	SORVU	SORHA
9	<b>SET sp.</b>	ERBVI	<b>CHEAL</b>
10		<b>AGRRE</b>	XANST
	RETAINED:	4/9	5/9
New York (NY)	Present (NY historical)	2030 (PA historical)	2084 (KY historical)
Weed rank			
1	<b>ABUTH</b>	AMBEL	SORHA
2	<b>CHEAL</b>	APCCA	SORVU
3	<b>MUHFR</b>	<b>SOL sp.</b>	AMBTR
4	ASCSY	<b>MUHFR</b>	AMPAL
5	<b>SOL sp.</b>	RUB sp.	PANDI
6	CAGSE	AGRRE	SIYAN
7	SET sp.	<b>ABUTH</b>	CMIRA
8		SIYAN	CONAR
9		CONAR	IPO sp.
10		<b>CHEAL</b>	XANST
	RETAINED:	4/7	0/7
New Jersey (NJ)	Present (NJ historical)	2030 (KY historical)	2084 (AL historical)
Weed rank			
1	APCCA	SORHA	SORHA
2	<b>SORVU</b>	<b>SORVU</b>	PANTE
3	ABUTH	AMBTR	BRAPP
4		AMPAL	IPO sp.
5		PANDI	PANDI
6		SIYAN	CASOB
7		CMIRA	AMA sp.
8		CONAR	CYP sp.
9		IPO sp.	
10		XANST	
	RETAINED:	1/3	0/3
Pennsylvania (PA)	Present (PA historical)	2030 (WV historical)	2084 (NC historical)
Weed rank			
1	AMBEL	SORHA	SORHA
2	<b>APCCA</b>	AMA sp.	PANTE
3	<b>SOL sp.</b>	<b>CHEAL</b>	BRAPP
4	<b>MUHFR</b>	<b>ABUTH</b>	CASOB
5	RUB sp.	<b>MUHFR</b>	IPO sp.
6	<b>AGRRE</b>	<b>AGRRE</b>	CYP sp.
7	<b>ABUTH</b>	CYP sp.	<b>SIYAN</b>
8	<b>SIYAN</b>	ASCSY	<b>SOL sp.</b>
9	CONAR	<b>APCCA</b>	<b>ABUTH</b>
10	CHEAL	<b>SIYAN</b>	CYNDA
	RETAINED:	6/10	3/10
S. Carolina (SC)	Present (SC historical)	2030 (LA historical)	2084 (FL historical)
Weed rank			
1	CYNDA	<b>SORHA</b>	<b>PANTE</b>
2	<b>PANTE</b>	ROOEX	DEDTO
3	<b>BRAPP</b>	<b>BRAPP</b>	<b>CASOB</b>
4	<b>SORHA</b>	<b>IPO sp.</b>	<b>SORHA</b>
5	<b>IPO sp.</b>	<b>XANST</b>	<b>XANST</b>
6	<b>CYP sp.</b>	<b>CASOB</b>	<b>IPO sp.</b>
7	<b>CASOB</b>	PANDI	ACNHI
8	PANDI	AMA sp.	<b>CYP sp.</b>
9	<b>AMA sp.</b>	<b>XANST</b>	<b>AMA sp.</b>
10	<b>XANST</b>		DIG sp.
	RETAINED:	3/10	7/10

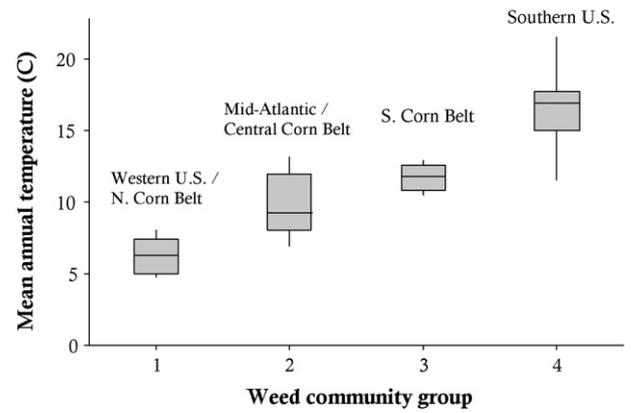


**Fig. 4.** Principal coordinate analysis (PCoA) of troublesome weed communities in maize for all 38 U.S. states surveyed by Bridges (1992). Euclidean distances indicate the degree of similarity between weed communities. Cluster analysis was used to divide the weed communities into four mega-groups based on the first two PCoA coordinates. The general geographic region encompassed by these groups is noted in the figure key.

dissimilarities between states were translated into Euclidean distances with PCoA. The first two coordinates, explaining 35% of the total variance between states, are presented in Fig. 4. Four distinct mega-groups emerge which can be roughly generalized geographically as: (1) Northern Corn Belt/Western U.S., (2) Mid-Atlantic/Central Corn Belt, (3) Southern Corn Belt, and (4) Southern U.S. As determined by average damage rank, the following weed species most strongly characterize each group and are listed in descending order of importance: Group 1: *Panicum miliaceum* L., *Cirsium arvense* (L.) Scop., *Setaria* species, and *Elytrigia repens* (L.) Nevski; Group 2: *A. theophrasti*, *Setaria* species, *Apocynum cannabinum* L., and *Sorghum bicolor* (L.) Moench; Group 3: *S. halepense*, *S. bicolor*, *Ambrosia trifida* L., and *A. theophrasti*; Group 4: *S. halepense*, *Panicum texanum* Buckl., *Ipomoea* species, and *Urochloa platyphylla* (Nash) R.D. Webster. Note that Group 3 shares troublesome weed species with Groups 2 and 4 and therefore represents a region of transition and overlap rather than an entirely unique suite of damaging weed species.

A key point derived from Fig. 4 is that climate differences are non-linear predictors of weed community differences between states. For example, the annual temperature climatology of Tennessee (13.9 °C, TN) is approximately equidistant between Ohio (10.2 °C, OH) and Georgia (17.5 °C, GA). In contrast, from the Euclidean distances separating troublesome weed communities in Fig. 4, it is clear that communities in TN are very similar to those in GA and very different than those in OH. Hence comparable change in climate may have quite diverse, location-dependent impacts on weed community composition.

For predicting the potential impact of climate change on troublesome weed communities in general terms, it is useful to identify climate thresholds that segregate major community types. Fig. 5 presents box and whisker plots for mean annual temperature among states that belong to the four major groups identified in Fig. 4. Despite the very coarse spatial and temporal resolution of state-based mean annual temperature, there is very little overlap between Groups 1, 2, and 4 in Fig. 5. For example, all 12 states with



**Fig. 5.** Box plots of mean annual temperature (°C) for U.S. states that belong to each of the four weed community groups identified in Fig. 4. The middle line in the boxes is the median value with the 25% quartiles indicated by ends of the box and the most extreme values by the whiskers.

mean annual temperatures above 13.2 °C belong to weed Group 4 (i.e. ‘Southern U.S.’). Groups 1, 2, and 4 represent very distinct weed community types, whereas Group 3 shares attributes of Groups 1 and 2 and is less readily distinguished on the basis of annual temperature. Overall, linear discriminant analysis demonstrates that state-based mean annual temperature can be used to correctly predict weed community types for 29 out of 38 states (76% accuracy). The temperature thresholds derived from this analysis suggest proximate weed community transitions at 8.1 °C (Group 1 → 2), 10.8 °C (Group 2 → 3), and 14.1 °C (Group 3 → 4).

3.3. Damage niche range transformations for individual species

Damage niche range rules for *S. halepense* and *A. theophrasti* based on annual precipitation and temperature climatology are reported in Table 3. These species are troublesome to maize production primarily in the eastern half of the U.S., with *S. halepense* damage to maize restricted to regions where mean annual temperatures exceed ~10.5 °C and *A. theophrasti* restricted to regions below ~12.4 °C. Based on the range rules presented for these species in Table 3, the historical distribution of the damage niche in the conterminous U.S. and projected future distributions under a ‘business-as-usual’ climate change scenario for 30-year climatology centered on 2030 and 2084 are presented in Figs. 6 and 7.

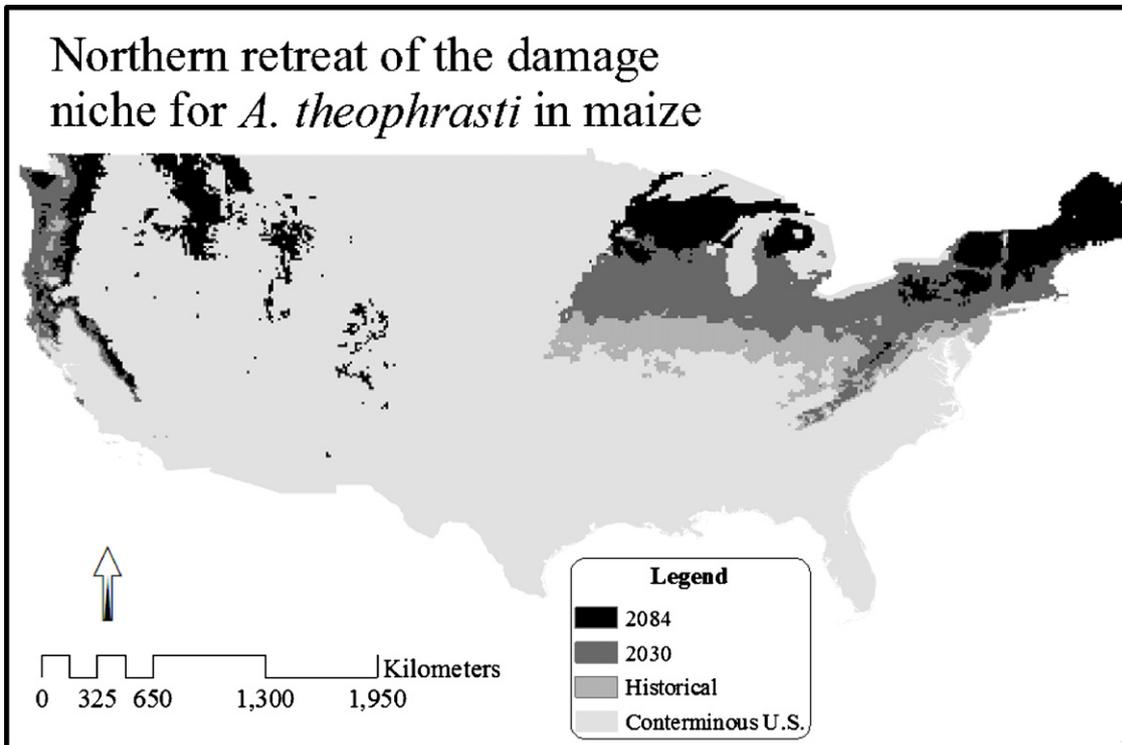
At present, *A. theophrasti* is damaging to maize production across the Great Lake States, Corn Belt, Mid-Atlantic, and Northeastern States. For 2030, our projections suggest a 100–300 km pole-ward migration of conditions that favor *A. theophrasti* damage to maize. Near the end of this century, this pole-ward retreat may extend approximately 200–650 km north of present-day boundaries and *A. theophrasti* may only be damaging to maize in the northern portions of the Northeast (i.e. Vermont, New York) and in the Great Lake States (i.e. Minnesota, Wisconsin, Michigan).

In contrast to *A. theophrasti*, *S. halepense* will likely expand its historical range of damage to U.S. maize with projected changes to

**Table 3**

Damage niche range rules for *A. theophrasti* and *S. halepense*. These rules define the range of annual climate conditions (30-year averages for precipitation and temperature) where these weed species have historically been judged troublesome to maize production. In parentheses are the U.S. state abbreviations for the geographic sources of the climate values that set the range limits for each species.

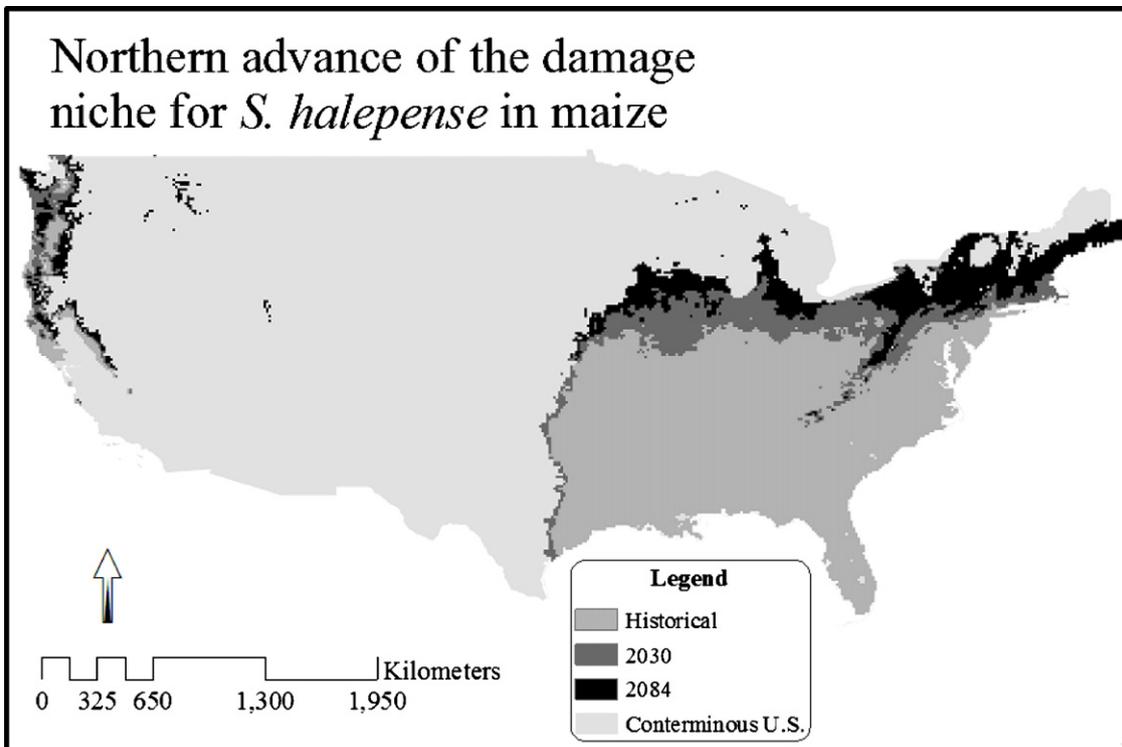
	Maximum temperature (°C)	Minimum temperature (°C)	Maximum precipitation (cm)	Minimum precipitation (cm)
<i>A. theophrasti</i>	12.4 (MO mean)	3.7 (WI minimum)	129.4 (NJ maximum)	80.3 (MI mean)
<i>S. halepense</i>	24.5 (FL maximum)	10.5 (WV mean)	161.7 (LA maximum)	94.1 (IL mean)



**Fig. 6.** Historical and projected distribution of the damage niche for *A. theophrasti* in U.S. maize cropping systems. Projections are for climatology centered on 2030 and 2084 under a 'business-as-usual' GHG emission scenario. Towards the end of the century, the damage niche for *A. theophrasti* may experience a pole-ward retreat of approximately 200–650 km north of present-day boundaries.

climate. At present, *S. halepense* is not judged troublesome in the Northern Corn Belt, Northeastern States, or Great Lakes States. In coming decades, the damage niche will likely extend through much of the Corn Belt and into southern portions of the

Northeastern States. By the end of the century, the damage niche will encompass much of the Northeast and southern parts of the Lake States. Overall, the pole-ward advance of the *S. halepense* damage niche will likely extend from 200 to 600 km beyond its



**Fig. 7.** Historical and projected distribution of the damage niche for *S. halepense* in U.S. maize cropping systems. Projections are for climatology centered on 2030 and 2084 under a 'business-as-usual' GHG emission scenario. Towards the end of the century, the damage niche for *S. halepense* may experience a pole-ward advance of approximately 200–600 km north of present-day boundaries.

historical boundaries towards the end of the century under the 'business-as-usual' GHG emission scenario.

Species distributions do not conform to political boundaries and it is clear that in several states where a species has been judged troublesome that this designation does not hold for every location within that state. The opposite is also true, with some species not considered troublesome at the state-scale that are damaging to crop production in smaller regions within a state. For mapping the historical extent of the damage niche, our method results in predictions that alternately appear to both over and under-predict the geographic range of the damage niche. In the case of *S. halepense*, our rule encompasses 86% of the land area in states where this species was judged troublesome; on the other hand, approximately 21% of the overall extent is in states where *S. halepense* is not currently judged damaging to maize. These projections may prove to be an accurate depiction of reality, but this cannot be assessed without weed survey data at a finer scale than what is provided by Bridges (1992). Hence, our projections of historical and future damage ranges are best viewed in a comparative sense and not as precise predictions.

#### 4. Discussion

It is important to emphasize that the results of this study suggest how the geographic distribution of troublesome weeds in U.S. maize will *potentially* evolve in a changing climate. Many factors other than climate substantially influence *actual* species distributions including competitive exclusion (Mack, 1996; Davis et al., 1998a,b), dispersal limitations (Lawton, 2000), and patterns of disturbance (Guisan and Thuiller, 2005). That acknowledged, annual cropping systems have several attributes that may make climate considerations particularly important for predicting future weed distributions. Activities such as tillage and crop harvest are relatively uniform and predictable perturbations. Ecosystems with high levels of disturbance are more vulnerable to colonization by newly introduced plant species and are likely to reach a comparatively rapid equilibrium with emergent climate factors (Hobbs and Huenneke, 1992; Milchunas and Lauenroth, 1995). Further, weed dispersal processes are facilitated by the high level of habitat continuity in major cropping systems like maize production in the U.S. and also by vectors like tillage, manure spreading, and seed exchanges that facilitate seed movement within and between farms (Cousens and Mortimer, 1995). Moreover, many weed species that are climatically favored to become troublesome in new regions are already present in the landscape, even though they are not damaging at present (see Fig. 1). For these species, dispersal processes will not limit damage niche range transformations in a changing climate.

There are, however, other challenges to predict the potential impact of climate changes on agricultural weeds that must be acknowledged. Agronomic practices for particular crops are not static in time and space; new classes of herbicides, cultivars, tillage innovations, use of irrigation, and seed cleaning practices can all influence the geographic distribution and crop damage caused by agricultural weeds (Salisbury, 1961; Froud-Williams et al., 1984; Clements et al., 1996). For example, evidence suggests that the recent introduction of glyphosate resistant crops can significantly change weed community composition (Harker et al., 2005). Since the development and use of different agricultural practices is highly unpredictable, there is an inherent element of uncertainty to the use of bioclimatic envelopes or space-for-time substitution for projecting future weed distributions. Also, the possibility that agricultural weed populations will evolve new traits in response to emerging climate and non-climate selection pressures cannot be discounted (Clements et al., 2004). Perhaps most importantly, biogeographic methods do not account for the impact of evolving

atmospheric chemistry on competitive interactions. Any environmental change that differentially affects the morphology, growth, or reproduction of interacting plant communities has the potential to modify the spatial extent of the damage niche (Patterson, 1995; Bunce, 2001). However, since maize possesses the  $C_4$  photosynthetic pathway and does not respond dramatically to  $CO_2$  enrichment, it is likely that most weed species will either become more competitive ( $C_3$ ) or maintain similar competitive abilities ( $C_4$ ) at elevated  $CO_2$  concentrations (Patterson, 1995; Patterson et al., 1999). Hence, if a weed is presently characterized as damaging to maize under a certain set of environmental conditions, it is likely that it will remain so as atmospheric  $CO_2$  increases.

Potential changes in the weed biogeography of agricultural systems pose a challenge to management, but also an opportunity. If weed species can be identified as favored due to emergent climate conditions in a given region, nascent populations can be targeted for control before they become well established. This study can be viewed as a 'proof of concept' and a first step towards developing this type of information for major cropping systems. Finer-scale survey data for the present-day geography of weed damage would enable more quantitative and spatially resolved predictions of potential range transformations in a changing climate.

#### 5. Conclusion

With U.S. maize as a model system, our results suggest that the community composition of damaging agronomic weeds may be fundamentally transformed by climate change. In some U.S. states, potential changes in coming decades are similar to those possible by the end of the century. Regions such as the Northeastern U.S. may prove particularly vulnerable, with future climates projected to favor few weed species of present-day significance. Other regions are likely to experience rather minor weed community shifts, even with a similar magnitude of climate change. For a given region, potential community impacts appear to be chiefly contingent on proximity to climate transition zones that separate major weed community types. For individual species, pole-ward migration of the damage niche may be on the order of 200–600 km by the end of the century. If weed species can be identified as favored due to emergent climate conditions in a given region, expanding or newly introduced populations can be targeted for control before they become well established. The accuracy of these types of projections can be refined by collecting finer-scale survey data for troublesome weeds species in major cropping systems.

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