Climate Resilient Potato Systems for the 21st Century and Beyond

Brett A. Lynn

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by

Brett Allan Lynn

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Brett Allan Lynn, D.P.H.

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Advisor: Gary L. Hein

Climate change's effects will dramatically reshape food systems and food security in the twenty-first century and beyond. Given potato's susceptibility to heat and drought, climate change is poised to disproportionately affect potato production. Globally, potato is the fourth most important crop and yields a higher caloric density than any other commercial crop. Thus, disruptions to potato production bear serious implications for global food security.

In the United States, considerable potato production occurs in the arid West, which already faces water scarcity. This scarcity is anticipated to increase in many areas due to climate change. In addition to scarcity, growers will face a concomitant increase in evapotranspiration as temperatures continue to rise. Consequently, a need exists for growers to judiciously irrigate to protect yields and conserve water. Fortunately, irrigation technologies and strategies already exist to increase water use efficiency, and additional technology is under development.

Climate change's threats to potato production are not limited to direct meteorological effects (i.e., water scarcity). Nefarious potato pests, such as Colorado potato beetle, are anticipated to thrive under climate change. Increasing temperatures

could result in range expansion and additional generations in areas currently occupied by these pests. The increased pest pressure increases the potential for pesticide resistance caused by historical overreliance on pesticides. Increased pest pressure and pesticide resistance necessitate growers abandon the historical unilateral chemical approach and embrace integrated pest management.

Implementing the system-level changes necessary for successful adaptation will be difficult and requires experts with a broad understanding of potato production systems. Plant health practitioners possess the experience and education to identify risks and develop system-level solutions to mitigate the deleterious agronomic, social, and economic effects caused by climate change. This document provides an in-depth analysis on prospective threats and potential solutions through the lens of a practitioner’s experiences in Michigan and Texas potato production.

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Preface

Agronomic and genetic advances have steadily increased potato yields from the mid-twentieth century and into the twenty-first century. Climate change is poised to subvert these advances and potentially reverse course if left unchecked. Researchers and pundits frequently dissect climate change's individual elements and potential impacts. Collectively, elements comprising climate change will deliver devastating blows to global food security. However, it is improbable a single element will be responsible for threatening food security and undermining potato production. Climate change will present new threats, albeit the greatest threat will be the exacerbation of contemporary plights. As such, climate change is best conceptualized as a force multiplier.

Climate change was brought to the forefront of the author's mind while in the Texas Panhandle near Dalhart, TX. The evening of July 4th, 2021, an isolated thunderstorm passed through the area. Rapid storm development is not uncommon on the High Plains; however, this storm cell would prove unique. Potato fields in early bulking, with lush vines providing full groundcover were pulverized. Defoliation approached 100 percent in the worst fields. Conversely, fields several miles to the North were spared.

The author had encountered severe weather in the Upper Midwest while in central Michigan the previous summer; however, weather was largely attenuated by Lake Michigan. Storms developed slower, and damage was of a much lower magnitude. The stark contrast between weather events yielded more questions than answers. Were the disparate weather events due to disparate climate types? Would severe weather frequency increase in the years to come? Was the contrast in weather attributable to climate types? How will climate change affect potato production?

The tragedy experienced in Texas and the author's unanswered questions serve as the impetus for this document. Chapter 1 discusses the definition of climate change, climate change projections, and the implications for potato ecophysiology. Later, climate change serves as backdrop for discussions on potato irrigation (Chapter 2) and pest management (Chapter 3).

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Chapter 1 – Potato Production and Potential Impacts of Climate Change

Introduction

Arguably, no other force poses a greater threat to global food security than climate change. Potatoes will be no exception. However, the specific consequences remain unclear to many because climate and climate change remain shrouded in ambiguity from years of misconceptions. This ambiguity presents barriers to food system adaptation because stakeholders may not agree upon the underlying causes or threats. As such, establishing common definitions for climate and climate change is a requisite for climate-based decision making.

Foremost, climate must be differentiated from weather. Briefly, climate is an average of weather events for a given period, in a given place. Climate change occurs when the distribution of said average shifts. This may manifest as colder winters and hotter summers. While aberrant weather events are often the face of climate change, the gradual shift in distribution will place the greatest strain on potato production systems. Special emphasis is given to shifts in precipitation and temperature in the U.S.

Shifts in precipitation and temperature will likely cause the most profound disruptions to potato production. Consequently, precipitation and temperature frame the discussion around climate change’s implications to potato physiology and production. Potential impacts to canopy vigor, tuber yields, and tuber quality are discussed. Lastly, system level climate adaptations are discussed.

Climate versus Weather

Popular pieces such as Al Gore’s 2006 documentary, *An Inconvenient Truth,* cast light on climate change, reaching a broad audience. Consequently, climate and climate change are now in the everyday vernacular. While Gore’s work and other pieces raised awareness, they also injected contention and confusion. The notion that climate change’s scope is limited to global warming is too prevalent and misrepresents the problem. Moreover, individuals began to conflate weather for climate and vice versa.

Delineating climate change and weather is inherently difficult, because the two are inextricable. Pielke and Waage (1987) use the illustration of a weather report featured on a television news program. The broadcast declares daily temperatures were above or below normal. “Normal” is based on the climate, and daily weather varies around the normal. Simply, climate is what someone anticipates, whereas weather is what one receives for the day (Tomlinson et al., 2015). Therefore, weather is useful for day-to-day decisions, and climate guides long-term planning.

Climate change has been defined in many ways. Some definitions are borne from specific applications, whereas others offer insight into perspectives on climate. The following five criteria for developing a suitable climate change definition were adapted from Werndl (2016).

1) Be amenable to an empirical understanding of climate;
2) effectively delineate different climate periods that are uncontested;
3) delineation remains static regardless if the body of knowledge on climate change grows or diminishes;
4) applicable to climate from the inception of the planet and into the future;

5) lastly, the definition should be underpinned by mathematics.

A definition has not yet been developed to fully satisfy all five criteria. This paper will adopt the Intergovernmental Panel on Climate Change's (IPCC) definitions on climate and climate change which follow:

> **Climate** in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.
>
> **Climate change** refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of climate which is attributed

> directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.' The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition and climate variability attributable to natural causes.

The IPCC's definition of climate change reflects atmospheric conditions are in constant spatiotemporal flux, thus climate is a snapshot of weather over time for a given area to form an average. Averages were first formally reported around 85 years ago for the period 1901-1930 at the behest of the International Meteorological Organization, now known as the World Meteorological Organization (Arguez and Vose, 2011). Today, these averages are known as normals and feature the following characteristics defined by Arguez and Vose (2011):

1) it is a temporal average;
2) the average is unweighted;
3) the averaging period is 30 consecutive years;
4) it is a causal filer (using past and current values only); and
5) it is updated once per decade.

This approach has been universally accepted and used by laymen and experts alike; however, these characteristics create challenges for application and potential mischaracterization of the climate. An implicit assumption underlying normals is the climate must be stationary. A stationary climate is a climate in which a single Gaussian distribution reflects the variance of weather events for a given period. The current rate of climate change suggests a 30-year period is no longer stationary in some areas.

Normals are presented as singular values, thus a weatherman's reference to above or below normal may provide a false sense of unseasonable weather. In reality, normals are the mean along a distribution (Arguez and Vose, 2011; Pielke and Waage, 1987). Weather events fall along this distribution; however, modest deviation from the mean should not be viewed as unseasonable. Rather, unseasonable events should be identified via a simple t-test or more robust statistical procedure (Pielke and Waage, 1987; Stephenson, 2008). However, an appropriate distribution must be available for this approach to be effective.

Severe, rare, extreme, and high-impact weather events are apt to increase as the climate changes; however, these events may reflect a new normal (Stephenson, 2008). As these events increase in frequency, the Gaussian distribution shifts. Consequently, a distribution based on a 30-year average may disproportionately place current weather events at the outer regions of the distribution.

Arguez and Vose (2011) suggest the World Meteorological Organization reduce the time interval for reporting normals, with reductions varying between meteorological variables. These individual reductions would bear the same effect: reducing the period from 30-years would enhance distribution fidelity. Reporting intervals should be short enough to reflect a stationary period, but sufficient in length to establish an appropriate weather distribution. Further, the authors support reporting climate normals on a rolling basis (i.e., annually). Increasing reporting frequency could have a similar effect to shortening the reporting period by ensuring that distributions are abreast with the rate of climate change. Modern technology allows for automation of this process, thus large capital investments would be unnecessary.

Shortening the reporting period for normals and increasing reporting frequency could immediately affect society. Distributions that are stationary allow for appropriate statistical analysis to identify abnormal weather events. Delineating modern abnormal weather from historical abnormal weather could inform allocation of finite resources, such as monetary relief to potato growers during drought.

Addressing reporting period and frequency will not resolve all issues associated with climate normal. Normals are retrospective values commonly informing prospective policy decisions (Arguez and Vose, 2011). Comparing normal values and shifts between reporting periods are commonly employed in models and influence policymakers' decisions that will carry effects many years into the future. Normals conforming to the World Meteorological Organization's standards will be referenced in this paper as a baseline to compare with climate simulations for future time periods. While imperfect, these normals represent the best available data of the climate. It is incumbent upon the reader to bear in mind the pitfalls associated with these values and construe the text accordingly.

Greenhouse Gases

The previous section established that climate change is a shift in distribution. Earth's climate has evolved since its inception; however, the rate that distributions are shifting is unprecedented. This rapid evolution is anthropogenically driven. Consequently, the current epoch has been dubbed the Anthropocene. Humans are profoundly altering the Earth and its climate. Exploitation of energy stored in carbon bonds of fossil fuels is the principal driver (Raupach and Canadell, 2010).

Ekwurzel et al. (2017) evaluated emissions from 90 major carbon producers from 1890 – 2010. Many within the cohort were petroleum producers. The combustion of products produced by this cohort was responsible for a 58.8 ppm increase of atmospheric carbon dioxide (CO_2) from 1890 – 2010. The addition of CO_2 caused a 0.4 degrees Celsius increase in average global temperature. Disturbingly, 43.8 of the 58.8 ppm of CO_2 was introduced into the atmosphere from 1980 – 2010. This resulted in 0.28 degrees Celsius increase over 30-years.

Agriculture is directly and indirectly linked to these precipitous increases in CO_2 emissions. Fossil fuel combustion to power equipment for field preparation, planting, harvesting, etc. is an apparent contributor. While not as obvious as fossil fuel combustion, nitrogenous fertilizer use contributes to agricultural emissions. The Haber-Bosch reaction to convert atmospheric nitrogen into ammonia is energy intensive (Norskov and Chen, 2016). Furthermore, greenhouse gas contribution from nitrogenous fertilizers do not stop after manufacturing. A product of denitrification is nitrous oxide. Nitrous oxide’s greenhouse gas potential is 298 CO_2 equivalents over a 100-year period (Forster et al. 2007). A CO_2 equivalent is a mean to compare the global warming potential per unit mass for greenhouse gases for a defined interval. Thus, nitrous oxide has 298 times greater global warming potential than CO_2 for a 100-year period on a mass basis. Consequently, relatively low nitrous oxide emissions profoundly affect the climate.

Little is understood about nitrous oxide emissions from potato production; however, research conducted on similar soil textures for other crops yields insight.

Between 0.4 – 0.11% of nitrogen supplied to a Minnesota corn field featuring a loamy sand was converted to nitrous oxide (Maharjan et al., 2014). Potatoes are commonly raised on coarse textured soils such as sandy loams. Notably, nitrous oxide potential may be lower in potatoes due to frequent, small nitrogen applications specific to crop demand. Risk of nitrous oxide production increases exponentially as nitrogen inputs exceed crop demand (Shcherbak et al., 2014). To date, research on cropping systems greenhouse gas emissions have largely targeted row crops and small grains. Research investigating greenhouse gas emissions from potatoes and other specialty crops will be an important step towards climate change mitigation.

Greenhouse gases such as CO_2, methane, and nitrous oxide have different origins; however, they are aptly named given their similar atmospheric effects. Greenhouse gases in the atmosphere are permissive of short-wave electromagnetic radiation entering Earth’s atmosphere. Soil and other terrestrial elements absorb short-wave radiation. Absorbed short-wave radiation excites electrons at the atomic level, thus increasing soil temperature. A fraction of short-wave radiation is re-emitted as long-wave radiation. Greenhouse gases absorb long-wave radiation and prevent it from escaping Earth’s atmosphere. Consequently, long-wave radiation is absorbed by and excites atmospheric particles, thus heating the atmosphere. Fundamentally, this phenomenon parallels the physics that enable a greenhouse to be warmer than ambient temperature. The greenhouse effect and global warming are often used synonymously; however, equating climate change effects solely to warming via the greenhouse effect diminishes the multiplicity and profound ways climate change is altering Earth.

Unfortunately, climate change is not easily reversed, nor stopped. Emissions introduced to the atmosphere surpass the emitter's lifespan. Carbon dioxide may appear innocuous relative to nitrous oxide which has a greenhouse warming potential 298 times higher per unit mass; however, the sheer volume of CO_2 emission is particularly problematic (Forster et al. 2007). Moreover, CO_2 decays slowly under atmospheric conditions compared to other greenhouse gases (Solomon et al., 2010). Carbon dioxide's ability to persist and the rate at which it is emitted establishes it as the principal driver of climate change.

Oceans can allay some of the deleterious effects of anthropogenic CO_2; however, they cannot protect Earth from the acute change which is occurring (Solomon et al., 2009). Carbon dioxide reacts with water to form carboxylic acid, a weak acid. As a weak acid, dissolved CO_2 and carboxylic acid concentrations attempt to equilibrate. Emissions have increased approximately two percent annually, thus equilibration has not occurred. Further, the carbon burden born by the atmosphere and oceans is not equal. If equilibration occurred, approximately 80% would remain in the atmosphere and the remaining 20% would be absorbed by the ocean depending on ocean acidity and temperature (Solomon et al., 2010). Under a total emissions cessation, equilibration would likely occur in 1,000 years. A fraction of the CO_2 removed from the atmosphere and the time required for equilibration limit ocean utility to alleviate climate change. Moreover, ocean acidification resulting from CO_2 withdrawal from the atmosphere may profoundly affect marine ecosystems and biogeochemical cycles in ways not yet understood.

Human activity has markedly altered the composition of Earth's atmosphere (Raupach and Canadell, 2010). Namely, fossil fuels have caused an inordinate increase in atmospheric CO_2 (Ekwurzel et al., 2017). This carbon dioxide traps electromagnetic radiation in the Earth's atmosphere, thereby increasing the average global temperature. It is not feasible to reverse climate change's course because of CO_2's persistence in the atmosphere; however, society can soften the trajectory (Solomon et al., 2010). Dramatic departure from fossil fuels is necessary if the direst climate predictions are to be avoided.

Climate Change Effects

Climate change's effect on temperature is well established. Greenhouse gas emissions result in a perennial increase of average global temperature; however, temperature changes are spatially and temporally variable. Understanding current and future spatiotemporal shifts in temperatures at a local scale is imperative for developing climate resilient strategies for agriculture.

Crimmins and Crimmins (2019) analyzed weather data for the continental United States from 1948 – 2016. Specifically, they analyzed the data in a biologically relevant manner by using growing degree days. Growing degree days correspond to phenological development of many plant species. Crimmins and Crimmins selected a base temperature of 10 degrees Celsius and calculated calendar days to reach 50, 250, and 450 growing degree days. Multiple growing degree day benchmarks offer insight into compression or extension at different periods in the growing season. Unsurprisingly, growing degree accumulation varied substantially across regions; however, consistent trends were not observed across latitude or longitude. For instance, days between 50, 250, and 450 growing degree days being reached in lower and higher latitudes is increasing in the western United States, whereas days between each benchmark are decreasing in the eastern United States. Days between these benchmarks in the central United States is relatively steady. Major potato producing regions are not immune to these changes. Early season growing degree day accumulation is extending, whereas it remains static in the Upper Midwest. Interestingly, late season growing degree day accumulation is being compressed in both areas. Changes in growing degree day accumulation could have serious implications for management, market availability, and storage duration.

Direct effects from temperature changes pose a threat to agricultural production; however, temperatures indirect effects may prove equally grievous. A linear relationship between temperature and precipitation is commonplace (Solomon et al., 2009). The Southwest is largely an arid region already plagued by water deficits, thus a 10% decrease in precipitation would have devastating consequences (Winzeler et al., 2013). For instance, precipitation in the southwestern United States could decrease 10% should temperatures increase by 2^{o} C. For perspective, a 10% decrease in precipitation heavily contributed to the Dust Bowl during the 1930s (Solomon et al., 2009).

Changes in precipitation have already occurred as temperatures increased during the last century, albeit the magnitude and timing has differed (Bartels et al., 2019). Bartels et al. examined precipitation data from 167 weather stations across the United States collected from 1951 – 2015. Precipitation days increased in the Midwest and Northeast, whereas precipitation days decreased in the Pacific Northwest and Southeast. Changes in precipitation days manifested first in the Northeast and towards the mid to latter end of the period examined for the remainder of the United States. Important to potato production, the Pacific Northwest's precipitation days are forecasted to remain steady. Precipitation days are projected to increase in the Midwest. It is important to remain mindful of the limitations of using historical data for future insights because contemporary climatic change is largely outpacing historical climate change (Arguez and Vose, 2011).

While average temperature has increased across United States, precipitation days have only increased in some regions. This may seem to contradict the inverse relationship between temperature and precipitation described by Solomon et al. (2009); however, there are several potential explanations. First, precipitation days do not reflect cumulative rainfall. An area may experience more precipitation days, although reduction in event totals could reduce annual precipitation. Conversely, a decrease in precipitation days may not reduce annual precipitation because events on average are larger. Second, it would be remiss to solely attribute changes in precipitation to temperature increases.

Moore et al. (2021) found land use to significantly influence a phenomenon known as rainfall feedback. Rainfall feedback is the effect a precipitation events has on future precipitation events. Simply, rainfall events are statistically dependent. Weather data analysis for the contiguous United States from 1849 – 2016 suggests land use affects rainfall feedback and seasonality of rainfall feedback. During this period the West brought substantial land into agricultural production, whereas the East was predominated by urban development. Agricultural development favored an increase and decrease in rainfall feedback for the winter and summer, respectively. Conversely, urban development favored a decrease and increase in rainfall feedback for the winter and summer, respectively. Underlying mechanisms behind shifts in rainfall feedback are poorly understood. An opportunity exists to elucidate these mechanisms that may provide avenues to mitigate precipitation changes due to shifts in land use.

Changes in rainfall feedback described by Moore et al. (2021) illustrate the complexity of understanding changes under an evolving climate. Temperature acts as the principal driver; however, other factors influence spatiotemporal precipitation dynamics. Further research is necessary to understand the underlying mechanisms to better predict climate change outcomes and plan for the future.

Potatoes and Climate Change

Figure 1.1 shows commercial potato yields have steadily increased since the 1940s (National Agricultural Statistics Service).

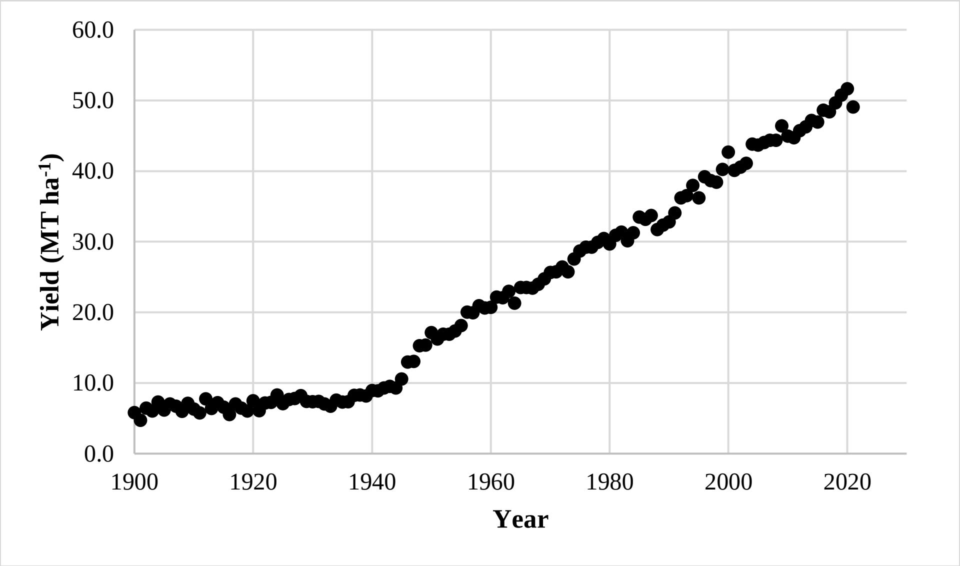

Figure 1.1 – U.S. potato yields from 1940 – 2021 (National Agricultural Statistics Service).

Genetics and management have garnered much attention for the steady increases in potato yields for the past 80 years, although environment will likely steal the show moving forward. Long-term planning is based on climate, but in-season decisions are based on weather (Tomlinson et al., 2015). A non-stationary climate infuses unprecedented challenges into the planning process (Arguez and Vose, 2011). Agriculture's vulnerability to weather and how uncertainty from climate change could exacerbate this vulnerability is illustrated in a study by Lazo et al. (2011). Average annual gross domestic product (GDP) for U.S agriculture from 1996 – 2000 was 135.88 billion USD. Weather accounted for 12.1% of the variability for agricultural GDP; second only to mining. The authors ascribe this vulnerability to decisions that must be made before accurate meteorological forecasts are available. In short, weather will dictate outcomes from growers' decisions; however, growers must make these decisions based on knowledge of the climate, not near-term forecasts. As the climate variability increases, growers' knowledge of climate for the area may not be as useful in making sound management decisions. Unreliability of historical insights predisposes growers to risk.

At local levels, changes in weather patterns and severe weather events such as the hail witnessed by the author could prove devastating to individual operators. However, atmospheric CO_2, temperature, and precipitation across regions will dictate whether historical areas remain viable for production, as well as if areas historically unsuitable become conducive to potato production. Carbon dioxide offers an ideal starting point for discussion because it is largely governed by anthropogenic activity and influences other factors such as temperature and precipitation.

Intuitively, elevated CO_2 should prove beneficial to potato production. Potatoes rely on C3 photosynthesis to harvest CO_2 from the air and convert it into the photosynthates necessary for biomass production (Dahal et al., 2019). Ribulose-1,5-biphosphate carboxylase-oxygenase (RuBisCO) is the enzyme responsible for CO_2 fixation during the Calvin cycle (Taiz et al., 2015). RuBisCO has a strong affinity for oxygen that increases with temperature. The affinity for oxygen is particularly troublesome under drought conditions often accompanied by warm temperatures. When plants are drought stressed, stomata partially or entirely close to conserve water. Subsequently, leaf mesophyll CO_2 depletion ensues because CO_2 does not pass from the atmosphere through the closed stomata. Consequently, RuBisCO begins to act upon oxygen, known as photorespiration. Photorespiration is energetically unfavorable and retards plant growth.

Elevated atmospheric CO_2 lowers the risk for photorespiration. Stomata tighten their aperture in response to elevated CO_2 (Dahal et al., 2019). This lowers stomatal conductance; however, CO_2 concentration in leaf mesophyll cells is maintained because of higher atmospheric CO_2. This concomitantly maintains photosynthesis while lowering transpiration.

Leaf mesophyll CO_2 is not always static in response to elevated CO_2; rather, CO_2 increases inside the cells. Higher CO_2 in leaf mesophyll cells leads some to posit that higher atmospheric CO_2 could be a harbinger for potato production. Higher CO_2 in mesophyll cells can accelerate photosynthesis; however, results from experiments investigating the effects of elevated CO_2 are inconclusive. Early development exposure to elevated CO_2 in some experiments has stimulated photosynthesis, aboveground biomass, and tuber yield; however, acclimation to elevated CO_2 occurs and photosynthesis returns to baseline levels (Finnan et al., 2005; Kaminski et al., 2014). Acclimation has not been documented in all experiments, thus leaving open how genetics, environment, and/or management may influence the process (Lee et al., 2020). The physiological mechanisms underpinning acclimation are poorly understood. Selection for genotypes that do not experience acclimation to elevated CO_2 offers the potential to safeguard potato productivity as CO_2 increases.

A useful review by Finnan et al. (2005) illustrates the effects from higher CO_2 extend beyond changes in above- and belowground biomass. Plant senescence accelerates as CO_2 increases. Premature plant senescence may limit the utility of long-season varieties that have been proposed to increase yields as temperatures increase in higher latitudes (George et al., 2018). The chemical constituents above- and belowground also change as CO2 increases. Starch increases in leaves and tubers as CO_2 increases (Finnan et al., 2005). Changes in starch abundance may have implications for phosphorous nutrition. Increased starch accumulation may translate to less phosphorous in the chloroplasts. In addition to starch, tuber dry matter exhibits a positive correlation to CO_2. Conversely, tuber nitrogen and glycoalkaloids exhibit a negative correlation to CO_2. In addition to nitrogen, Lee et al. (2020) found significant decreases in tuber magnesium and phosphorous under increased atmospheric CO_2. Changes in tuber composition under climate change could bring serious economic and societal implications. Increase in dry matter would appeal tremendously to chip processors. However, decreases in tuber nitrogen may affect people in areas where potatoes are a primary source of sustenance.

Direct effects of elevated atmospheric CO_2 will largely be beneficial; however, indirect effects of CO_2 on potato production will be much more nefarious. The benefits or setbacks will depend on temperature (Kaminski et al., 2014). Elevated CO_2 is the impetus behind the greenhouse effect, which is increasing global average temperature. Higher temperatures directly impact potato productivity; however, interactions between temperature and CO_2 are still being elucidated (Dahal et al., 2019; George et al., 2018; Hastilestari et al., 2018; Kaminski et al., 2014; Krauss and Marschner, 1982). Directly, higher temperatures elevate cellular respiration. Greater cellular respiration counters elevated photosynthetic rates measured under elevated CO_2. Further, photosystem II activity is hindered under high temperatures (i.e. >35 °C) (Dahal et al., 2019). Lower net photosynthesis stemming from increased cellular respiration and decreased photosystem II activity translates to lower above- and belowground biomass.

Loss in tuber yields extends beyond photoassimilate availability for biomass production. Tuber initiation is influenced by photoperiod and temperature (Krauss and Marschner, 1982). For tuber initiation to occur, abscisic acid must increase and gibberellic acid must decrease. Under elevated temperatures, abscisic acid increases at tuber initiation; however, gibberellic acid remains static. Gibberellic acid remaining static precludes tuber initiation. More recent data from Hastilerstari et al. (2018) confirm and build upon Krauss and Marschner’s findings. Hastilestari et al. noted that a shift in sink from tubers to foliage was measured when temperatures increased. The authors ascribed this to changes in abscisic levels. Findings from both studies suggest dynamic source/sink relationships may constrain yield potential due to an imbalance between abscisic and gibberellic acid induced by temperature increases.

Krauss and Marschner (1982) also elucidated nitrogen’s influence on abscisic and gibberellic acid levels. A high nitrogen rate was maintained as potato plants were ready to undergo tuber initiation. High nitrogen suppressed abscisic acid and fostered high gibberellic acid levels, thereby preventing tuber initiation. Disrupting the continuous high nitrogen rate increased abscisic acid levels and decreased gibberellic acid, thus resulting in tuber initiation. This disruption could further compromise tuber initiation and tuber yields as global temperatures rise.

Soil mineralization increases with soil temperature (Miller and Geisseler, 2018). Moreover, it is well established that increasing soil organic matter generally results in more nitrogen available from mineralization. While potatoes are often grown on low organic matter soils, particulate organic matter can significantly affect nitrogen mineralization (Luce et al., 2016). Areas that experiencing increased freeze-thaw cycles may observe increased nitrogen availability as occluded particulate organic matter is rendered into free particulate organic matter (Ruan and Robertson, 2017). Greater free particulate organic matter can increase nitrogen mineralization. Increased nitrogen mineralization from warmer soil temperatures and increased free particulate organic matter could increase nitrogen availability early in the season (Miller and Geisseler, 2018; Ruan and Robertson, 2017). Accordingly, growers should adjust nitrogen budgets to avoid tuber initiation losses due to excessive nitrogen (Krauss and Marschner, 1982).

Similar to CO_2, higher temperatures also affect plant composition. Increasing ambient temperature lowers tuber sucrose and starch levels (Hastilestari et al., 2018). Although, Hastilestari et al. (2018) discovered lowering soil temperatures under elevated aboveground temperatures partially restored sucrose and starch levels. Sucrose and starch are constituents of importance to processors. Opportunities exist to manage soil temperature for quality via plant residues to alter the surface energy balance and lower temperatures via irrigation. Irrigation water is often cooler than ambient conditions, evaporative cooling reduces canopy and soil temperatures, and water’s high specific heat suppresses soil temperature fluctuations relative to the atmosphere.

Despite many drawbacks to increasing temperatures, opportunities for potato production may occur in areas where traditional caloric sources have been compromised. Indigenous populations in Canada’s subarctic are experiencing drastic diet modifications due to climate change (Barbeau et al., 2015). Loss of traditional food coupled with an influx of highly processed foods has precipitated an obesity crisis. Researchers explored alternative cropping systems to introduce healthier foods into communities at a lower cost. Historically, potato production was not viable due to temperature regimes in the region; however, a potato and bush bean rotation yielded comparably to commercial yields. Further, using this rotation in an agroforestry system provided frost insulation compared to conventional cultivation. Globally, rising temperatures may undercut potato production; however, higher temperatures may offer new opportunities for some of the most vulnerable populations to adapt. Notably, these opportunities largely hinge on earlier last spring frost and/or later first fall frost dates, which vary by locality (McCabe et al., 2015).

In addition to heat vulnerability, potatoes are a drought sensitive crop. In some regions, the threat from higher temperatures might be eclipsed by drought. Particularly for regions where rainfed production remains prevalent. Timing and duration of drought determine plant outcomes which can include slow emergence, poor root proliferation, fewer stems and stolons, tuber malformation, less above- and belowground biomass, and premature plant death (George et al., 2018; Obidiegwu et al., 2015). Higher CO_2 may soften the impacts from drought; because, increasing CO_2 promotes stomatal closure, which increases water use efficiency (Dahal et al., 2019). Conversely, stomatal closure beyond a threshold decreases water use efficiency. This occurs in response to abscisic acid increases induced by drought stress (Liu et al., 2005). Interaction between CO_2 and available plant water yield unique outcomes. A shift in sink from canopy to tubers caused by moisture raises harvest index, although harvest index increases further under elevated CO_2 (Fleisher et al., 2008). However, higher CO_2 does not affect harvest index when moisture is not limiting. Higher atmospheric CO_2 could alleviate the effects of drought in rainfed and limited irrigation cropping systems; however, the effects of concomitant heat that often accompanies drought is understudied.

As with higher CO_2 and temperatures, drought also impacts potato constituents. Grudzińska et al. (2018) measured the effects of intermittent and prolonged drought stress on tuber composition and storage of a drought tolerant and a drought susceptible variety. Both drought treatments reduced fructose, glucose, and starch in the tuber. Further, tuber respiration in storage increased from plants subject to drought stress; however, respiration was significantly higher for intermittent drought compared to prolonged drought stress. These findings warrant serious consideration of post-harvest implications stemming from drought. Processors may reject tubers subject to drought due to quality concerns or be forced to alter their manufacturing processes. Likewise, increased tuber respiration from drought stress may cause supply chain disruptions by curtailing storage longevity.

Collectively, elevated CO_2, higher temperatures, and drought will profoundly alter global potato production. The magnitude and location of impacts are still uncertain. Modeling conducted by Hijmans (2003) suggests global potato yields between 2040 – 2059 will be 18 – 32% lower than yields observed from 1961 – 1990. Developing heat tolerant varieties could limit decreases between 9 – 18%. In the United States, yields are projected to decrease 5.9 and 32.8% for the same period with and without adaptation, respectively. Interestingly, 1.4% of potato production land in the United States is projected to experience increased yields, whereas the percent of land experiencing higher yields increases to 20% with adaptation. Factors such as a longer growing season contribute to prospective yield increases under climate change. Moreover, the potential for adaptation creates promise that society is not beholden to climate change.

A more recent study paints a less dire picture, albeit the studies modeled slightly different time periods. Raymundo et al. (2018) projects global yield declines for 2040 - 2070 between 2.1 – 5.6% compared to yields observed for the period 1979 – 2009. Yields are projected to steeply decrease between 1.8 – 25.8% for the period 2071 – 2100. The study suggests areas already experiencing high yield variability will be most affected by future yield declines.

Disparities between model outcomes are inevitable. Foremost, these productivity models include projections from multiple climate models that favor different outcomes. Moreover, predictors vary between models. Consequently, it is difficult for growers and processors to plan for changes in the supply chain. However, these models clearly illustrate major change is likely and adaptation must be executed with urgency.

Response

Irrespective of climate change's precise trajectory, dramatic action is necessary to shore up vulnerabilities in potato production and safeguard yields that are critical to supporting a growing global population. Exhaustively addressing potential responses to develop climate resilient potato systems is beyond the scope of this paper; however, it would be remiss to not highlight a few imperatives that should be addressed. Chapters 2 and 3 will address irrigation and pest responses, respectively, thus this section will emphasize general approaches, genetics, and tangential climate responses.

There are three adaptation types within agriculture: 1) incremental adaptation; 2) systems adaptation; and 3) transformational adaptation (Rickards and Howden, 2012). Transformational adaptation constitutes the most profound change resulting in one of two outcomes for the cropping system: 1) temporal or spatial redistribution, or 2) change of goal. Temporal and spatial redistribution are underway and apt to accelerate as the climate evolves. Potato production is shifting towards higher latitudes favored by milder temperatures (Haverkort and Verhagen, 2008). Producers' goals may shift through anticipation of lower yields or poorer quality if they continue to produce in the same area.

While transformational adaptation will be necessary to develop climate resilient potato systems, the prospects may not be binary as proposed by Rickards and Howden (2012). Incremental adaptation, modifications to individual practices, and systems adaptation, integrated modifications to practices, will partially stave off yield losses from climate change. The potential impact of incremental adaptation is illustrated by findings from Hijmans (2003). Hijmans forecasted global yields to decrease 18 – 32% by mid-century; however, introduction of heat tolerant varieties could reduce yield losses 5 –

10%. Coupling heat tolerance with traits that prevent photosynthetic acclimation to elevated CO_2 could further allay climate change's impacts. The opportunity to stave off yields losses through breeding exists, albeit the tedious nature of the current breeding pipeline will not suffice. Capital investments into existing and new potato breeding programs could catalyze varietal introduction. Varieties developed by a host of programs will be critical moving forward because varieties will need to have a more intimate relationship with the climate they are intended for. George et al. (2018) call for development of long-season varieties to capitalize on longer growing seasons. This approach could increase yields in some regions, although shifting entirely to long-season varieties could prove disastrous for other regions. Some regions may need a short-season variety that can be planted early and harvested prior to inhospitable heat arriving. Likewise, rainfed producers may seek short-season varieties that align with their moisture regime.

Genetic engineering could circumvent the need for developing multiple maturities to address the same issues such as heat, drought, etc. Traits to improve drought or heat tolerance could be inserted into existing varieties that represent a breadth of maturities. Currently, public perception towards genetically engineered crops would likely preclude commercialization and development of new transgenic varieties.

Notably, not all threats posed by climate change to the potato supply chain originate in the field. In central Michigan, where the author worked in 2020, days with favorable ambient temperatures for potato storage are projected to decrease 11 – 17 days by mid-century (Winkler et al., 2018). Many storage facilities are ill equipped for changes of this magnitude. Consequently, growers and processors should anticipate a shorter storage season and/or prepare to add or bolster climate control systems. Climate control is an energy intensive process, thus augmenting climate control systems could reduce profitability and enlarge the greenhouse footprint of potato production.

Urgent action is needed to mitigate climate change’s deleterious effects in the field and supply chain. Climate change’s exact trajectory remains cryptic; however, empirical evidence suggests that current trends in precipitation and temperature pose serious threats. The worst course of action is inaction. Novel approaches will be necessary, although producer and consumer acceptance are requisites for success.

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Chapter 2 – Potato Irrigation in the Face of Water Scarcity

Introduction

Financial and food security risks are apt to increase in the coming century due to drought precipitated by climate change. Crop loss via drought is a serious financial risk to potato growers. Crop insurance is available to potato growers, but high premiums have resulted in low adoption. Consequently, many growers assume full risk if a rainfed crop is lost to drought. Drought's impacts extend beyond bottom lines by undermining global food security. Potato is an important caloric source worldwide, and vulnerable subsistence growers are likely to bear the brunt of crop loss from drought.

A shift in production geography has been proposed as a climate change adaptation measure (Rickards and Howden, 2012). This is practical at a macro-level, which could create economic opportunities in new regions while keeping the supply chain intact. However, this overlooks the considerable capital investment potato producers have in machinery specific to potato production. Thus, the transition to alternative crops would likely be an economic burden. Additionally, shifting production is not viable for food insecure populations that lack access to global markets.

Irrigation insulates potato growers from drought's devastating effects. As such, irrigation development is likely to increase in the coming years to avert displacement. However, irrigation development is contingent on available water sources. Ground- and surface water sources are finite, thus shifts in precipitation and water usage may preclude the sustainable irrigation. Proper stewardship of these finite resources will be critical to weathering climate change.

Whether a grower relies on crude furrow irrigation or state-of-the-art microirrigation, the principles for increasing water use efficiency (WUE) are largely the same. This chapter will survey water availability and quality, potato WUE, and irrigation management, and scheduling to navigate production under the variable conditions brought on by climate change.

Water Availability and Quality

Irrigation can safeguard growers and the food supply chain from climate change by supplementing natural precipitation to satisfy crop evapotranspiration (ET). Expanding or maintaining irrigated land only remains viable if water sources are physically and legally accessible (Craig et al. 2017). Moore et al. (2015) examined water consumption by sector in the United States from 1980 – 2000. Agriculture accounted for approximately 80% of water consumption during this time. Further, 50% of food crops were grown in water scarce basins. This is compounded by water impairment and irrigation suitability concerns as water sources are depleted (Corwin, 2020).

The implications of water scarcity were felt firsthand by the author while in the Texas Panhandle. Annual withdrawal rate from the Southern High Plains Aquifer reported by Meixner et al. (2016) is 72 mm, whereas the recharge is 8 mm. Withdrawal rates surpassing recharge rates endangers the longevity of the aquifer and the potato producing area in this region. Manifolding of wells and reduction of planted area were used to deliver adequate water to the crop as aquifer levels continued to drop. Additionally, potato irrigation was prioritized above all other crops.

These experiences are not limited to the Texas Panhandle. Across the western U.S., groundwater is the lynchpin of agricultural production where precipitation is insufficient to support a crop and surface water is scant. Meixner et al. (2016) evaluated aquifer recharge for aquifers West of the 100th meridian. Specifically, they investigated the underlying mechanisms affecting net recharge rate. Net recharge rate is total recharge minus withdrawals. There are four primary recharge mechanisms: 1) diffuse recharge; 2) focused recharge; 3) irrigation; 4) mountain recharge. The dynamics of recharge mechanisms are unique to each aquifer and beyond the scope of this paper; however, general patterns and implications will be discussed.

Northern aquifer recharge is anticipated to remain static or marginally increase (Meixner et al. 2016). Conversely, southern aquifer recharge is projected to decline 10 – 20%. This is consistent with temperature and precipitation trends from North to South in the American West. For aquifers proximal to mountain ranges, reductions in annual snowpack will reduce mountain recharge. Similarly, aquifers underlying major surface water sources will likely experience slower focused recharge as surface water dwindles due to increased withdrawals and precipitation reductions. These are general trends; outcomes will vary between and within aquifers. To illustrate the uncertainty within an aquifer, the Southern High Plains Aquifer recharge rate is projected to decline ten percent; however, uncertainty in climate change and specific recharge mechanisms results in a large confidence interval of ranging from a 50% decline to a 24% increase.

Commonly discussed as discrete entities, it is remiss to overlook the interconnectedness between surface water and groundwater. Zou et al. (2018) found after the 2012 drought that surface water receded faster in California and the Southern Great

Plains compared to other drought afflicted areas. Authors attribute this rapid recession to recharge of the underlying aquifers. This disparity between lands overlying aquifers and those not overlying aquifers could be amplified under a changing climate. Zou et al. (2018) indicates that drought prone areas such as the West are already experiencing a decline in surface water area, whereas surface water area is expanding in the Southeast United States and the Northern Great Plains. Underlying aquifers could accelerate surface water declines. This would carry serious implications for agricultural and municipal water supplies largely dependent on surface water overlying aquifers.

Given their interconnectedness, it is important to analyze groundwater and surface collectively. Averyt et al. (2013) examined water supply stress across the contiguous United States and forecasted stress for the mid-twenty-first-century. Hydrological delineation was based on United States Geological Survey’s eight-digit hydrologic unit code (HUC-8). Stress was determined via the water supply stress index (WaSSI). The equation for WaSSI is below:

$$WaSSI = \frac{WD}{SW + GW}$$

Equation 2.1 – WaSSI = water supply stress index; WD = watershed annual demand; SW = annual surface water supply; GW = annual groundwater supply.

Equation 2.1 was also modified to calculate WaSSI for specific sectors such as agriculture.

Unsurprisingly, the Western United States is experiencing the greatest stress. Declines in surface water are mostly responsible. Major population centers such as Los Angeles and energy production impose considerable stress in individual watersheds, albeit agriculture is the largest consumer across the West. In many western watersheds, WaSSI calculated for agricultural annual demand exceeds 90%, which is higher than the national average presented by Moore et al. (2015).

The water outlook is unlikely to improve in the coming years. For the western U.S., WaSSI for surface water will be up to 30% higher by 2041 – 2060 compared to 1900 – 1970. Again, reduction in surface water availability is contributing to the increase. However, rapid population growth in certain areas further strains an already compromised system. The concomitant population increase could further subvert irrigation capacity because domestic water needs supersede appropriation rights.

Overall, nine percent of watersheds will experience demand that eclipses supply in the contiguous United States by 2103. This type of net water availability budgeted at a yearly scale is likely suitable for high-level policy planning; however, seasonal water availability is commonly at its lowest when demand is at its highest. From 1980 – 2000, 13.7% of basins in the contiguous United States were water scarce; however, water scarcity increased by 3.6% during the summer months (Moore et al. 2015). Agronomic and policy changes could better synchronize water supply with demand, thereby lowering stress on individual basins.

Lastly, some areas facing increasing water scarcity are concurrently experiencing a decline in water quality. This is problematic for potatoes because they are sensitive to salinity (Dahal et al., 2019; George et al., 2018). In California’s San Juaquin Valley, saltwater intrusion resulting in higher groundwater salinity remains an issue and is anticipated to worsen with climate change (Corwin et al. 2020). Greater drought frequency will increase groundwater pumping, which will likely accelerate soil salinity issues.

Salinity concerns are not limited to coastal areas where saltwater intrusion risk is high. Soils with an electrical conductivity (EC) ≥ 2 dS m^{-1} in the Red River Valley, a major potato production area, increased by 30% from 1979 – 2007. Considerable swaths of land are now saline (EC ≥ 4 dS m^{-1}) with pockets exceeding 8 dS m^{-1} (Corwin et al., 2020). Rising water tables are largely responsible because salts accumulate as water is wicked into the upper profile via capillary action. This phenomenon is likely to increase in areas with shallow water tables.

Water quantity and quality are issues for potato irrigators that will continue to be at the forefront. Understanding the underlying issues, risks, and probable changes will enable shrewd agronomic and business planning. The following sections provide information that will help growers efficiently use an increasingly finite resource.

Water Use for Potato Production

Potatoes are a shallow-rooted crop that produce a lush canopy. Classified as drought sensitive, potatoes have a high demand for available water to optimize yield. Consequently, there is a strong incentive for growers to overwater (Shock et al., 2007). Understanding total water demand and how water demand varies within season and across various environmental conditions can inform growers' management decisions, thereby enhancing WUE while maintaining or improving yields. Improving WUE which is critical in the face of water scarcity.

Considerable variability in total ET exists in and between growing regions, which contributes to WUE variability in and between these regions. Hane and Pumphrey (1984) reported optimum yields in the Columbia Basin when seasonal ET was 625 – 650 mm. An experiment conducted in Turkey reported season ET between 501 – 683 mm, whereas another reported season ET of 196 – 473 (Erdem et al., 2006; Onder et al., 2005). Differences in ET between sites may be partially attributable to irrigation itself. Nocco et al. (2019a) found center-pivot irrigation in Wisconsin's potato producing Central Sands region increased the daily minimum temperature and decreased the daily maximum temperature, which resulted in a three degrees Celsius temperature range reduction. Moreover, the vapor pressure deficit decreased by 0.10 kPA. These microclimate changes can profoundly affect season total ET. Consequently, confounding factors such as differences in irrigation systems, irrigation scheduling, and interannual variability could explain the marked differences between the results of the two experiments in Turkey; however, it underscores the need for site-specific management to synchronize irrigation scheduling with the field's microclimate.

Recently, researchers in South Africa investigated inter-season ET demands (Machakaire et al., 2021). Total season ET for a winter-spring crop was 338 mm, whereas the spring-summer crop required an additional 128 mm. Consequently, winter-spring crop WUE (3.55 kg dry tuber $m\text{-}^{3}$ H_2O) was approximately 17% higher than spring-summer WUE (3.03 kg dry tuber m^{-3} H_2O). It has been proposed that long-season varieties be grown to capitalize on a longer growing season driven by climate change, although maintaining or reducing varietal maturity coupled with earlier cultivation could enhance WUE due to similar yields and lower seasonal ET. Moreover, a growing season shift could mitigate the temporal misalignment between water availability and crop use (Moore et al. 2015).

While total ET varies between seasons, daily ET differs as the crop matures. Relative water consumption is best compared through crop coefficients (Equation 2.2).

$$K_c = \frac{ET_c}{ET_0}$$

Equation 2.2 – K_c = crop coefficient; ET_c = crop ET; ET_0 = reference ET (Machakaire et al. 2021).

Crop coefficients are commonly lowest during emergence, peak near tuber initiation or early bulking, and gradually decline until canopy senescence. Hane and Pumphrey (1984) reported a crop coefficient of 0.3 at emergence and a maximum coefficient of 0.8 at full canopy. This is consistent with contemporary results from Machakaire et al. (2021) that reported a minimum crop coefficient of 0.45 during vegetative growth of the winter-spring crop and a maximum coefficient of 1.15 during tuber initiation for the spring-summer crop. Understanding the temporal shifts in crop water use illustrated by the change in crop coefficient values is essential for effective irrigation scheduling. Moreover, analyzing crop coefficient differences between seasons can guide crop planting so crop water demand better aligns with irrigation supply.

Total season ET and crop coefficients can guide cultural practices from planting date to irrigation schedule so tuber yield and water can be conserved, in turn improving WUE. General trends in ET throughout the season are well understood; however, high variation exists within current data. To effectively base site-specific decisions on these data, research is needed across additional irrigation systems, scheduling regimens, varieties, and climate types.

Irrigation Management and Scheduling

Irrigation systems in potato production are extremely diverse and vary based on economics, climate, soil type, cultivation, and grower knowledge. Given the diversity, an extensive review of systems and their implications for production and water conservation is beyond the scope of this paper. Rather, select studies will be highlighted to underscore the principles that should be considered when selecting a system.

The principal criterion in system selection is uniformity because uniformity drives efficiency. Shock et al. (2007) contends irrigation will proceed until the driest portion of the field is sufficiently watered. It is unlikely a grower would inundate most of a field to deliver adequate water to a dry patch; however, uniformity is important for minimizing moisture variability for plants with similar moisture demands. Generally, modern sprinkler and drip irrigation systems provide adequate uniformity and control to reach reasonable efficiency. However, older forms of irrigation, including furrow irrigation, are known for poorer uniformity resulting in lower efficiency.

Furrow irrigation inherently has low uniformity, resulting in runoff and percolation beyond the effective root zone (Shock et al. 2007). A Turkish experiment conducted in 2003 and 2005 compared furrow and surface drip irrigation (Erdem et al., 2006). Yields were the same under both irrigation systems at a maximum allowable depletion (MAD) of 30%; however, irrigation applied differed substantially. Average irrigation applied for both years was 527 and 404 mm for furrow and drip irrigation, respectively. Drip irrigation reduced average water applied 23%. Water reductions of this magnitude could significantly reduce strain on basins, although the capital investments may be insurmountable for some growers.

Drip irrigation can enhance water use over furrow irrigation; however, how it is deployed impacts its effectiveness. Onder et al. (2005) assessed the agronomic and economic outcomes of surface versus subsurface drip irrigation on potatoes raised in Turkey in 2000 and 2002. Tuber yield for surface drip irrigation with a MAD of 34% was equal to or significantly higher than all other treatments. Moreover, WUE for surface drip at a MAD of 34% was 101.0 kg tuber mm $^{-1}$, whereas subsurface drip's efficiency was 84.5 kg tuber mm^{-1}. Further, economic analysis revealed surface drip generated a larger profit, which is largely attributable to lower cost associated with surface drip. These results are consistent with concerns raised by King et al. (2020). Subsurface drip is costly to implement and maintain. Furthermore, it is not amenable to potato tillage and harvest practices. Nor is it well suited for a shallow rooted crop such as potatoes on coarse-textured soils. Eighty-five percent of potato roots are located within the upper 30 cm of soil (Opena and Porter, 1999). Shallow roots, low capillary action, and percolation beyond the root zone render subsurface drip systems that are buried deep enough not to interfere with cultivation or harvest, ineffective.

The challenges resulting from 85% of roots in the upper 30 cm are not limited to subsurface drip irrigation. Best management practices include maintaining a relatively wet profile when root development is in its infancy and crop water use is lowest (Hane and Pumphrey, 1984; King et al., 2020; Machakaire et al., 2021). King et al. (2020) recommends plant available water (PAW) be maintained between 70 – 80% at planting, 70 – 85% during active growth, and 60 – 65% at vine kill. Maintaining 70 – 80 % moisture at planting to emergence is conducive for percolation beyond the root zone and consequent nutrient leaching; however, this range in moisture is critical for satisfactory stands.

Beyond temporal variation, spatial variation must be acknowledged if WUE is to be improved. Variable rate irrigation (VRI) has been commercially available prior to the new millennium, although adoption remains low. Many cite a low return on investment, thus the technology remains cost prohibitive (King et al., 2006). Low return on investment could be explained by lack of ET and/or soil moisture status heterogeneity within fields or the inability to delineate this status.

Irrigation systems are capable of effectively implementing variable rate prescriptions. Speed and zone control are the two means that variable rate prescriptions are realized through for pivot and linear irrigation systems (O'Shaughnessy et al., 2019). Speed control is most effective if field variability presents in a radial fashion; however, variability presenting in a radial fashion is rather uncommon in nature. Zone control breaks the pivot or linear into sections, and each section can apply a different rate based on moisture needs. Consequently, section control is better suited to address variability common in fields; however, section control systems generally cost more than speed control systems.

Concerns about VRI effectiveness may arise from uniformity concerns. Particularly for speed control VRI where variable frequency drives change duty cycle to accelerate and decelerate the system across the field per the prescription. Dukes and Perry (2006) compared application between uniform and VRI applications for speed controlled linear and pivot systems on fallow. Average coefficients of uniformity were 84 and 93% for the linear and pivot systems, respectively. No significant difference ($\alpha = 0.05$) in uniformity was observed between uniform and VRI applications for the linear or pivot systems. However, uniformity significantly differed between fixed plate and rotator nozzles. As such, uniformity should not be a barrier to VRI adoption; rather, growers should be meticulous in nozzle selection.

In reality, the principal barrier to effective VRI implementation remains zone delineation, not irrigation systems' abilities to execute VRI prescriptions. Early VRI zone delineation was predominantly based on PAW mapping. King et al. (2006) found VRI application rates in Idaho potatoes were 82 – 119% of the uniform application rate. Marginal differences in application rates were not economically justifiable. King et al. suggested PAW be paired with ancillary data to enhance zone delineation and possibly improve system return on investment.

Haghverdi et al. (2015) evaluated ancillary data sources to support zone delineation based on PAW in cotton. Ancillary sources included soil apparent electrical conductivity, satellite imagery, and historical yield data. Soil apparent electrical conductivity serves as a proxy for relative soil texture, which can be mapped using platforms such as those developed by Veris Technologies®. Soil apparent electrical conductivity was the metric identified as enhancing VRI zone delineation. Similarly, (Nocco et al., 2019b) evaluated the utility of ancillary data in supporting zone delineation based on ET for potatoes and other crops in Wisconsin's Central Sands. Integrating soil apparent electrical conductivity with ET data improved zone delineation compared to ET data alone. Improvements in zone delineation were greater for shallow rooted crops such as potato and sweet corn. Soil apparent electrical conductivity's utility for aiding VRI zone delineation is well established and is apt to become prevalent as commercial soil apparent electrical conductivity mapping platforms increase in availability and decrease in price.

Whether uniform irrigation or VRI is chosen, measuring soil water status and plant water needs is critical to yield and water stewardship. One approach is the use of soil tensiometers. Tensiometers quantify soil water potential, which is useful for understanding the physical availability of water to the plant (Shae et al., 1999). Barriers to adoption include sensitivity to improper installation and the need for a soil water retention curve developed for each soil type to determine irrigation rate.

Models fed remote sensing imagery from unmanned aerial systems and satellites have gained traction in irrigation scheduling. Karthikeyan et al. (2020) posits current models are inadequate at estimating ET and soil moisture based on such data for most crops, thus remote imagery should supplement other measuring techniques. Inability to accurately model ET was underscored in a Nebraska corn and soybean irrigation study (Barker et al., 2018). Satellite imagery capturing crop reflectance was used to approximate ET for VRI applications. Irrigation based on crop reflectance was approximately 480% higher compared to the uniform application for one site-year because the model overestimated evaporation. Further, cloud obstruction of satellite images created challenges in maintaining a sufficient image frequency for irrigation scheduling.

Proximal plant sensing (plant feedback) augmented with microclimate data and in-situ soil water measurements may address remote sensing's deficiencies.

O’Shaughnessy et al. (2020) compared the irrigation scheduling supervisory control and data acquisition (ISSCADA) system with and without soil moisture data measured via time domain reflectometry to manual scheduling based on neutron probe measurements. This experiment was conducted in Bushland, TX, which is near where the author worked in the Texas Panhandle during 2021. In 2018, the ISSCADA treatments combined reduced total irrigation by nine percent; however, this significantly reduced tuber yield. In 2019, the ISSCADA treatments reduced total irrigation 19% while maintaining yield. An adjustment made to ISSCADA’s MAD between the first and second year could partially explain the absence of a yield penalty in 2019. Although, precipitation differences in 2018 (dry) and 2019 (wet) may have contributed to the differences.

O’Shaughnessy et al.’s (2020) results offer promise for better irrigation management tools in the future, albeit the results underscore growers should regard models as fallible tools and continue to ground truth. Capturing more metrics within the field and better understanding what actions should be taken based on those metrics will pave the way for better water stewardship via uniform or VRI. However, these steps are likely null if growers do not heed the following fundamentals from Shock et al. (2007):

1) Only irrigate when water is needed.
2) Only apply the amount of water that the soil can hold and the crop can use.
3) Monitor your irrigation system so you know how much water has been applied and how much water will be delivered in a given amount of time.
4) Check the uniformity of your system.
5) Change nozzles or flush the drip lines as needed.
6) Support ET_c estimation networks.

7) Follow irrigation criteria with irrigation scheduling tools.

Resiliency Building Against Climate Change

Bolstering potato production systems' resiliency against climate change and water scarcity begins on the farm. Foremost, growers should put into practice the tenets outlined by Shock et al. (2007). Moreover, growers should become early adopters of irrigation technology. As VRI adoption increases, prices are apt to lower. Likewise, greater model adoption increases opportunities for model refinement. Technology adoption is important for water conservation, albeit growers' on-farm water stewardship should extend beyond technology adoption. Examples include weighing agronomic practices such as planting date and variety maturity to synchronize water availability and crop water use (Moore et al., 2015).

Data at a higher resolution than previously collected will be needed to support growers' efforts. Treatment levels for irrigation scheduling experiments must become smaller than the 20% or higher MAD levels historically used (Erdem et al., 2006; O'Shaughnessy et al., 2020; Onder et al., 2005; Shock et al., 1998). Moreover, these data are needed for specific regions, soils, and varieties. Lastly, varieties with high WUE and salinity tolerance are desperately needed.

Shifting potato production centers may partially resolve climate change disruptions to the supply chain. However, this overlooks the economic displacement. Nor does it account for the existing and intellectual capital current growers possess. Consequently, adaptation in current production centers is apt to occur before relocation.

Early technology adoption and reliance on irrigation fundamentals will be necessary to persist in areas where climate change is driving water scarcity.

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Chapter 3 – Climate Change and the Rise of Potato Pests

Introduction

Meteorological impacts associated with climate change will extend beyond physiological ramifications to potato production. Potato pests, including arthropods and pathogens, are intimately connected to precipitation and temperature regimes. Shifts in interspecific competition between potatoes and pests brought on by climate change will further compromise potato productivity.

Solutions to offset climate change's physiological implications for potatoes could precipitate pest issues. Namely, late-maturing varieties have been proposed to harness a longer growing season (George et al., 2018). However, multivoltine arthropods and polycyclic diseases will benefit from suitable environmental conditions and the extended presence of susceptible hosts. Arthropods are projected to be particularly problematic in agroecosystems due to their dispersal ability, thereby elevating the likelihood of range expansion (Hulme, 2017). Although, Hulme emphasizes range expansion from climate change will pale compared to anthropogenic introductions.

Although anthropogenic spread will predominate, it would be remiss to overlook climate change's impacts on potato pests. Potato production faces many pest threats that vary among geographies, and the dynamics are apt to shift with the climate. To date, there is little research into the potential shift in pest specific dynamics and its potential impact on production. Arguably, the most robust research focuses on Colorado potato beetle (CPB), *Leptinotarsa decemlineata* (Say) (Coleoptera: Chrysomelidae). Colorado potato beetle will serve as an example of climate change's potential impacts and how integrated pest management (IPM) can serve as a framework to address increased CPB pressure due to climate change.

Colorado Potato Beetle and Climate Change

Increasing average temperature is a focal point of climate change and is the impetus of increasing pest threats, CPB is no exception. Colorado potato beetle is anticipated to persist within its historical ranges and expand towards the poles (Wang et al., 2017). This range expansion could coincide with new potato production opportunities for Canada's Indigenous populations already facing food scarcity (Barbeau et al., 2015). Although range expansion is problematic, the underlying issue is the host's inability and the pest's ability to capitalize upon increasing temperatures. Arthropods are ectotherms, which benefit via growth and development as temperature increases within cardinal limits (Hulme, 2017). Although plants are ectotherms, plant growth is less affected by increasing temperature and more affected by photosynthetically active radiation within cardinal temperatures (Taylor et al., 2018). Consequently, CPB and other arthropods gain a competitive advantage as temperatures increase.

Analysis of potato and CPB key dates for Polish potato production from 1958 – 2013 benchmarks how key dates for both organisms shift as temperatures increase (Tryjanowski et al., 2017). For every one-degree Celsius increase, the following shifts occurred in potato production: planting – two days sooner; leafing – 3.04 days sooner; flowering – 3.80 days sooner; harvest – 3.42 days sooner. For CPB, a one-degree Celsius increase resulted in first insecticide application occurring 4.66 days sooner. Moreover, an additional 0.204 insecticide applications were made per one-degree Celsius increase.

Key milestones for potato and CPB development are consistent with findings from Crimmins and Crimmins (2019). Degree day accumulation is accelerating in certain regions, thereby accelerating the phenological calendar. Colorado potato beetle is present earlier in the season, which is particularly detrimental for managing multivoltine pests. Earlier emergence creates the potential for larger and additional generations; however, photoperiod induced diapause may limit an additional generation and the extension of adult feeding during the fall (Lehmann et al., 2015).

Although photoperiod induced diapause will likely preclude CPB from capitalizing on a later growing season in the fall, earlier CPB emergence could still subvert current management strategies. Contemporary CPB management relies heavily on synthetic insecticides. Longer seasons increase the demand for chemical control, which increases the likelihood of resistance development.

Insecticide Resistance in Colorado Potato Beetle

Spray schedules have been employed for CPB insecticide timing since the 1950's (Alyokhin et al., 2015). Indiscriminate insecticide use in an effort to control CPB has resulted in the Red Queen's race. Growers increase application rates when reduced efficacy is observed for the current application rate. Higher rates are applied, which may temporarily be effective for quantitative resistance and entirely ineffective for qualitative resistance; however, growers often reach a point in the race where all rates are deemed ineffective. Subsequently, a different active ingredient is selected and the process repeats. In CPB, resistance manifests through decreased absorption rates, enhanced metabolism, and improved excretion (Alyokhin et al., 2008). As a result, CPB populations have collectively developed resistance to at least 52 active ingredients.

Neonicotinoids received no impunity from the perils of the Red Queen's Race. From 1998 – 2001, resistance to imidacloprid was scarcely interspersed in CPB populations in the Northeast (Szendrei et al., 2012). By 2004, imidacloprid resistance was detected in Midwest CPB populations. As of 2009, 95 percent of CPB populations tested in the Midwest and Northeast were resistant to imidacloprid. Furthermore, resistance to the neonicotinoid thiomethoxam was detected during this period. Alyokhin et al. (2007) found resistance levels of 37X and 10X the application rates for imidacloprid and thiomethoxam, respectively. Interestingly, overwintering adults show greater susceptibility to neonicotinoids than summer adults, which may be partially explained by greater body fat in summer adults (Szendrei et al., 2012).

Fortunately, insecticide resistance in CPB is often accompanied by a high fitness cost (Alyokhin et al., 2008). Thus, rotating sites of action resulting in the cessation of the application of certain insecticides has the potential to restore susceptibility. Additionally, quantifying the economic cost of resistant alleles and incorporating those costs into economic thresholds could promote more vigorous practices to preserve and increase frequency of susceptible alleles (Alyokhin et al., 2014). Alyokhin et al. (2008) recommends the following on-farm practices for resistance management:

1. Supplementing insecticides with non-chemical control methods (particularly crop rotations).
2. Alternating insecticides with different modes of action.

3. Using economic thresholds when making decisions about spraying. Trying to kill all the beetles with insecticides usually results in killing all susceptible beetles, while resistant beetles survive and quickly build up their numbers.
4. Leaving untreated refuges for susceptible beetles. Economic thresholds cannot be used when insecticide is applied at planting time in furrow or as a seed treatment. Therefore, spatial refuges are required to maintain populations of susceptible beetles.
5. Using full label rates of insecticides. Because resistance is usually incompletely dominant, sufficiently high dose of a toxin will kill the beetles that are heterozygous at the resistant allele.
6. Monitor for the signs of decreasing insecticide efficacy.

Integrated Pest Management for Colorado Potato Beetle

Integrated pest management employs multiple tactics to reduce, but not eliminate pest damage (Alyokhin et al., 2015). This framework contrasts with the unilateral chemical approach that often relies on spray schedules, not pest pressure, that is largely responsible for the increased development of CPB insecticide resistance. Insecticides can be a component of IPM; however, they should be used strategically and in conjunction with other tactics. Furthermore, IPM can address the resistance crisis facing CPB management, because effective IPM strategies include the tenets for resistance management put forth by Alyokhin et al. (2008).

Despite research-based solutions to implement CPB IPM on-farm, chemical management has predominated. There are multiple factors that contribute to low IPM adoption. Integrated pest management components such as biological control lower populations, although they often provide insufficient control alone and must be paired with other components (Hare, 1990). This contrasts to the striking lethality observed from synthetic insecticides when resistance is not prevalent. The perceived marginal return from non-chemical control measures is another barrier to adoption. Waller et al. (1998) surveyed Ohio potato growers' willingness to adopt alternative overwintering hosts, trap crops, and adult flaming as cultural practices. Most participants were unwilling to adopt any practices due to perceived lack of return due to associated logistical burdens. Lastly, social norms may in part preclude IPM adoption. Boiteau (2010) indicates historical IPM efforts often centered the on long-term objective of eliminating insecticide use. In turn, insecticides were vilified in some growers' eyes, thus a dichotomy was established between growers using insecticides and environmentalists. Consequently, IPM adoption likely suffered.

It is important for plant health practitioners to understand historical and contemporary barriers to IPM adoption so IPM programming may evolve to increase adoption. However, rampant insecticide resistance and additional CPB generations may coerce growers into abandoning unilateral chemical control and adopting IPM (Alyokhin et al., 2008; Tryjanowski et al., 2017). The following sections will focus on individual IPM components and pragmatic solutions growers can implement.

Colorado Potato Beetle Monitoring and Thresholds

An important aspect of IPM is the reduction of the pest's impact, not the elimination of the pest (Alyokhin et al., 2015). Action thresholds guide timing of therapeutic actions, which further differentiates chemical approaches based on spray calendars from IPM. Thresholds rely on direct or indirect CPB measurements.

Thresholds based on direct CPB measurements are limited and often dated. One example is from Martel et al. (1986) who established a sequential sampling technique. The approach requires a minimum sample size of 600 CPB larvae and imposes a sampling limit of 40 plants. If the minimum CPB sample size has been satisfied, the sampling limit has not been reached, and the average is ≥20 CPB larvae per plant, then an insecticide application is advised. Generally, sequential sampling improves sampling efficiency; however, counting a minimum of 600 CPB larvae is tedious. Future efforts building on this work could explore speed sampling that differentiates infested versus non-infested plants. Such an approach may prove as effective and reduce sampling time.

More recent approaches have focused on indirect CPB measurements by quantifying defoliation (Stieha and Poveda, 2015; Zehnder et al., 1995). These action thresholds correspond to the percent defoliation equivalent to the damage boundary. In eastern Virginia, Zehnder et al. (1995) found maximum allowable defoliation without yield loss steadily increased through the growing season (Table 3.1).

Plant Growth Stage	**Action Threshold** (% defoliation)
Emergence – early bloom	20
Early bloom – late bloom	30
Late bloom - harvest	60

Table 3.1 – Colorado potato beetle action thresholds from Zehnder et al. (1995).

Stieha and Poveda’s (2015) findings differed slightly from Zehnder et al. (1995). They found greater tolerance for defoliation and greater relative tolerance early in the season (Table 3.2). Moreover, they determined that thresholds should be adjusted depending on stem injury. Stem injury substantially reduced tolerable defoliation.

Plant Growth Stage	**Action Threshold** (% defoliation)	
	w/o stem injury	w/ stem injury
Emergence	60	35
Pre-bloom - bloom	40	20
Post-bloom	60	52

Table 3.2 – Colorado potato beetle action thresholds from Stieha and Poveda (2015).

Results from Zehnder et al. (1995) and Stieha and Poveda (2015) are remarkably similar despite being published two decades apart from one another. Their consistency provides reasonable comfort as decision-making tools for practitioners; however, critical information is still unaccounted for in both data sets. Varietal specific tolerance remains largely uncharacterized. Further, economics are often unaccounted for by action thresholds; rather, action thresholds are based on an agronomic optimum, not necessarily an economic optimum. Conversely, economic thresholds account for potential yield loss, insecticide expenses, and other extraneous factors such as resistant allele cost. In short, action thresholds fail to account for the value of susceptible alleles in the population as proposed by Alyokhin et al. (2015) to combat resistance. Thus, a shift from action thresholds to economic threshold is necessary to accommodate Alyokhin et al.'s (2015) recommendations.

Future work on threshold development should also account for how in-field measurements are acquired. Remote sensing via satellites and unmanned aerial systems (UASs) offer opportunities to capture data that were not available a few decades ago. Hunt and Rondon (2017) compared normalized difference vegetative index (NDVI), object-based, and height-based UAS sampling techniques for CPB detection. The object-based approach sought to identify contrasting NDVI kernels to distinguish defoliation. All three techniques successfully detected CPB arrival to a field based on defoliation. Additionally, object and height-based techniques provided infestation rankings; however, these techniques required more operator expertise than NDVI. Pairing UASs with appropriate statistical procedures could further reduce sampling time compared to UAS sampling alone. Weisz et al. (1995) found simple interpolative techniques such as inverse weighted distance accurately reflected threshold densities more than 85% percent of the time. This would enable systematic UAS sampling that could reduce time and overcome logistical challenges associated with UAS battery life.

While tools to guide economic decisions exist, much of the available data are dated and designed primarily for chemical control. The potato industry needs new thresholds that account for other therapeutic tactics and pest complexes under an evolving climate. Moreover, these thresholds must be amenable to input data that is acquired in a manner that growers are willing to adopt. For now, growers should use the available thresholds to guide their IPM programs; however, new thresholds are needed if CPB IPM is to be successful as the climate evolves.

Colorado Potato Beetle Chemical Control

Although insecticide resistance is prevalent in CPB populations, it is likely insecticides will remain a focal point in growers' CPB management portfolios as they shift towards IPM. Insecticides are a tool that can aid CPB management if used properly.

Specific insecticide recommendations are beyond the scope of this document; however, general stewardship considerations and recommendations will be provided.

An advantage in managing CPB compared to some other pests is that a single life stage predominates at a given time (Zehnder, 1986). As such, growers should select an insecticide or any other therapeutic tactic that is best suited for the dominant life stage at application time. The goal is to achieve maximum efficacy against CPB while mitigating impacts to non-target organisms. To accomplish this goal, growers must consider physiological and ecological selectivity.

Broad-spectrum insecticides such as pyrethroids suppress CPB, but they are very deleterious to beneficial arthropods such as minute pirate bugs (Hemiptera: Anthocoridae) and spiders (Reed et al., 2001). Declines in beneficial arthropods can hasten CPB resurgence from a loss of biological control. Care should be taken in choosing selective products that will minimize non-target effects.

Although active ingredient selection for CPB management is important, it is insufficient to focus on pesticides for a single pest. Clements et al. (2018) evaluated CPB LD50 values for imidacloprid when applied after exposure to two common potato fungicides, boscalid and chlorothalonil. The detoxification mechanisms for all three pesticides were similar. For instance, boscalid exposure increased glutathione s-transferase activity, which underpins glutathione conjugation involved in boscalid and imidacloprid metabolism. Interestingly, increased glutathione s-transferase activity from boscalid exposure did not increase the LD50 for subsequent imidacloprid exposure; rather, it decreased the LD50 for imidacloprid. Conversely, chlorothalonil exposure preceding imidacloprid exposure increased the LD50 for imidacloprid. Clements et al.

(2018) work illustrates the importance in accounting for antagonistic and synergistic interactions; however, much research is needed to characterize potential physiological interactions between common potato pesticides.

In addition to physiological consideration, ecological selectivity of application practices is important for growers to consider. Lucas et al. (2004) found the beneficial 12-spotted lady beetle, *Coleomegilla maculata lengi* Timberlake (Coleoptera: Coccinellidae), larvae and adults were highly susceptible to imidacloprid exposure. Consequently, foregoing foliar imidacloprid application would preserve 12-spotted lady beetle populations. However, imidacloprid is systemic, and as a seed treatment it offers reasonable suppression of overwintered adult CPB (Szendrei et al., 2012). Using imidacloprid as a seed treatment allows for the inclusion of neonicotinoids as a site of action, but it is ecologically selective so CPB are suppressed while mitigating 12-spotted lady beetle exposure to imidacloprid. The shortcoming to seed treatment pesticides is they are prophylactic, thus thresholds cannot be employed.

Furthermore, growers should consider how they are managing pesticides across the landscape. To date, whole field applications predominate; however, site-specific techniques create refugia opportunities for resistance management and preservation of beneficial arthropods. Midgarden et al. (1997) compared whole field versus grid-based CPB management and the effects on total insecticide use and resistant alleles. Grid-based management lowered insecticide use by 66 percent for the season compared to whole field management. The reduction in insecticide use likely explains a greater presence of Hymenoptera parasitoids and generalist predators in the grid-based management plots. Additionally, resistance to the insecticides used in the study, esfenvalerate and piperonyl butoxide, was 100% higher in whole field management compared to grid-based management by the end of the season.

Applying pesticides in a site-specific fashion could be challenging or impossible for growers depending on their site-specific capabilities. Push-pull techniques present opportunities to concentrate CPB in a known location, such as a field-edge, where targeted applications can be conducted without innovative sprayer technologies. Martel et al. (2005a) evaluated an anti-feedant and a kairomone mixture consisting of three volatile organic compounds (VOCs) in a greenhouse experiment. Plants treated with anti-feedant experienced less defoliation and plants treated with the VOC mixture attracted CPB. In a subsequent field trial, the kairomone mixture was applied to form a trap crop. Plots bordering a trap crop had denser canopies, yielded the same, and received 44% less insecticide compared to plots not bordering a trap crop (Martel et al., 2005b). Using kairomones to establish in-field trap crops for targeted insecticide application may offer similar benefits to grid-based management described by Midgarden et al. (1997), without the added complexities associated with grid-based management.

Using chemical control as an IPM tactic is much more complex than selecting an insecticide and applying it. Physiological and ecological selectivity should be considered to maximize efficacy against the target pest while mitigating non-target effects. Moreover, the introduction of pesticides for managing other pest complexes adds additional complexity to management decisions. Additionally, growers must place decisions in a spatial context because landscape-level treatment decisions serve an important role in managing resistance and providing refuges to safeguard beneficial organisms. To shift from a unilateral chemical approach to chemical control as an IPM component, research is needed to address these complexities followed by subsequent outreach efforts to growers.

Colorado Potato Beetle Biological Control

The prominence of unilateral chemical control in CPB management has left biological control a largely unexplored area. Existing research is mostly centered on beneficial arthropod conservation through insecticide management (Lucas et al., 2004; Reed et al., 2001). Further, lack of beneficial organisms with adequate functional and numerical responses to provide adequate CPB suppression alone may contribute to the neglect of biological control as a management tool (Hare, 1990). Biological control suppression levels may not be abreast with historical insecticide efficacy; however, biological control can contribute to CPB suppression as an IPM component. Two beneficial arthropods and one beneficial fungus will be highlighted.

Biever and Chauvin (1992) conducted cage studies to evaluate the potential of two stinkbugs, *Perillus bioculatus* (F.) and *Podisus maculiventris* (Say) (Hemiptera: Pentatomidae), as biological control agents. By introducing five to ten stinkbugs per plant, both species were able to reduce CPB larvae at high densities by approximately 50%. However, *P. bioculatus* was better at reducing defoliation than *P. maculiventris*. Introducing three *P. bioculatus* per plant resulted in tuber yields 65% greater than the control. Further, *P. bioculatus* is readily reared in the lab, thus presenting commercial opportunities for augmentative releases.

Entomopathogenic fungi also have demonstrated potential to suppress CPB. Wraight and Ramos (2015) evaluated *Beauveria bassiana* spray programs for CPB management. Single and multiple sprays targeting late instar larvae reduced adult emergence by 60 and 80%, respectively. Accordingly, yields were five and 18 percent greater than the control. Promisingly, *B. bassiana* formulations are commercially available, and spray application of this material may be more comfortable to growers compared to beneficial insect releases.

The historical neglect of biological control as CPB management tool means it remains in its infancy. Foundational research is needed to understand how and when biological control agents should be deployed in the field. Likewise, research is needed to understand how biological control interacts with other IPM components. Lucas et al. (2004) demonstrated imidacloprid’s high toxicity to the 12-spotted lady beetle. Similarly, Anderson and Roberts (1983) found the pyrethroids permethrin and fenvalerate were toxic to *B. bassiana*, thus unviable tank-mix partners. They further discovered *B. bassi*ana is incompatible with emulsifiable concentrates formulated with xylene-based solvents. Findings such as these are critical to the advancement of biological control. Antagonistic relationships between biological control and other management practices could lead to the dismissal of biological control as ineffective.

Colorado Potato Beetle Host Plant Resistance

Host plant resistance offers opportunities to manage CPB through antibiosis, antixenosis, and/or tolerance. Although, host plant resistance is not broadly employed in the potato industry (Hare, 1990). This could be attributable to the arduous potato breeding process or that with potatoes end-user traits supersede agronomic traits. Moreover, CPB dynamics challenge the development of host plant resistance.

Crossley et al. (2018) evaluated F2 clones from potato (*Solanum tuberosum*) crosses with the wild relatives *S. berthaulti* and *S. chacoense*. Clones were planted across three Wisconsin sites. Efforts focused on the effects of trichome density and glycoalkaloid levels on CPB. Trichome density was negatively correlated to defoliation and positively correlated to CPB mortality. Glycoalkaloid levels of chaconine and solanine did not affect CPB. Furthermore, effects on CPB significantly varied between populations (sites). Whether differential responses exist due to ecophysiological or heritable variation, it underscores that developing host plant resistance suitable for numerous geographies may prove challenging.

Crossley et al. (2018) found the glycoalkaloids chaconine and solanine levels did not correlate to antibiosis. Lyytinen et al. (2007) also found neither glycoalkaloid to influence antibiosis; however, solanine was found to affect antixenosis. Solanine levels were positively correlated to female oviposition and male feeding. Selecting varieties with low solanine production could support non-preference or selection of varieties with high solanine levels could be used as trap crops to attract CPB.

Solanine is not the only kairomone affecting CPB preference. Some ontogenetic relationships in potato lead CPB to overlook young plants (2 – 3 weeks post-emergence) and infest mature plants (5 – 6 weeks post-emergence). However, young plants become attractive to CPB when injured via mechanical damage or herbivory (Bolter et al., 1997). Volatile organic compounds including terpenoids, alcohols, and aldehydes are emitted by undamaged plants; however, they increase during injury. Some continue to increase afterwards, whereas others return to baseline levels after the injury has occurred. Bolter et al. (1997) determined that CPB are initially attracted to volatiles stemming from the injury. Later, CPB are attracted to volatiles induced by herbivory brought on from the feeding of CPB attracted by the initial volatile organic compounds (VOCs). As with solanine, an opportunity exists through breeding and genetic engineering to manipulate VOC expression to reduce CPB preference.

Results from multiple studies suggest host plant resistance has potential as a CPB IPM component. A clearer understanding of the genetic underpinnings of potential resistance mechanisms is needed. Likewise, a better understanding of how CPB interpopulation variability interacts with host plant resistance will be crucial moving forward.

Colorado Potato Beetle Cultural Control

The final IPM component is cultural control. A stigma exists around cultural practices due to perceptions of logistical difficulty and poor return on investment (Waller et al., 1998). However, some of the most effective practices in the IPM toolbox are cultural practices and have been widely adopted. A selection of the common cultural practices for CPB management will be discussed.

Wright (1984) demonstrated that rotation to a non-host grain crop significantly reduced overwintering CPB adult survival. Rotation led to substantially lower early-season CPB pressure compared to continuous potato fields. Despite late-season CPB densities being similar between rotated and continuous fields, an average of one insecticide application was eliminated by rotating due to less early season pressure. Research conducted by Weisz et al. (1994) confirmed Wright’s findings and yielded additional insights into the value of distance between rotated fields. They found an inverse exponential relationship between inter-field distance and CPB infestations. Distancing rotated fields by 0.4 and ≥0.64 km reduced CPB adults present at potato emergence by 60% and 100%, respectively. This resulted in a 50% reduction in insecticides applied for potato fields 0.3 – 0.9 km from the previous year's potato fields. Lastly, Weisz et al. (1994) also determined that rotating to a non-host with a dense stand, such as hay or winter wheat, reduced overwintering CPB adult dispersal.

The spatial relationships described by Weisz et al. (1994) may prove valuable in managing alternative CPB hosts. Colorado potato beetle can complete part of its life cycle on many alternative hosts and its entire life cycle on a few alternative hosts, namely Solanaceous weeds such as buffalo bur (*Solanum rostratum*) (Horton et al., 1988; Hsiao and Fraenkel, 1968). In areas where potato growers control large areas of land, managing alternative hosts within the field and outside the field may be valuable in reducing CPB reservoirs. Likewise, this concept applies to volunteer potato management. Potato fields in Michigan are commonly rotated to corn the subsequent year because volunteer potatoes are readily controlled by mesotrione and other herbicides.

Cultural practices such as crop rotation, distancing, and alternative host management are valuable and common IPM practices. These preventative practices reduce the pressure placed upon therapeutic practices such as insecticide applications. Greater research is needed to explore cultural practices that are effective against CPB and logistically acceptable to growers as the industry shifts from a unilateral chemical approach to IPM.

Conclusions

Longer growing seasons, earlier CPB emergence, and insecticide resistance all threaten the unilateral chemical approach most used by the potato industry race. The Red Queen's race is untenable and CPB populations could be left unchecked. Integrated pest management offers a multi-faceted framework that seeks to reduce the impact of pests, not eliminate them (Alyokhin et al., 2014). This is an economically viable and environmentally sound approach to addressing CPB and other nefarious potato pests.

For IPM to be effective, new research is desperately needed to update thresholds, identify and characterize biological control agents, develop resistant varieties, and understand the interactions between these elements. Moreover, these solutions should be developed with growers and end-user markets in mind (Waller et al., 1998). With these new tools in hand, it will be incumbent on the industry to adopt and implement them. The status quo is not enough for managing our most troublesome pests, the time to act is now.

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