Journal of Integrated Pest Management, (2024) 15(1): 3; 1–7
https://doi.org/10.1093/jipm/pmad029
Issues

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Agricultural issues with climate change—case studies with 3 soybean pests: Johnsongrass, kudzu bug, and charcoal rot

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Subject Editor: Jeffrey Davis

Received 9 May 2023; Editorial decision 15 November 2023

Agricultural production and crop yields are threatened around the world by the emergence and spread of agronomical pests, including diseases, insects, and weeds. Due to changes in precipitation, carbon dioxide levels, and warming temperatures being experienced throughout most of the world, new challenges are emerging for pest management in virtually all major cropping systems. While precise environmental impacts due to climate change are impossible to predict, they will require innovative and new solutions for pest management. In this article, we explore the challenges of 3 problem pest species with soybean: Johnsongrass, kudzu bug, and charcoal rot. Understanding pest responses to climate change is vital for better understanding the new agricultural innovations that will be required to manage them in the future.

Key words: soybean, climate change, Johnsongrass, kudzu bug, charcoal rot

With a growing global population, farmers will need to produce 60% more food than they do today (FAO 2023). However, food production is threatened by the emergence and spread of agronomic pests, including diseases, insects, and weeds, which threatens crop yields worldwide. Commerce among countries fuels the introduction of novel organisms to new regions (Chapman et al. 2017, FAO 2023). The global online trade in seeds and live plants, for instance, is a potent source of pest plant introduction into the United States, and accidental or intentional mislabeling of plants is very common (Oele et al. 2015). Despite the efforts of plant protection officials, insects enter on numerous materials, such as dry goods, wood packaging, cargo containers, cut flowers, and live plants, and pathogens are introduced on live plants, wood, produce, and seeds (Work et al. 2005, Chapman et al. 2017, Ristaino et al. 2021). Thus, as international travel and global commerce continue to increase, invasive pests are expected to continue to spread to areas outside of their native range, further impacting larger and developing agricultural areas (FAO 2023).

With the current changes in climate changes (e.g., rising sea levels, shrinking glaciers and accelerating ice melt in Greenland, Antarctica and the Arctic, and shifts in flower/plant blooming times, etc.) being experienced throughout most of the world, new challenges are emerging for pest management in virtually all major cropping systems (IPPC Secretariat 2021, Clements and DiTommaso 2022). For example, regional warming, droughts, intense storms, and other extreme weather events are likely to cause direct changes to pest phenology, natural enemy interactions, population dynamics, and even distribution of pests (Juroszek and Von Tiedemann 2013, Finch et al. 2021, IPPC Secretariat 2021). More frequent and intense extreme weather events are already becoming apparent, favoring both short- and long-term dispersal of invasive species (Solomon 2007, Finch et al. 2021). Wind and storms can transport insects, plant propagules, and pathogen spores over long distances (Stinner et al. 1983, Jarnevich et al. 2014, Rieux et al. 2014, Harvey et al. 2023). In a review of global plant pest observations from the 1960s to 2010s, Bebber et al. (2013) found that pest movements were observed ~2.7 km/yr poleward from previous reports. This contributed to a significant trend for increased pest presence at higher latitudes. While precise environmental impacts with climate change are impossible to predict, they will require innovative and new solutions for pest management.

Aside from climate change impacts on pest pressures, environmental changes have the potential to affect the field performance of crops of all types. Increases in temperature and carbon dioxide (CO_2) can cause increased crop yields in some locations and decreases in others. The temperature optima for growth and reproduction of any crop will strongly influence the impacts from increased aerial and soil temperature growth and reproduction (Hatfield et al. 2014). Warming of significant magnitude may benefit the types of crops that are typically planted in already warm areas, or it might force farmers to shift to crops that respond positively to higher temperatures. No matter the crop, cultural practices, planting dates, and yields will be impacted. Soybean (*Glycine max* (L.) Merr.) yield loss, for example, is expected to experience between 3% and 6% yield loss for each 1 °C rise in global mean temperature (Zhao et al. 2017, Silva et al. 2023). This estimate does not consider the other climate-related factors that can impact crop yield such as extreme weather events and pest pressure.

Climate change is an unpredictable driver of the growth environment, pest modifications, and interactions between the 2 factors, and environmental and pest interactions will likely differ among crop species. In this article, we explore the complexities of 3 problem pest species with. Soybean was selected as a target crop because of its agricultural importance in the United States. In 2022, soybean was grown in 29 states and harvested from 86.3 million acres, with a value totaling 61.1 billion USD, making the United States as one of the world's top producers and exporters of soybean (USDA-NASS 2023a, 2023b).

The 3 pests to be considered are the weed [Johnsongrass (*Sorghum halepense* L. Pers.) (Poales: Poaceae)], the insect [kudzu bug (*Megacopta cribraria* F.) (Hemiptera: Plataspidae)], and the soilborne fungus [charcoal rot (*Macrophomina phaseolina* (Tassi) Goid.) (Botryosphaeriales: Botryosphaeriaceae)]. Unfortunately, not all pests have as much climate response data as would be preferred. For example, Johnson grass is an exotic invasive grassy weed that has been researched going back to 1983 (Warwick and Black) and is predicted to respond to warming temperatures by moving into agricultural areas previously uninhabitable by this plant (Warwick and Black 1983, McDonald et al. 2009). Kudzu bug, though it attacks only soybean and the invasive and pervasive weed kudzu [*Pueraria montana* (Lour.) Merr.] and early-planted soybean, this pest is still considered a serious threat to soybeans in the South (Amarasekare and Link 2023). Charcoal rot is a disease with a broad range and few management options. It is also understudied in relation to potential climate impacts on this organism. But as a soilborne fungus, it can be used as a model for other soilborne fungi and can give the reader an idea of the concerns related to how climate is expected to influence other similar soilborne fungi. While these are only 3 examples of the types of pests soybean farmers face, the brief case studies may provide an assessment framework that can help inform the agricultural community as it continues to adjust to ever-changing climatic challenges.

Johnsongrass

Johnsongrass, *Sorghum halepense*, is a perennial C_4 grass native from southeastern Europe to India (Warwick and Black 1983). It is a natural hybrid between the crop plant sorghum (*S. bicolor*) and the Asian species *S. propinquum* (Sezen et al. 2016). Johnsongrass was introduced into the United States as a potential forage grass and has also been unintentionally introduced in sorghum seed lots (Warwick and Black 1983, Sezen et al. 2016). It spreads aggressively by seeds and rhizomes in agricultural systems, natural areas, and grasslands (Warwick and Black 1983, Sezen et al., 2016, Klein and Smith, 2021). It forms dense, spreading patches that smother other plants, and its rapid growth depletes soil of nutrients and causes significant yield reductions in soybean, sugarcane (*Saccharum officinarum* L.), and maize (*Zea mays* L.). Seeds are spread by water, wind, agricultural equipment, ingestion by animals, and in contaminated hay and grain (Warwick and Black 1983). Its success as a weed is due in part to its rapid growth rate, rhizomatous growth, regeneration from cuttings, prolific seed production, and tolerance to disturbance (Warwick and Black 1983, Sezen et al. 2016).

Johnsongrass has been recognized as a weed in most tropical and temperate areas of the world (Klein and Smith, 2021). While rhizomes appear sensitive to both extremely high and low temperatures (Warwick and Black 1983, Rosales-Robles et al. 2003), its movement is generally limited by lack of cold tolerance of rhizomes to freezing temperatures (−3 °C). Nonetheless, Johnsongrass is advancing northward in North America, likely due to genetic variation, as well as warming due to climate change (Warwick et al. 1986, McDonald et al. 2009, et al. 2016). It is now appearing in Canada (Klein and Smith 2021), where its spread has been attributed mainly to the typical seed dispersal paths (e.g., water, wind, agricultural equipment, ingestion by animals, in contaminated hay and grain, etc.) (Warwick et al. 1986). Additionally, it has been spreading north in Austria and Germany since the 1990s (Follak et al. 2017, Klein and Smith 2021).

Vinall (1926) reported that the species was adapted to conditions south of 38° latitude in North America, but by 1971, it overwintered at 40°, and then at 43° latitude by 1979 (Warwick and Black 1983). It has since been observed in Canada at 45° latitude (GBIF 2023). It has been predicted that climatic suitability for Johnsongrass will markedly increase in many areas by 2100, but perhaps most in the upper Midwest and Great Plains regions of the United States (Lakoba 2021).

Johnsongrass costs US farmers tens of millions of dollars annually in control programs and yield losses (Sezen et al. 2016). A survey of Johnsongrass impact to soybean and cotton (*Gossypium hirsutum*) crops in Arkansas, Louisiana, and Mississippi concluded that infestations cost farmers approximately $5.8 million in cotton and $23.7 million annually in soybean yield reductions (McWhorter 1993). Field studies in soybean showed that 6 wk of Johnsongrass competition reduced soybean yield up to 38%, 7 wk of competition reduced yield up to 69%, and full-season competition reduced soybean yield up to 88% (Williams and Hayes 1984). In another field study, Johnsongrass infestations reduced soybean yields by more than 50% at densities typically found in the southeastern United States (McWhorter and Hartwig 1972).

Physiologically, the climate changes we are already experiencing can potentially influence growth and competitiveness of plant species in 3 general ways, which can help to explain how Johnsongrass competitiveness might change in future years (Ziska and George 2004, Landau et al. 2022). One way is the direct impact of increasing temperatures on plant metabolism and growth processes. Different plant species have very different growth optima and tolerance ranges, and responses in the field may not always be as expected. In one study in soybean, for example, increased temperature from 20.1 to 22.6 °C during the growing season had little impact on yield, evidently because the temperature remained within the acceptable soybean performance range (Piper et al. 1998). The second is a direct impact of increasing atmospheric CO_2 concentrations on photosynthesis, that is, carbon fixation rates. Plants that are C_3 are more likely to have increasing photosynthetic rates with increasing CO_2. An early example of this comes from a 1984 study of Johnsongrass in competition with soybean (Patterson et al. 1984). The results showed that under higher CO_2, growth of soybean was enhanced more than that with Johnsongrass. Still, increasing CO_2 impacts can lead to unforeseen consequences. In soybean experiments with high CO_2, protein and nitrogen contents were reduced, resulting in a loss of quality (Wang et al. 2015). The third most likely impact of climate change on plant species is on water use. It is widely accepted that C_4 plants like Johnsongrass are more efficient water users (Patterson et al. 1984, Morgan et al. 2011, Shi et al. 2018).

Plants using the C_4 metabolic pathway typically respond more positively to higher temperatures. Because Johnsongrass is a C_4 plant, the logical expectation with climate change is that its photosynthetic rate will not be greatly impacted by the higher atmospheric CO_2, but that it will grow more vigorously with increasing temperatures, just as observations suggest is happening with its northern geographical movement. Furthermore, as a C_4 plant, Johnsongrass will have greater resilience to lowered moisture conditions and increasing frequency of periodic droughts. At least physiologically, it is very likely that Johnsongrass vigor in the field will increase with climate change (Klein and Smith 2021).

The potential problems with drought as the climate changes are particularly troublesome for agricultural production in many parts of the United States. Since 1901, precipitation rates in the United States have increased by about 4% in the Midwest plains and the northeastern United States, but it has generally decreased in the Southwest and Southeast (Easterling et al. 2017). The agricultural areas in the Southwest have been particularly hard hit by drought for many years. Total precipitation, however, is not always the key agricultural issue. A major problem is that there have been substantial changes in seasonal consistency of rainfall. Too much winter and spring rain in the Midwest, for example, causes severe delays in planting and shortens growing seasons. Dry periods in late summer and early fall cause lowered grain yields (Yu et al. 2018, Liu et al. 2020).

On balance, the primary environmental drivers of climate change on agricultural productivity are heat and irregular or limited water (Ramadas and Govindaraju 2015, Peña-Gallardo et al. 2019). With the heat resilience of Johnsongrass and its improved water use efficiency, the most likely agricultural future is that Johnsongrass will become more competitive in US agriculture. Any advantage gained with increased photosynthesis by C_3 crops (e.g., soybean) probably will not offer a competitive advantage as great as those with temperature response and water use efficiencies inherent to C_4 Johnsongrass.

No matter which of the projections about climate change impacts on crop plants proves more accurate, it seems apparent that the threat of weeds in US agriculture likely will become greater with time. A 2004 review concluded that the growth responses of numerous noxious weeds in the United States are projected to increase ~60% due to increased CO_2 (Ziska and George 2004). Additionally, changes in rainfall are likely to affect herbicide uptake and distribution in plants and soil, which will affect weed control and crop yield (Clements and DiTommaso 2022, Landau et al. 2022). If crop weeds perform as expected in the higher carbon, warmer future, chemical, and mechanical control of such weeds may become more difficult and costly (Ziska and George 2004). Additionally, Johnsongrass is exhibiting some resistance or tolerance to some commonly used herbicides (Heap 2023), making control more costly and less effective. The movement of weeds such as Johnsongrass northward is likely to cause increased yield losses in crops and, subsequently, an increase in management costs (McDonald et al. 2009).

Kudzu Bug

Kudzu bug, *Megacopta cribraria*, is native to southeastern Asia and Australia (Lahiri and Reisig 2016) and was first discovered in the United States in Georgia in 2009 (Suiter et al. 2010). Two years after its discovery, kudzu bug had spread to most of Georgia and South Carolina and much of North Carolina (Zhang et al. 2012). Since then, it has been found as far north as Maryland and as far west as Texas (Grant et al. 2014, Merchant 2020). The movement of kudzu bug from its initial place of discovery in Georgia to its expansion to the east and northeast could be attributed, in large part, to the climatic La Niña weather patterns in 2011 (Blunden and Arndt 2012, Gardner et al. 2013). Long distance dispersal of adult kudzu bugs is likely due to changes in jet stream air currents like those occurring during this time, which are known to transport insects over variable distances (Gardner et al. 2013).

Kudzu bugs feed primarily on kudzu [*Pueraria montana* (Lour.) Merr.] and soybean (Suiter et al. 2010), but they have been found to feed on other hosts. Through DNA extraction from adults, it was found that kudzu bugs feed on peanut (*Arachis hypogaea* L.), walnut (*Juglans* sp.), lettuce (*Lactuca sativa* L.), lespedeza (*Lespedeza* sp.), sweet gum (*Liquidambar styraciflua* L.), black medic (*Medicago lupulina* L.), white sweet-clover (*Melilotus albus* Medik.), pine (*Pinus* sp.), red oak (*Quercus rubra* L.), tomato (*Solanum lycopersicum* L.), and sorghum (*S. bicolor* (L.) Moench) (Lovejoy & Johnson 2014). Developmental hosts include kudzu, soybean, and pigeon pea (*Cajanus cajan* (L.) Huth) (Zhang et al. 2012, Del Pozo-Valdivia and Reisig 2013, Blount et al. 2015). Adults and nymphs suck the sap from the new growth of leaves, petioles, and stems, causing reduced photosynthesis, underdeveloped pods and seeds, and yield loss (Wang et al. 1996, Eger et al. 2010). Yield reduction of up to 60% has been found in soybean (Seiter et al. 2013).

Three generations per year have been reported in China (Wu et al. 2006), while 2 generations per year have been reported in the United States (Zhang et al. 2012, Grant and Lamp 2018). For eggs to hatch, they require 80 Celsius degree-days (CDD) at a minimum temperature of 14 °C, while nymphs require 545 CDD with a minimum temperature of 16 °C for development (Grant and Lamp 2018). First-generation kudzu bugs can complete their development on kudzu and early-planted soybeans at the beginning of summer (Del Pozo-Valdivia and Reisig, 2013, Gardner et al., 2013), while the second generation develops primarily on soybean or kudzu later in the summer season (Greene et al., 2012). Zhang et al. (2012) found early-instar nymphs around the same time second-generation adults were emerging, indicating a partial third generation may occur later in the season. Depending on temperature and location, females have been reported to lay up to 274 eggs in their lifetimes, with development time from egg to adult lasting 6–8 wk and adult longevity lasting upwards of 7 wk (Eger et al. 2010, Greene et al. 2012, Del Pozo-Valdivia and Reisig 2013). Adults overwinter in any location that provides refuge, with common refuges being under bark, leaf litter, or inside homes, and they emerge in the spring (Greene et al. 2012).

Increased seasonal temperatures can result in accelerated insect development, movement, abundance, and survival and increased geographic range (Bale et al. 2002). Because global temperatures are rising during the winter in North America, particularly in the higher latitudes (Vose et al. 2017), freezing temperatures and snow may become less common, with the number of freezing days decreasing by approximately 90 days across parts of coastal western Canada and the United States (Rawlins et al. 2016, Burakowski et al. 2022). Some experts predict that winter warming will increase by 3 °C by the end of the century (IPCC 2013). Rapid winter warming may extend the range of kudzu bug through southeast Pennsylvania into Massachusetts (Grant and Lamp 2017). Because spring temperatures are increasing as well (EPA 2023), kudzu bugs may emerge and oviposit sooner. In general, rising temperatures may lead to an increase in the number of generations per year for this species (Tobin et al. 2008).

Kudzu bug is a relatively new introduction into North America (Suiter et al. 2010), and few climatic studies are available. However, with the understanding that climate change is also increasing the number of days with extreme summer temperatures (IPPC 2013, Ma et al. 2021), we can make some predictions about how kudzu bug may be impacted. Over the next several decades, high temperatures will occur more frequently and last longer (Meehl and Tebaldi 2004, IPPC 2013). In insects, elevated temperatures and environmental changes induce heat shock proteins (HSP) (King and MacRae 2015), which act to protect insects from thermal damage, ultraviolet radiation, drought and dehydration, and biotic stresses (Zhao and Jones 2012). High-temperature stress studies on kudzu found multiple HSP, of which 3 are linked to insect temperature adaptability (Chen et al. 2014, Cui et al. 2019) and 5 linked to increase insect temperature tolerance (King and MacRae 2015). Knowing that kudzu bugs prefer warm humid climates (Wang et al. 1996), such as those in their native range, it is likely this pest will remain a problem in the Southern United States and poses a higher invasion and establishment risk in new geospatial regions with mean winter temperature above 0 °C (Wiens and Graham 2005, Wanwan et al. 2018). Kudzu bug is susceptible to many of the insecticides currently used on stink bugs and other soybean pests, with pyrethroids offering the best control (Greene et al. 2012, Seiter at al. 2015), though these broad-spectrum insecticides also kill predatory insects and other beneficials and work against an acceptable integrated pest management (IPM) strategy (Lahiri and Reisig 2016). Early-planted soybeans, conventionally tilled fields, and soybeans planted in narrow rows are more susceptible to kudzu bug infestations (Lahiri and Reisig 2016). Alternative pest management options are also available, including cultivation practices such as adjusting planting dates, tillage, row spacing, and crop rotation can help manage these pests but are not always suitable due to certain financial limitations growers face (Lahiri and Reisig 2016). Four soybean varieties have been identified to display resistance to kudzu bug (Bray et al. 2016, Fritz et al. 2016), although the mechanism of resistance is not well understood (Lahiri et al. 2020). Many growers are choosing not to plant these resistant varieties. This is in large part because they are more concerned with managing the far more costly seed feeding complex of stink bug (Hemiptera: Pentatomidae), which represented yield losses of 0.8% and management costs of ~$2.48/ac, comprising 28% of all combined insect costs losses (Musser et al. 2022).

Kudzu big remains an important pest of soybean in the southeastern United States and has the potential to become a significant pest and economic drain for farmers in the upper Midwest as average winter temperatures continue to rise (Wanwan et al. 2018). Early detection in areas that do not currently have kudzu bug infestations is an important part of a sound IPM plan for managing this pest in the future.

Charcoal Rot

Charcoal rot, caused by *Macrophomina phaseolina*, is a primarily soil-inhabiting fungal pathogen that affects over 75 plant families and about 500 plant species, including soybean, sorghum, cotton (*Gossypium hirsutum* L.), peanut, and other important food crops worldwide (Su et al. 2001, Gupta et al. 2012). It was first reported in India in the mid-1930s, where it remains one of the most significant barriers to sorghum production during the post-rainy season (Madhusudhana 2019). This disease causes significant economic losses in many countries around the world. In the United States, it is widely reported as an economic issue across the country, particularly in the southern states of Texas and Georgia (Wyllie and Scott 1988).

In the early to mid-2000s, charcoal rot was reported consistently as one of the top 5 yield-reducing diseases of soybean across the eastern United States (Allen et al. 2017), with an estimated yield loss of ~1.9–2.0 million metric tons, depending on the year (*in* Romero Luna et al. 2017). Yield loss due to charcoal rot varies among years primarily due to both the fact that it is commonly misdiagnosed and that climate factors impact the severity of the disease (Romero Luna et al. 2017).

The charcoal rot fungus survives in the soil as hard, black fungal structures, called microsclerotia, which germinate between 20 and 40 °C and infect root tissue seedlings, and young and mature plants (Collins et al. 1991). Plants can be infected at any time during the growing season, although temperatures of 25–30 °C and extended periods of dry weather (soil moisture below 60%) are optimal for disease development (Pearson et al. 1984, Diourte et al. 1995, Smith and Carvil 1997). The charcoal rot fungus typically infects seedlings and remains in the plant tissue until conditions are optimal, usually when additional stress on the plant makes it more susceptible to the pathogen (Gupta et al. 2012). Under conducive environmental conditions (primarily hot and dry), the charcoal rot fungus infects the vascular system, interfering with normal plant functions, including water and nutrient transport, and causing the common disease symptoms of wilting and premature leaf death (Mengistu et al. 2011). The fungus overwinters as microsclerotia in residue of host tissues and can survive for at least 2 yr in dry soil, although pathogenicity has been reported to decrease after 6 months (Reis et al. 2014). After plants are harvested, microsclerotia in the plant residue return to the soil.

At present, there is no reliable method for controlling charcoal rot, and effective disease management requires an integrated approach. While the use of chemical fungicides is a potential management tool for charcoal rot (Shoaib et al. 2022), the high economic cost of chemical fungicides, as well as their potentially harmful effects on the environment, farm workers, and other organisms that may encounter them have tremendous negative implications. With integrated and sustainable agriculture in mind, such approaches should be avoided when possible, and other integrated management approaches are encouraged.

Due to the wide host range of the charcoal rot fungus, crop rotation is not considered a reliable management strategy. Cultural practices which enhance shredding of crop residue and burial through tillage practices may increase the rate of wood degradation or colonization by saprophytic fungi that reduce the relative longevity of the charcoal rot fungus in debris (Gupta et al. 2012). Implementation of no-till or strip-till systems to increase soil microbial activity and conserve soil moisture has been reported to reduce charcoal rot incidence. Irrigating soybean to reduce drought stress can limit yield losses due to charcoal rot, even though losses may still range from 6% to 30% (Mengistu et al. 2011). Research has been focused on breeding for resistance, but to date, only a few soybean cultivars from maturity groups IV and V have shown resistance to drought and charcoal rot (Romero Luna et al. 2017), Due to the other IPM options available, growers should utilize current planting and cultural strategies (row spacing, fertility and tillage practices, irrigation, etc.) and weeds control and reduce stress where possible to reduce the negative impacts of this disease.

There is a deficit of literature on how climate change might impact soilborne diseases (Allen et al. 2017, Zhao et al. 2017); with a few articles focused on belowground organisms or processes, only a small fraction of those address the effects of environmental changes (Allen et al. 2017). Also, there is a lack of research on how climate change might impact charcoal rot, specifically. Increases in air and soil temperature and elevated CO_2 will influence soil organisms both directly and indirectly (Pritchard 2011, Delgado-Baquerizo et al.

2020). It is logical to surmise that this fungus will respond similarly. An increasing concentration of CO_2 in the atmosphere is unlikely to directly affect soilborne pathogens, although changes in soil community composition are likely to occur (Pritchard 2011). A warmer environment (i.e., fewer frost dates, warmer mean winter temperatures) likely means that the disease will overwinter more effectively and is more likely to spread north, as has already been reported for charcoal rot (Bebber et al. 2013).

Conclusion

In conclusion, higher temperatures, extreme weather events, and changes in precipitation are likely to result in the spread of many plant pests (Rosenzweig et al. 2000, Finch et al. 2021). The climatic changes are predicted to be especially beneficial to the competitiveness of some C_4 weeds and invasive insects, as warmer temperatures can positively impact their phenology, dispersal, and survival (Bale et al. 2002, Deutsch et al. 2008, Finch et al. 2021). Climate impacts on soilborne pathogens have been underexamined, but managing them can be even more difficult than their aboveground counterparts, in that they are more difficult to detect before serious damage occurs and control measures are often impractical (Chester 1950, Dixon and Tilston 2010). Understanding pest population responses to climate change is vital for better understanding and predicting the most likely pest/crop dynamics and the new agricultural innovations that will be required to manage them in the future.

Funding

Funding from Environmental Defense Fund provided partial support for this paper.

Author Contributions

Danesha Carley (Conceptualization [Lead], Project administration [Lead], Writing—original draft [Equal], Writing—review & editing [Equal]), Jennifer Cook (Project administration [Supporting], Writing—original draft [Equal], Writing—review & editing [Equal]), and Sherrie Emerine (Writing—original draft [Equal], Writing—review & editing [Equal])

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