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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.

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_2 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_2 (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

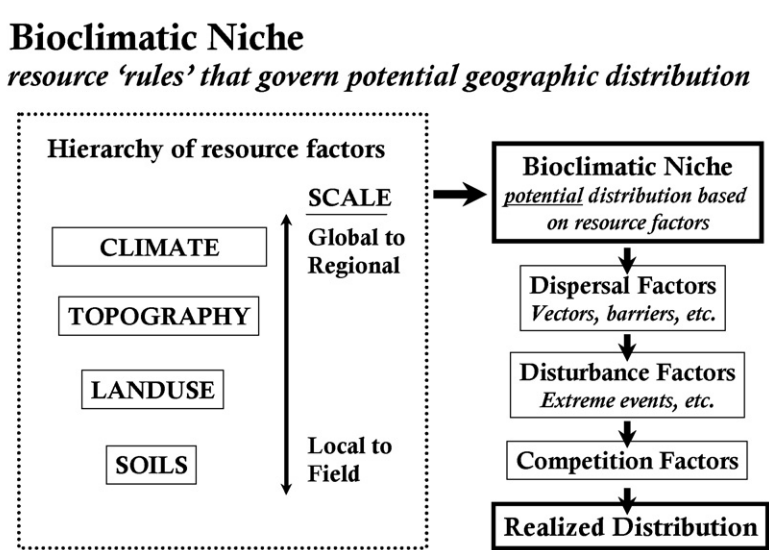

Fig. 1. Hierarchy of resource factors that determine the bioclimatic niche. The bioclimatic niche establishes the potential geographic range for a species. The realized range of a species is influenced by factors such as dispersal, disturbance, and competition processes.