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Intricacies in Agronomic Management: The Role of Interdisciplinary Education

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INTRICACIES IN AGRONOMIC MANAGEMENT: THE ROLE OF INTERDISCIPLINARY EDUCATION

by

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INTRICACIES IN AGRONOMIC MANAGEMENT: THE ROLE OF INTERDISCIPLINARY EDUCATION

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As a science, agronomy is built upon the connection of inter-disciplinary fields of study. Management (M) of various discipline considerations (and their subsequent interactions) can be influenced by and have significant effects on genetic by environment (GxE) expression. This has led to the promotion of GxExM systems. However, optimizing GxExM programs requires extensive, interdisciplinary knowledge. To evaluate interdisciplinary training provided in undergraduate education, 11 four-year universities were selected in the United States that offer baccalaureate degree majors in agronomy or crop science. Surveys of undergraduate programs of study were conducted, with all required coursework separated into general degree components (general education, agronomy major, agronomy option, free electives). Agronomy-related coursework was subsequently separated into 20 subcategories and ranked by total credit requirements. Averaged across universities, survey results indicate an average of 71.4 ± 8.4 credits are available for agronomic training. Most universities provide robust academic training within the subcategories of soil science and soil fertility (8.8 ± 0.8 credits), crop production and crop science (6.9 ± 1.4 credits), and business and economics (5.4 ± 1.1 credits). Course requirements within the crop protection category (entomology, plant

pathology, weed science, and integrated management) were significantly reduced in comparison, ranging from 2.8 ± 0.3 to 3.5 ± 0.4 credits. Seven of the 11 universities did not require coursework on integrated management systems. Time constraints present within undergraduate education presents significant challenges in addressing these concerns because adding additional coursework requirements is not a pragmatic solution. Three mitigation strategies are presented: (1) increased emphasis on experiential learning opportunities through diverse internship experiences; (2) development and further refinement of capstone courses with a focus on integrated management systems; and (3) promotion of co-curricular courses as electives to further advance and reinforce classroom concepts. Implementation of these strategies can help address student knowledge gaps, and enhance the ability to develop and implement comprehensive GxExM management programs.

DEDICATION

This doctoral document is dedicated to all the remarkable undergraduate students I taught and coached during my graduate experience at the University of Nebraska–Lincoln. It was an utmost privilege to be a part of your educational experience, and I thank you for sharing your passions for agronomy with me each week.

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I would like to express my sincere gratitude to the DPH program director, Dr. Gary Hein for the essential role he has had played in shaping my graduate studies, as well as my professional career. His belief in my abilities as a plant practitioner and personal guidance as I navigated the turbulence found within graduate school was greatly appreciated. Likewise, I also would like to extend my heartfelt thanks to my current and past committee members; Dr. Tamra Jackson-Ziems, Dr. Robert Wright, and Dr. Don Lee for the guidance and support they have offered me during my studies at UNL. Further thanks are needed for the Department of Agronomy and Horticulture department heads Dr. Roch Gaussoin, Dr. Richard Ferguson, and most notably Dr. Martha Mamo for supporting both me and the NACTA Crops Judging team over the past five years. I also want to acknowledge Dr. Amit Jhala, my MS advisor for the flexibility and understanding he extended to me while I pursued my DPH degree, taught classes, and volunteered with the State FFA Association. Likewise, I want to also extend my earnest gratitude to the selection committees and generous donors involved with the William J. Curtis fellowship and the Earle Raun fellowship for enabling me to further my educational goals within the DPH program.

A program is only as good as its weakest students. Luckily, my studies at UNL were a wonderful experience due to the high caliber graduate students in both the DPH and AGRO/HORT department who served as colleagues, mentors, and friends (Dr. Lee Briese specifically). I will miss all of our late-night discussions about the world, agriculture, and life in general. I’d like to formally recognize my fellow graduate student Dr. Mary Happ for the critical role she has played in my graduate school experience at

UNL, and teaching me to appreciate (and slightly fear) bioinformatics. Our comradery, tempered through the highs and lows throughout five years of graduate studies together will undoubtedly serve as the solid foundation for a lifelong friendship: hopefully with visits aplenty to the habitat of our favorite alpine mammal, the American pika.

As I reach the end of the long list of people I want to acknowledge, I feel it important to also recognize my siblings, Sarah and Megan for their support, enthusiasm, and much needed moral support they have provided me throughout this endeavor. Ultimately, my educational journey at UNL would have not been possible without the unwavering love and support of my parents, Mike and Suzette Striegel. Thank you for all the grammar checks and proof reads throughout the last nine years of higher education, and for igniting my passion for agriculture at a young age.

PREFACE

During the fall of 2015, I met Dr. Gary Hein for the first time at a graduate school fair at a Tri-society meeting. After discussing the DPH program with me, he handed me a pamphlet which I found myself curiously examining later that afternoon with great interest. A few hours later at an awards banquet, I was introduced to Dr. Roch Gaussoin (the department head of Agronomy and Horticulture at the time). I told him of my initial interests in the DPH program, and of my background experience in the NACTA Crops Judging contest. As we parted ways, he informally offered me partial teaching stipend if I ended up choosing to pursue the DPH program at UNL, in exchange for creating a teaching undergraduate course for students interested in the NACTA Crops Judging contest.

The final event of the evening was a social networking event hosted by Monsanto at a local restaurant. It was there I met Dr. Derek Pruitt, current student (now alumni) of the DPH program who was completing a six-month internship with Monsanto. What ensued was a multi-hour-long conversation about the program and his experiences as a student which galvanized my decision to apply to the DPH program. As I recount this story, it feels like the universe seemingly aligned for me all at once. I know the DPH program was where I was meant to be.

I ultimately chose to pursue the DPH program due to significant knowledge gaps present within my educational training at the bachelor’s level. These educational deficiencies presented themselves across multiple, fundamentally separated disciplines which could not be properly addressed by any traditional MS or PhD program. It is my strongly-held belief that the discrepancies present within my own agronomic training at

the undergraduate level were not unique to me, nor Iowa State University but endemic of higher education itself due to inherent time constraints. While not every undergraduate student has the same motivators for post-graduate education, it is with this belief I have strived the last five years as a teacher, as a mentor, and as a coach to promote the importance of interdisciplinary content knowledge and training and provide the same type of meaningful agronomic training which ignited my passion for agronomy (and inevitably led me to the DPH program). This doctoral document serves to review the current state of agronomic education and provide my personal philosophy in education as it pertains to agronomy and its practical application in the field.

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CHAPTER 1: THE FOUNDATION OF AGRONOMY

Defining Agronomy

The achievements and accomplishments of the human race have been made possible due to giants present throughout our long and storied history as a species. Giant's whose shoulders we now stand upon. Through countless scientific advancements and relentless exploration and study of the natural world, these giants pioneered new ages of understanding of the complex ecological systems we are a part of. With the uncertain and perilous nature of climate instability threatening our planet, collaboration between scientific disciplines and subdisciplines to foster advancements in agricultural production practices is paramount. One such agricultural collaboration is well-established: Agronomy.

According the American Society of Agronomy (ASA), agronomy is the integrated view of agriculture as it pertains to the fields of crop and soil science as well as ecology (ASA, 2021). The term agronomy is often used synonymously with similar terms such as crop science and plant science. As with other scientific fields of study, agronomic research is largely dominated by discipline- and subdiscipline-specific specialists. In contrast, agronomic production is predominantly comprised of agronomic generalists trained in the integration of multiple diverse scientific disciplines (University of California-Davis, 2021) with an emphasis on crop management. Despite these dissimilarities, agronomy is also intricately intertwined with the field of economics (Heady & Shrader, 1953).

Fully detailing the influence of economics in management decisions in agronomy is challenging due to the complexity of production systems. For example, economics can

influence crop or variety selection (Kumar, Singh, Kumar, & Singh, 2015; Wright, Griffin, Guha, & Bouldin, 2018), crop protection products used (Oerke, Dehne, Schönbeck, & Weber, 2012), soil fertility and tillage practices (Sharma et al., 2009; Usman et al., 2013), as well as weed management tactics or programs used (Gaban, 2013; Reddy & Whiting, 2000; Striegel et al., 2020). Limitations in research funding can result in the simplification of production systems, with alternative and minor crops "left behind" in favor of more mainstream crops better supported by agronomic research and the commodity markets (Shah, Khan, Iqbal, Turan, & Olgun, 2020). For most cropping systems, economics emphasizes increasing the overall quantity and quality of the marketable products, but they often exclude the components or practices focused on ecological benefits because these components are difficult to quantify. As such, it is at the intersections of different factors directly related to yield that the discussion of Agronomy begins.

Genetics, Environment & GxE

Genetics – Selecting for Performance

While our species has endured on Earth for nearly 100,000 years, the transition from nomadic hunter-gathers to farmers happened relatively recently around 10,000 BCE (Gowdy, 2020). As civilization developed, our ancestors and the crops they relied on co-evolved together (Reeves & Cassaday, 2002). During this process, genomic selection of crop species was made primarily by farmers with the retention of seeds from the highest yielding plants for use in the next cropping season. This selection system prevailed for millennia with our ancestors unaware of the complexities underlying these selection

events. It wasn't until observations by Gregor Mendel in the mid-1800s that the mysteries shrouding these selections first began to unravel (Henig, 2000). Mendel's foundational work served as a giant leap in our scientific understanding of the world around us.

Over the next hundred years, Mendel's contributions to the science of genetics served as a springboard for the men and women who followed in his footsteps. One such man was Nikolai Vavilov, a soviet plant geneticist and agronomist who toiled tirelessly in the 1930s and 1940s to establish the centers of origins for cultivated plant species (Malone, Kennard, McCain, Oyster, & Wells, 1980). As untold Russian civilians starved due to crop failures, Vavilov and his team understood that in order for crops to win the "battle" against agronomic concerns present within their growing environments, systematic and conscious breeding efforts must be focused on discovering and integrating novel genetics into existing cultivars (Vavilov, 1951).

As the world emerged from the destruction wrought during World War II, agricultural research and plant genetics entered a phase of massive development and advancement. Referred to as the Green Revolution, it was during this period Norman Borlaug developed semi-dwarf wheat (*Triticum aestivum*, Rht-1) varieties within a famine-stricken region of Mexico. With plant heights reduced by 20%, yields increased almost immediately 5-10% (Jobson, Johnston, Oiestad, Martin, & Giroux, 2019) due to resistance to late-season lodging that resulted from heavily laden seed heads (Hedden, 2003). These dwarfed wheat varieties stemmed the tide of hunger in Mexico, and quickly spread across the globe to other food-insecure regions, such as Pakistan and India (Jain, 2010). The increased food production from semi-dwarf wheat varieties developed by Borlaug as well as semi-dwarf rice (*sd*1) cultivars are estimated to have saved 1.3 billion

human lives (Jobson et al., 2019). These accomplishments stand as resolute examples of the power of agricultural advancements.

Several decades later in the mid-1980s, the science of plant breeding and plant genetics took another giant leap with the development of genetic engineering and genomic transformation technologies (James, 2003). Using a variety of genetic techniques, two main classes of novel engineered traits emerged: insect resistance and herbicide resistance. While initially well received for a host of economic and agronomic reasons (James, 2003), positive and negative impacts have been claimed to varying levels of accuracy and relevancy. (National Academies of Sciences, Engineering, and Medicine, 2016). While transgenic crops are widely accepted in the United States (Kniss, 2018), other countries have rejected these advancements and opted to ban their use instead (Romeis, McLean, & Shelton, 2013).

Ultimately, the guiding mission for plant breeders has remained unchanged. This goal is shared in every plant breeding program and approach: produce plant varieties and/or hybrids which provide superior yield and performance in the environment they are grown. It is with this guiding principle the discussion of environment begins.

Environment – The Tests of Mother Nature

Discussion of the field of agronomy would be inadequate without first acknowledging the significance of environment. Once placed within a growing region, plants are entirely reliant on their local surroundings for all plant nutrients essential for survival. As complex organisms, the natural environment for all plants is made up of a collection of stressor events of both biotic and abiotic nature (Cramer, Urano, Delrot,

Pezzotti, & Shinozaki, 2011). Through intricate biochemical regulation, plants utilize specialized hormones and enzymatic pathways to respond to ever-fluctuating environmental conditions ranging from water availability, nutrient availability, light quality and day length, temperature, relative humidity, and carbon dioxide concentrations. As an integral component of nearly all terrestrial ecological systems, plants endure a variety of biotic stressor events ranging from attack from various insects, plant pathogens, and animals (Lipson & Näsholm, 2001). The interaction of crop genetics with the cropping environment is where a large portion of plant breeding has been focused (Annicchiarico, 2002; Brummer et al., 2011; Hill, 1975).

Accounting for GxE interactions

Since the green revolution in the 1950s and 1960s, agricultural production has largely kept pace with the world's demand for food. These achievements were made possible through agronomic inputs coupled with the success of plant breeding programs to select robust crop varieties more resilient to the effects of abiotic and biotic stress events (Brummer et al., 2011). Improved resilience observed in many crop species during this time is due in part to the deliberate selection of cultivars with yield stability across multiple testing environments. From a plant breeder perspective, crop cultivars that provide consistent performance across different environments are most often preferred. This resiliency of crop cultivars is often due to the complexity of many quantitatively-inherited traits. For instance, crop yield is a culmination of numerous genes interacting to affect the production of grain or biomass. Thus, it is often the most important metric used to evaluate cultivars (Falconer, 1996).

As genomic data has increased in availability and decreased in price through low readthrough, high throughput means (Happ, Wang, Graef, & Hyten, 2019), plant breeders and geneticists have intensified efforts to identify plant genotypes with robust tolerances to abiotic and biotic stresses (Kang, 1997). These efforts have proven arduous, as the same loci which provide superior performance in one testing environment might result in a negative impact in another (El-Soda, Malosetti, Zwaan, Koornneef, & Aarts, 2014). Nonetheless, the ability to model and forecast these genetic interactions via quantitative trait loci (QTLs) has become a vital step in the production of commercial cultivars of many crops with resistance to biotic and abiotic stressors. These capabilities have enhanced crop yield and yield stability across different growing environments (Buerstmayr, Ban, & Anderson, 2009; Chung et al., 2003; Concibido, Diers, & Arelli, 2004; Kaur et al., 2009; Khairallah et al., 1998; Paterson, Saranga, Menz, Jiang, & Wright, 2003).

Incorporating Management into GxE: GxExM

Quantification and prediction of GxE interactions on crop productivity is essential in providing robust cultivars that perform even under significant stress. However, the effect of agronomic management on GxE (e.g. GxExM) has not been emphasized until recently (Hatfield & Walthall, 2015). Previous literature supports an expanded GxExM model. For example, the genetic advancements made during the green revolution via developing semi-dwarf cultivars of rice and wheat were integral in addressing food security concerns (Jain, 2010). However, increases in grain production for these cultivars would have been only marginally improved compared to traditional cultivars if

agronomic management did not also change. Large increases to grain production were due to GxExM interactions, with the dwarfed cultivars accompanied by intensification of agricultural inputs and irrigation within highly-productive regions (Cleaver, 1972; Lynch, 2007). This point is illustrated by the trends in global nitrogen fertilizer use, which has increased seven-fold since the 1960s (Vitousek et al., 1997). These increases came with concurrent increases in pesticide discovery, commercialization, and use of crop protectant products (fungicides, insecticides, and herbicides) in many cropping systems (Jain, 2010). An estimated 40% of agricultural produce is lost due to plant pathogens, insect pests, and weeds (Mahmood, Imadi, Shazadi, Gul, & Hakeem, 2016). Therefore, crop protectant products are uniquely positioned as tools to safeguard agricultural production.

The successes of the green revolution were unfortunately not without downfalls. Overreliance and misuse of pesticides led to the destruction of biodiversity of birds, aquatic life, and animals worldwide (Mahmood et al., 2016). Improper use of synthetic nitrogen fertilizers has led to the acidification of many soils, streams and lakes as well as the widespread decline of estuarine and nearshore ecosystems (Vitousek et al., 1997). Poor stewardship of herbicides led to the selection for herbicide-resistant weeds and wide-spread shifts in species composition (Heap, 2014; Owen, 2008). Escalating effects of pesticide resistance have been observed in plant pathology and entomology as well (Casida & Quistad, 2000; Ishii & Hollomon, 2015). The risk and widespread damage to biodiversity from rampant use of pesticides was first publicized by Rachel Carson's 1962 book, *Silent Spring* which called for increased pesticide regulation (Carson, 1962). In the years that followed, many harmful products were removed from the market, with other

products being re-evaluated for safety and ecological effects periodically (US EPA, 2013).

Mankind stands on the cusp of entering an unprecedented era of food insecurity and human hunger. With the population expected to crest at 9 billion people by the year 2050, many researchers are calling for a new, or second green revolution to address food production concerns (Wollenweber, Porter, & Lübberstedt, 2005). However, as Lynch (2007) explained, the second green revolution must build upon the successes of the first, but in a more ecologically sustainable manor (Lynch, 2007). To do so, the examination of GxE interactions must transcend the current paradigm and focus instead upon interdisciplinary research and maximize understanding of GxExM interactions.

Management Considerations

The effect of agronomic management has immense ramifications for overall crop productivity. As an integrated science, agronomy is comprised of multiple scientific disciplines working together in tandem. In each of these disciplines, different management concerns exist that must be considered when optimizing agronomic management. A brief review of the following scientific fields and their relationship with agronomic management are provided below.

Soil Science – The Foundation of Agriculture.

Paul Harvey once famously said that despite all our artistic pretensions, sophistications, and many accomplishments, we owe our existence to a six-inch layer of topsoil and the fact it rains. It is with this account the discussion of management

considerations begins with the discipline of soil science not from the “ground up”, but from the “rhizosphere up”.

As a scientific discipline, soil science is primarily separated into two main branches of study: pedology (the study of natural soil morphology, soil-forming factors, soil classification, and soil geography/mapping) and edaphology (the study of soil-dependent uses and biotic interactions) (Bockheim, Gennadiyev, Hammer, & Tandarich, 2005; Chertov, Nadporozhskaya, Palenova, & Priputina, 2018; Richter, 2007). Both branches have a cascading effect on optimizing soil management as it pertains to GxExM.

From a pedology perspective, classic soil surveys have traditionally integrated pedological information into the sampling programs to account for low sample numbers and improve accuracy (Walter, Lagacherie, & Follain, 2006). This success can be improved by focusing pedological data to consider the behavior of different soils found within a landscape (Bouma et al., 1999). High quality pedological data assessed at the landscape level can enable robust modelling applications, such as risk assessments and impact studies (Bouma, Stoorvogel, Alphen, & Booltink, 1999; Walter et al., 2006).

All soils are comprised predominantly of mineral particles with the remaining composition consisting of soil organic matter (SOM), air, and water. Within the mineral component, soil texture classes are assigned based on the proportion of different mineral particle sizes: sand, silt, and clay. Different proportions of sand, silt, and clay within a soil series can have significant influences on soil management concerns such as such as erodibility, stability, fertility, and soil drainage (Mullen, 2015). Likewise, the physical arrangement of these mineral particles within the soil profile (i.e. aggregation or soil

structure) can directly influence macro and micro porosity, water-holding capacity, infiltration and permeability (Mullen, 2015). In addition to these influences, attributes derived from soil texture and structure can affect the concentrations of soluble salts (salinity) found within a soil profile (Li, Chang, & Salifu, 2013). Due to these differences, GxExM interactions inform producers on specific crop species or cultivars more suited to certain growing regions. Mismanagement of soils also affects crop productivity. For example, high traffic during wet conditions often results in soil compaction, and this physical degradation of soil structure results in reduced porosity, permeability, and nutrient availability (Nawaz, Bourrié, & Trolard, 2013).

Soil physical factors impact soil management decisions for agronomic crops. For example, barley (*Hordeum vulgare*) is often selected to be grown in high-saline areas over wheat, and small-grains or dry beans (*Phaseolus vulgaris*) are preferable to corn (*Zea mays*) or soybean (*Glycine max*) in moisture limited areas. In high clay soils, producers are more likely to adjust supplemental irrigation scheduling in comparison to sandier soils, and in non-moisture limited environments, opt for installation of drainage tile (if available) to drain excess moisture.

In addition to the physical properties of soil, soil is teeming with complex and dynamic chemical properties. At any given time, large numbers of chemical reactions are occurring within the soil profile, ranging from the breakdown of organic substrates and mineral components, mineralization and fixation of soil nutrients, to local pH changes (Mullen, 2015). Similar chemical processes also occur with agricultural inputs added to the soil, for example the degradation and acidification of synthetic pesticides and fertilizers (Arias-Estévez et al., 2008; Zeng et al., 2017).

Despite the long and storied history of agricultural advancements and the development of soil science during the late-Roman era (Frink, 2011), the scientific study of soil fertility lagged behind. In the mid 1800's, the German scientist Justus von Liebig produced the first comprehensive review of mineral nutrition of plants (Marschner, 2011). Liebig's publication established soil fertility as a full-fledged subdiscipline. This led to rapid experimentation and advancements in mankind's understanding of plant nutrition dynamics (Marschner, 2011). In the years that followed, use of synthetic potassium and phosphorus containing fertilizers, planned rotations to legume crops for nitrogen-fixation credits, and eventually use of synthetic nitrogen fertilizers increased dramatically across Europe as producers sought an increase production of agricultural crops (Chorley, 1981).

From the soil management perspective, increased agricultural production has been enabled by our knowledge of plant nutrition. As with other aspects of agronomy, a "one-size-fits-all" approach for soil fertility is inappropriate due to the dynamic nature of soil systems. Within each soil, chemical attributes bestowed by the molecular structure of the mineral components of sand and silt (e.g. quartz and aluminosilicate feldspars) and clay (phyllosilicates) can range wildly. Of these, phyllosilicate and other clay minerals (< 2 mm in size) can have a profound impact on numerous soil chemical reactions and processes (Sparks, Ginder-Vogel, & Singh, 2021). Of these, cation exchange (CEC) and anion exchange capacities (AEC) serve as a great paradigm for optimizing soil fertility management. Simply put, the surface of each soil particle has both positive and negative electrical charges due to different chemical functional groups (such as hydroxyl, OH), as well as the edges of lattice minerals. Positive charges enable the attraction and retention

of negatively-charged compounds called anions (e.g. $H_2PO_4^-$, $Mo_4O_2^-$, NO_3^-). Likewise, negative charges enable the attraction and retention of positively-charged compounds called cations (e.g. NH_4^+, K^+, Mg^{++}) (Sumner & Miller, 1996).

Clay minerals have much higher CEC in comparison to other soil components due to the isomorphic substitution of atoms found in the center of their crystalline structure (Sparks et al., 2021). However, SOM (e.g. hummus) is often the largest contributor to CEC found within the soil with a charge of 200-400 cmol kg^{-1} (M. L. Thompson, Zhang, Kazemi, & Sandor, 1989). In contrast, secondary clay minerals range from 2 cmol kg^{-1} for one-to-one clays (e.g. kaolinite) up to 200 cmol kg^{-1} for vermiculite (Sparks et al., 2021). Generally, the higher a CEC, the more capable a soil is to buffer the acidification of the soil. This can manifest itself in ExM interactions. For example, in sandy soils with low clay concentrations, the naturally low CEC can influence producers to select residue management programs that retain or incorporate crop residue to increase SOM (Singh, Rengel, & Bowden, 2006). Likewise, depending on the CEC of a soil, different soil fertility management decisions may be made. For example, when determining the amount of a synthetic fertilizer to apply such as muriate of potash (0-0-60, K_2O), it is important to account for the competition potash can have with magnesium and calcium for active sites within the soil (Lin, 2010). This is typically accounted for by the percent base saturation, but as a general trend, soils with higher CEC and base saturations are more fertile and can retain more fertilizer than soils with low CEC and low base saturations (Mullen, 2015).

From an ecological standpoint, the capacity of a soil to maintain fertility needs to be taken into consideration when planning soil fertility programs to best address the nutritional needs of the crop, while simultaneously safeguarding environmental quality.

Mismanagement of soil fertility can have extensive environmental and ecological consequences. Prime examples of this include nitrate contamination of groundwater in North American watersheds (Almasri & Kaluarachchi, 2007) and the massive zone of hypoxia (i.e. the dead zone) in the Gulf of Mexico caused by off-target movement of fertilizers (Nassauer, Santelmann, & Scavia, 2010).

Soil is composed of largely inorganic constituents, but it is teeming with life on both a macroscopic and microscopic scale. For example, earthworms play a crucial role in increasing soil tilth and soil fertility by improving aggregation, breaking down plant residues, and aerating the soil (Mullen, 2015). The same can be said about microscopic organisms comprised of soil and plant associated fungi, soil bacteria, and nematodes.

In recent years, reduced tillage and no-tillage systems have been promoted heavily in traditional row-crop agriculture due to the potential for ecological, environmental, economic, and agronomic benefits. For example, no-tillage systems have been experimentally shown to reduce of soil erosion (Phillips, Thomas, Blevins, Frye, & Phillips, 1980), improve moisture holding capacity due to improved aggregation (Guo et al., 2020), and improve soil health (Thomas et al., 2019). Scientific consensus on best management practices for soil health are still being established, but the importance of eliminating or reducing tillage in increasing microbial biodiversity is well documented (Frąc, Hannula, Bełka, & Jędryczka, 2018).

Soil microbes are directly integrated in the process of nutrient cycling. Soil microbes are involved in the decomposition of crop residues (nutrients in organic form) to inorganic form and enable the cycling of those nutrients back to organic form through their uptake by plants for use in growth and development (Al-Kaisi & Lowery, 2017;

Mullen, 2015). One famous example is the nitrogen cycle. In soil systems, nitrogen is readily converted from ammonium to nitrite to nitrate by bacteria in the *Nitrosomonas* and *Nitrobacter* genera, respectively (Pepper, Gerba, Gentry, & Maier, 2011). Understanding the soil biology of this cycle has led to the development of different nitrogen stabilizer products which can be applied with synthetic fertilizer. These stabilizer products are successful in inhibiting nitrification and/or the activity of the urease enzyme to help prevent volatilization or leeching of nitrogen from the field (Halvorson, Snyder, Blaylock, & Grosso, 2014; Sha et al., 2020).

Management factors can have significant impact on soil microbes and nutrient bioavailability. Many plant species develop symbiotic colonization of plant roots by endomycorrhiza (e.g. arbuscular mycorrhiza) and ectomycorrhiza, and these relationships aid in the uptake of soil nutrients such as phosphorous (Lambers & Teste, 2013). These symbiotic relationships are usually much more energetically favorable than relying on direct root interception for water and nutrient uptake (Marschner, 2011). However, tillage can adversely affect arbuscular mycorrhiza community structure and enzymatic activity levels (Jansa et al., 2002). Brito et al., (2012) found that fungal diversity and colonization rate were correlated more strongly with tillage system than crop species. This is typically due to the dilution of fungal propagules by tillage (Kabir, 2011). Research has demonstrated favorable impact from inoculating arbuscular mycorrhiza species of agronomic and horticultural crops alike with emphasis on salinity alleviation, phosphorus uptake, drought tolerance, interactions with *Rhizobium japonicum* in soybeans, and crop yield (Bagyaraj, Manjunath, & Patil, 1979; Beltrano, Ruscitti, Arango, & Ronco, 2013; Fahramand, Adibian, Sobhkhizi, Moradi, & Rigi, 2014; Sabia et al., 2015).

Ultimately soil science serves as the basis that agronomy is built upon. Comprehensive understanding of soil science is essential to tipping the balance between success and failure of a cropping system. Management decisions made in fertility programs, in crop species/variety selection, and in tillage and residue management can directly affect the overall economic and ecological impacts of a cropping system. Likewise, the timing and implementation of field operations throughout the year can have cascading effects on the environmental and ecological ramifications associated with agricultural production. Implementation of conservation practices and science-informed, site-specific management can help agricultural production systems remain robust despite the challenges provided by global climate change.

Plant Physiology – Placing Plants in The Right Place.

Simply defined, plant physiology is the study of the processes which are associated with the growth and development of plants. More specifically, from an agronomic standpoint, plant physiology is focused on the production of agronomic and forage crops. At the simplest level, plant physiology studies the physical compositions of plants (e.g. plant cells, specialized tissue, vascular systems) and how these components interact physically and chemically with other plant components (Taiz, Zeiger, Møller, & Murphy, 2015*)*. As a discipline, plant physiology is intricately linked to all the other management sections discussed in this chapter. For example, crop physiology is directly related to plant nutrition and thus, soil science as previously described (Marschner, 2011). Likewise, plant hormones play an intricate role in the defense against insect pests as well as plant pathogens, but they are also integral to the plants response to abiotic

stressors (Alazem & Lin, 2015). Likewise, inherent differences in the biochemical process of photorespiration and carbon fixation in C3 and C4 plants directly impact their ability to provide adequate forage to livestock at different times of the year (Nelson & Moser, 1994), as well as their efficiency and suitability in different growing environments. In this section, a brief discussion of plant physiology management considerations is limited to photoperiodism, plant hormones, and carbon fixation/photorespiration.

As plants grow, eventually a physiological switch is triggered, to transition the plants from vegetative growth into reproductive development. This is usually triggered by changes to photoperiod length, with three broad groups corresponding to critical daylength values which must be met on a 24-hour cycle: short-day plants, long-day plants, and day-neutral plants (Hopkins & Huner, 2008). While short-day plants require daylength to be below critical maximum value, and long-day plants require daylength to be above a critical minimum. In contrast, day-neutral plants will transition into reproductive development regardless of daylength.

Differences between photoperiod groups are important GxExM considerations in agronomic management. For example, small grain crops such as wheat, cereal rye (*Secale cereale*), and triticale (*x Triticosecale*) are long-day plants. Reproductive development in spring cultivars can be forced to trigger when grown in controlled short-day conditions (i.e. in a greenhouse), whereas winter cultivars require a period of vernalization prior to reproductive development. In both cases, it is important to note that exposure to natural long-day conditions increases the rate of flowering considerably (Hopkins & Huner, 2008).

In the Midwest, the most common short-day crop produced is soybean. As the latitude of a growing region increases or decreases, recommendations for selecting optimum soybean maturity groups (MG) also change (Boerma & Specht, 2005). Consider soybean cultivars developed for the Southern United States (e.g. MG4-6). Critical maximums for flowering would occur at a much later date when grown in the Northern United States. Inversely, soybean cultivars developed for the Northern United States and Canada (e.g. MG00-3) would flower extremely early in the growing season if placed in southern growing regions. Manipulation or optimization of soybean MGs within a growing region (GxE) in combination with planting date (ExM) can result in significant yield increases, and have important ramifications in terms of irrigation and fungicide applications (Salmerón et al., 2016; Salmerón, Purcell, Vories, & Shannon, 2017). The effect of photoperiod in determining suitable growing regions and seasonality for short and long-day crops cannot be ignored if GxExM systems are to be optimized.

The second topic of plant physiology and their significance on GxExM interactions is plant hormones. Overall, plant hormones are critical in the biochemical regulation of plant processes, maintenance of plant homeostasis, and defense against abiotic and biotic stress events. As reported in by Taiz et al. (2015), the five historic groups of plant hormones were auxins, gibberellins, cytokines, ethylene, and abscisic acid (ABA). Recent research has identified a new plant hormone in the steroid category (brassinosteriods), first discovered in the common mustard plant (*Brassica napus*), and these steroids are believed to have widespread effects on plant development (Rao, Vardhini, Sujatha, & Anuradha, 2002). Likewise, a new class of plant hormone was discovered in the parasitic plant witchweed (*Striga* spp.) (Xie, Yoneyama, & Yoneyama,

2010) This hormone (strigolactone) has significant effects on the regulation of root and shoot development (branching) as well as the interactions with symbiotic arbuscular mycorrhizal (AM) fungi present within the rhizosphere (Seto, Kameoka, Yamaguchi, & Kyozuka, 2012).

Because of the integral role plant hormones have on physiological processes ranging from fruit ripening (ethylene) to promoting cell division (cytokinins) to regulating growth (auxins) and stomata conductance (ABA), a full discussion of plant hormones is impractical. From a plant defense standpoint, it is worth mentioning the crucial role of salicylic acid (SA) and jasmonic acid (JA) (Maruri-López, Aviles-Baltazar, Buchala, & Serrano, 2019). SA and JA have experimentally been shown to have independent and cross-talk roles in downstream signaling and activation of pathogen triggered immunity (PTI), the first layer of plant immunity that restricts pathogen proliferation (Campos, Kang, & Howe, 2014; J. Zhang & Zhou, 2010; W. Zhang et al., 2018). Likewise, JA and SA are also responsible for inducing defense responses to insect pests (Black, Karban, Godfrey, Granett, & Chaney, 2003; El-Wakeil, Volkmar, & Sallam, 2010; War, Paulraj, War, & Ignacimuthu, 2011) and triggering systemic acquired resistance (SAR) to biotic stressors (Klessig, Choi, & Dempsey, 2018). SA and JA activation of plant defenses stand to be critical to the maximization of GxExM interactions.

Carbon fixation and photorespiration and their effects on management focuses on the suitability and placement of C3 and C4 crop species for given precipitation and temperature regimes. Many crop species which have centers of origin in or near tropical and subtropical regions have evolved advantages to combat the warmer temperatures and

moisture regimes. Referenced as C4 plants (named for the four-carbon acid oxaloacetate), nearly 1,500 species of plants have been identified with these adaptations (Hopkins & Huner, 2008), with a majority of C4 plants concentrated as monocot species (Sage & Kubien, 2007). C4 plants are morphologically and biochemically different than C3 crops such as barley, wheat, soybean, and potato (*Solanum tuberosum*). Increased concentrations of photosynthetic pigment and anatomical adaptations (Kranz anatomy) has led to improved photosynthetic efficiency. The enzyme phosphoenolpyruvate carboxylase (PEPCase) enables C4 plants to utilize bicarbonate (HCO_3^-) as a substrate to fix carbon. While this process does require the use of ATP, no reduction in carbon is associated with carbon fixation in C4 plants, in comparison to the loss of carbon due to photorespiration in C3 plants. These differences, along with other evolutionary differences in C3 and C4 plants, leads to superior performance of C4 plants in hotter climates where they have greater exposure to moisture-stress and/or drought conditions. In contrast, in cool, moist growing environments or seasons, C3 plants often outperform C4 plants due to the increased energy requirements for C4 anatomical and biochemical adaptations. As such, selection of crop species (and carbon fixation system) for a given moisture regime or climate is an imperative GxExM consideration.

Entomology – Duality of Insects: From Plant Pests to Predators

Hailing from Greek origins, the word entomology translates roughly to "discourse on insects" (Srivastava & Singh, 1997). From an economic standpoint, entomology is a vastly important discipline due to the detrimental role insects play as plant pests both in the field and in storage. The duality of insect's role in agriculture is highlighted by the

positive effect insects fulfill as natural predators and parasites of many plant and animal pest species (Srivastava & Singh, 1997). Additionally, pollinator species such as the honey bee (*Apis mellifera*) play an essential function in plant pollination of many crop species, with the social gains estimated to range between 1.6 to 5.7 billion dollars annually in 1992 (Southwick & Southwick, 1992). The optimization of insect management and GxExM interactions must account for both these positive and negative roles.

As with other agricultural pests, management options and strategies of insect pests have evolved over time. For example, some of the first widely used insecticides popularized in the late 19th and early 20th century were highly toxic arsenic compounds (Flint and van den Bosch, 2012). With the discovery and commercialization of chlorinated hydrocarbon insecticides such as dichlorodiphenyltrichloroethane (DDT) in the 1940s, DDT quickly replaced the use of arsenic-based products and spread worldwide due to the cheap, highly efficacious control it provided for a broad spectrum of insect pest species (Flint and van den Bosch, 2012). DDT joined a quickly growing list of highly-effective (albeit toxic and potentially lethal) insecticide classes developed and commercialized during or immediately following World War II (e.g. organophosphates and carbamates).

The swift rise of the pesticide commercialization and nearly universal adoption of insecticides in agricultural production and human society as a whole, often led to the abandonment of non-insecticidal control methods and in turn, unintended ecological damage. In what was eventually hailed as the “dark ages of integrated pest control” (Newsom, 1980), one unintended ecological consequence was the bioaccumulation of

DDT that resulted in weakened eggshells of bald eagles and peregrine falcons, leading to critical endangerment (Flint and van den Bosch, 2012). In response to some of the ecological damages in the mid-1940s and 1950s, governmental regulation and de-registration/banning of harmful and dangerous chemistries have taken many of these older, more toxic insecticides off the market, with many producers transferring to newer chemistries and plant-incorporated protectant products (Romeis et al., 2013). A more important impact of these regulatory changes has been the re-emphasis of non-insecticidal control methods into integrated pest management (IPM). IPM programs originally were developed in the 1920s (Newsom, 1980), but they took on much more significance beginning in the 1970s (Kogan, 1998).

At the most basic level, IPM programs are ecologically-based pest management programs which focusing on preventing economic damage from pests. This is accomplished through the combination and integration of a variety of control tactics (University of California IPM program, 2021). Adoption and the rapid implementation of IPM programs for many pest species/crops were driven by widespread and extensive societal pressure to mitigate ecological impacts of insecticide misuse. While many agronomic systems promote IPM to prevent or slow the selection for insecticide-resistant insect populations (Kogan, 1998), the main tenets of IPM programs are to minimize risks to human health and the environment while maintaining economic production (University of California IPM program, 2021)

Within an IPM program, the various control tactics deployed are categorized by the mechanism by which they work. The main IPM tactic groups are comprised of cultural, physical, genetic, biological, and chemical methods. These groups can also work

in tandem with governmental regulatory actions (Penn State Extension, 2011). However, continual success of IPM programs relies heavily upon relevant economic research (Ehler, 2006) and accurate scouting data of pest populations. For example, accurate research predicting expected yield losses of a crop based on the insect population size and crop stage must be available to compare to costs of control. Further research is required to determine the pest density (economic threshold) when management action should be taken to ensure the level of economic loss due to insect damage does not exceed the cost of control (economic injury level) (Flint and van den Bosch, 2012).

Sustainability is also a large focus of insecticide resistance management (IRM). IRM seeks to delay selection for insecticide resistance in insect populations (Ehler, 2006). As such, IRM is a component within many IPM programs. When considering the complexity of GxExM interactions, it is clear special care must be taken to ensure management practices seek to maintain economic production while attempting to minimize ecological damage and unsustainable practices. A discussion of important G, E, GxM, ExM and GxExM concerns is provided below.

Arguably the foremost management decision as it pertains to insect management is the plant genetics placed within the field. Depending on crop species, vulnerability to a specific insect pest can vary. Likewise, within a given plant species, different cultivars can vary widely in the level of resistance (antixenosis, antibiosis, and tolerance) (Tabari, Fathi, Nouri-Ganbalani, Moumeni, & Razmjou, 2017). Referred to as host plant resistance, genetic resistance provides qualitative resistance against target insect pests for many crop species (Rouf Mian, Kang, Beil, & Hammond, 2008). One example is soybean resistance to soybean aphid (*Aphis glycines* Matsumura). Resistance to *A. glycines* in

soybean is provided by two genes, *Rag1* and *Rag*2 (Rouf Mian et al., 2008). Due to the presence of virulent biotypes of soybean aphids resistant to *Rag1* in the United States, researchers from Iowa State University recently evaluated the effect of pyramiding these resistance-genes (e.g. *Rag1* plus *Rag2*) into experimental soybean cultivars. Results from this study indicated no observable yield reductions in pyramided cultivars in comparison to 5% yield loss in single-gene lines, and a 14% yield loss observed in the susceptible check (McCarville et al., 2014). When genetic resistance is deployed as part of an IPM program, GxM interactions can provide robust defense against insect feeding.

With the advent of genetic engineering and plant transformations as described previously, one major class of novel proteins were incorporated into plants as plant-incorporated protectant products (PIPs). Common PIPs include various *Bacillus thuringiensis* (Bt) proteins, proteases, and more recently RNA interference (RNAi) technologies (Gordon & Waterhouse, 2007; Kennedy, 2008; M. E. Nelson & Alves, 2014). PIPs have been effective at controlling various insect pests in corn (Hutchison et al., 2010), soybean, rice (*Oryza sativa*), potato and many other crops (Nelson & Alves, 2014). These technologies can be deployed in tandem with management (GxM) to provide significant defense against insect-borne economic loss. However, these management options must also be incorporated into an IPM/IRM program to reduce the risks of resistance development.

Another avenue to consider the effects of management is ExM. In these scenarios, the local environment is altered to impact insect pest populations. A rather infamous example of ExM interactions which has received a lot of attention is the prevalent use of neonicotinoid insecticides as seed treatments to protect against soil associated insects

(Hladik, Main, & Goulson, 2018). Neonicotinoids mimic the effects of nicotine and bind to the nicotinic acetylcholine receptors within the insect nervous systems (Brandt, Gorenflo, Siede, Meixner, & Büchler, 2016). Despite their recent commercialization in the 1990s, (Casida & Quistad, 2000), neonicotinoid use has increased to account for over 25% of global insecticide use as the most widely used class of insecticide (Hladik et al., 2018). The use of neonicotinoids as seed treatments in corn is pervasive, with a majority of hybrid corn grown in the United States receiving at least one neonicotinoid active ingredient (C. H. Krupke, Holland, Long, & Eitzer, 2017). While at face value this example focuses on ExM management, ecological damage associated with off-target movement and/or activity of these insecticides again highlight the important of ecological damage. This is highlighted by multiple studies which have reported significant health effects on honey bees exposed to sublethal doses (Alaux et al., 2010; Brandt et al., 2016; Doublet, Labarussias, Miranda, Moritz, & Paxton, 2015; Fairbrother, Purdy, Anderson, & Fell, 2014; Santos et al., 2018; Tesovnik et al., 2017). For example, Krupke et al. (20017) reported that over 94% of honey bees in Indiana would be exposed to "neonicotinoid dust" created during the process of planting row crops. Krupke et al. (2017) called for integration of IPM tactics for deployment of seed treatments in order to mitigate potential harm to pollinator species. Despite these reports, consensus on the effects on bee colonies as a whole (rather than on the individual) has not been reached (Ratnieks, Balfour, & Carreck, 2018). An important caveat to consider is that neonicotinoids (and in turn, synthetic pyrethroids) have largely replaced older, more toxic compounds (i.e. organophosphates and carbamates), resulting in a "net positive" effect in comparison to

conventional chemistries (Carreck, 2017). Regardless of these perceptions and improvements, re-integration of IPM methodologies remains essential.

In IPM programs, recognition and avoidance of adverse effects of broad-spectrum insecticides on beneficial insects by insecticides is critical. For example, exposure to imidacloprid, malathion, methamidophos, acephate, acetamiprid, and abamectin have been reported to cause up to a 61% mortality rate on adult minute parasitic wasps in the *Encarsia* genus (M. Thompson, Gamage, Hirotsu, Martin, & Seneweera, 2017). Similarly, exposures to emamectin benzoate (which is heralded as highly selective) and *lambda*-cyhalothrin result in high acute toxicity and sublethal effects on lacewing (*Chrysoperla sinica*) larvae and adults (Shan et al., 2020). Application of broad-spectrum products can severely reduce the survival of natural predatory species, resulting in resurgence of pest species which would normally be controlled. Likewise, overreliance on broad-spectrum products can result in the selection for secondary pest species (Ndakidemi, Mtei, & Ndakidemi, 2016). Due to these concerns, it is clear special care must be made in selecting the most appropriate insecticide products, whenever their use is deemed necessary.

As a whole, the overwhelming importance of integrating IPM into the management system cannot be understated. Reliance on insecticidal products must be limited to situations where they are deemed economically appropriate, and care must be made to reduce off-target ecological harm as much as possible. Use of IPM tactics such as host plant resistance and novel PIPs (e.g. genetics) can further reduce need for chemical control. Integration of cultural management tactics (i.e., crop rotation, delayed planting, trap crops) can further reduce insect pressure on crop species and reduce the

selection of resistance in pest species. Inclusion of the effect of integrated pest management in the traditional GxE model as it pertains to entomology provides a far more comprehensive (and likely sustainable) metric to assess crop productivity.

Plant Pathology – A Never-Ending War Between Pathogens & Plants

The significance of plant diseases has been recognized for centuries, even if the sources of the diseases were not initially understood. In ancient Rome, red-colored dogs would be sacrificed to Robigus, the roman god of wheat in order to garner the god's favor and protection against "red dust" (i.e. rust diseases). Philosophers of the day such as Aristotle and Theophrastus wrote accounts of various plant diseases effecting cereals, legumes, and trees as early as 350 BCE (G. B. Lucas, Campbell, & Lucas, 1992). Despite the lack of comprehension on the causal agents of these diseases, some attempts to use seed treatments of various minerals and oils to reduce the risk of infection of seeds were effective (Smith & Secoy, 1975), as were cycles of liming and brining seed to reduce seed-borne diseases (Morton & Staub, 2008). These early successes help to frame the historic role agronomic management has had, even when operating without complete knowledge of the biological systems.

For much of human history the theory of "spontaneous generation" prevailed. With this theory, mankind had effectively traded in "wrathful gods cursing fields" for environmental conditions that spontaneously creating insects and disease. It wasn't until the 1860s when the results from Pasteur and Koch studying human pathogens disproved spontaneous generation and led to the development of germ theory (Morton & Staub, 2008). Several decades later the field of plant pathology was developed and separated

from the field of biology, becoming a full-fledged scientific discipline in 1913 (Morton & Staub, 2008). The focus was on the microbes responsible for causing plant disease, such as fungi and water molds, bacteria, nematodes, and viruses. Plant pathogens are responsible for estimated losses of 14.1% of all crop production (Agrios, 2005). Therefore, plant pathology is an essential component for GxExM considerations on a global scale. Contamination of grain with compounds produced by plant pathogens also result in significant reductions to crop quality and safety. This section is focused on the prevention and reduction of disease occurrence, as well the treatment or management of diseased plants.

A well-established cornerstone of plant pathology which relates well to the GxExM model is the disease triangle. The disease triangle serves as a conceptual model which shows the interactions between the environment (E), the host plant (G), and the biotic or abiotic agent. Disease development only occurs when all three of these components interact in such a way that allows a pathogen with virulence against a susceptible host plant to develop under favorable environmental conditions. Disruption of one or more of these components remains the mission of many disease management programs and can be accomplished in a variety of ways. In midwestern row crops, management of plant diseases is usually achieved through the use of cultural, genetic, and chemical control methods.

For cultural management, most methods are usually preventative, seeking to reduce or eliminate the occurrence of plant diseases (Howard, 1995). ExM methods focused on reducing the overall inoculum load are popular with many producers, including practices like crop rotation, incorporation of diseased residue into the soil

profile to promote microbial degradation, and use of certified disease-free seed. Likewise, agronomic management decisions on planting densities, planting date, and fertility can also be adjusted to enhance the vigor of the plants and/or to reduce the favorability of the environmental conditions, thus helping to minimize or reduce the economic severity of plant diseases (Howard, 1995).

The biological nature of plant pathogens inherently confines most pathogens to only host plant species they are virulent on. The size of this host range varies from pathogen to pathogen. Some plant pathogens require the use of multiple or alternate hosts to complete their life cycle. In instances like these, ExM interactions can be leveraged to culturally disrupt the life cycle and reduce the economic impact of the plant pathogen. For example, a historic ExM program which proved widely successful was the eradication of common barberry (*Berberis vulgaris*). Common barberry is an obligate alternate host for stem rust (*Puccinia graminis*) of wheat, and elimination of common barberry in growing regions significantly reduced disease pressure (Howard, 1995).

Another avenue of cultural and/or chemical control is the disruption of disease transmission. One such example is non-seedborne plant viruses which usually require vectors for transmission. ExM strategies to reduce or avoid insect vectors are common and include phytosanitary methods such as removing alternative hosts and volunteer crops, use of disease-free seed, and insecticide control of the vector (Agrios, 2005; Makkouk, Kumari, van Leur, & Jones, 2014).

One example of a cultural ExM program which has proven effective in Nebraska is the management of the wheat curl mite (WCM) (*Aceria tosichella*) to prevent viral diseases. The WCM is known to have a host range of > 90 grass species and is capable of

transmitting three different plant viruses in North America: Wheat streak mosaic virus, High plains wheat mosaic virus, and Triticum mosaic virus (Skoracka, Rector, & Hein, 2018). While four different virus resistance genes have been identified in wheat, management of WCM presently relies on the removal or control of volunteer wheat and grass weeds to reduce to reduce the survivability of WCM through non-crop period during the summer and thus eliminating one side of the disease triangle (Skoracka et al., 2018).

The importance of genetic resistance and GxM for managing plant pathogens cannot be understated. GxM management program which has increased in prevalence is the use of corn hybrids with resistance and/or tolerance to Goss's bacterial wilt and blight (*Clavibacter nebraskensis*) as well as several foliar, residue-based fungal diseases such as northern corn leaf blight (*Exserohilum turcicum*, sexual stage *Setosphaeria turcica*) and gray leaf spot (*Cercospora zeae-maydis*). For these diseases, crop rotation is a great way to reduce inoculum load, and in severe fungal infestations, use of foliar fungicides can help protect crop yield. However, for many producers who wish to grow corn-on-corn cropping systems, crop rotations aren't palatable. In these scenarios when the producer is planting corn into an already heavy-pressure scenario, management of crop residue (e.g. tillage, burning, baling, grazing) becomes critical. Often these management decisions are not enough, and must be coupled with the selection of hybrids with robust tolerance and/or resistance to these pathogens. This is especially true for bacterial diseases such as Goss's wilt. (Jackson, Harveson, & Vidaver, 2007; Jackson-Ziems, 2015; Rees & Jackson-Ziems, 2008). Using the conceptual model of the disease triangle as a reference,

this interference or removal of susceptible hosts (via genetics) can serve as another management strategy to reduce plant disease (Agrios, 2005).

Caution must be taken to avoid overreliance on genetic resistance, as overreliance on any one control tactic can result in selection of more virulent strains, or vectors. One such historic example is the management of WCM to reduce WSMV. Rather than developing resistance to the virus, genetic resistance to the mite vector was identified and widely deployed in Texas A&M's wheat cultivar TAM 107. However, this resistance broke due to overreliance and rapid adoption of TAM 107 throughout the Great Plains, leading to the resurgence of WCM and WSMV (Skoracka et al., 2018). The long-term efficacy of genetic resistance requires leveraging GxExM across the landscape, and diversification of management strategies through the use of IPM programs.

Nonetheless, a large emphasis has been put on the identification of resistance genes and integration into commercial cultivars. For example, many if not all seed corn companies provide disease resistance (e.g. complete plant "immunity") and/or disease tolerance (e.g., ability to tolerate damage while maintaining economic performance) ratings for several economically-important plant diseases. This occurs in nearly all commercially grown crops as disease resistance and/or tolerance information is often required for many producers to accept the risk of using a new cultivar or variety (Vanderplank, 1984). In fact, failure to screen for disease resistance can lead to resurgence of plant pathogens previously controlled due to the absence of active selection for tolerance and/or resistance. An example of this occurred for Goss's bacterial wilt and blight of corn (caused by *C. nebraskensis*) in Nebraska in 2006. At the time of the outbreak, only 25% of seed companies were evaluating hybrids for Goss's wilt

resistance/tolerance (Jackson et al., 2007). This resulted from reduced disease prevalence during previous years, and many seed companies opted to not include it in their screenings to reduce research costs. This led to increased susceptibility in many commonly grown varieties. Despite the dynamic nature of genetic resistance to plant pathogens (and subsequent loss of resistance), placing the most suitable germplasm in the right place is essential to providing long-term success of our cropping systems.

A discussion of plant pathology and disease management would be incomplete without a brief overview of chemical control. As with other avenues of crop production, the economic benefits and costs of chemical control products are intricately linked with adoption in the field. Use of antibiotics, bacteriophages, and plant activators that induce systemic acquired resistance (SAR) have proven effective in management of bacterial disease in extremely high-value horticultural crops and fruit orchards (Jones et al., 2007; Louws et al., 2001; Stockwell & Duffy, 2012). These methods are not commonly deployed in agronomic crops due to their significantly high economic cost. Similar trends are observed in antiviral compounds which have some applications in both animal and/or human health, but not in agronomic crops where such approaches have yet to be commercialized (Baranwal & Verma, 2000).

Management of plant-pathogenic nematodes has led to the commercialization of several fumigant and non-fumigant nematicide products. However, as with the case of antibiotics, widespread adoption in most agronomic crops have been limited due to economic costs (Jones, Kleczewski, Desaeger, Meyer, & Johnson, 2017) and often only moderate efficacy in non-fumigant products (Schmitt & Sipes, 1998). It is with these limitations that a sense of the arduous nature of nematode management in agronomic

crops comes to light. Some of this difficulty can be directly attributed to the challenges associated with obtaining a correct diagnosis or pathogen identification. With patchy appearance and sometimes symptomless (excluding gradual declines in crop productivity) injury from nematodes is often challenging to identify. This can be further complicated by management practices that impede rather than promote nematode management. For example, when agronomic crops perform poorly, often one of the first management tactics is to assume it's due to a limiting factor, such as lack of nutrients, or insufficient soil moisture. If a crop's poor performance is due to plant-pathogenic nematodes however, application of irrigation water and increased fertilizer can often exasperate the problem by creating more favorable environments for the nematodes (Schmitt & Sipes, 1998). Due to these issues and the concerns besieging nematicides, and impracticality of widespread solarization programs in agronomic crops, it is clear nematode management must be multi-faceted (Schmitt & Sipes, 1998), preferably designed as an IPM program that leverages the use of crop rotations, resistant cultivars (whenever identified), chemical and/or biological control programs. Likewise, in horticultural crops, soil solarization can also be very effective (to a limited depth) (Schmitt & Sipes, 1998).

From a chemical control perspective, most management options available in plant pathology are concentrated in compounds with fungicidal activity. As is the case for other pesticides, the years following WWII led to a dramatic increase in fungicide discovery and commercialization in the United States. Surprisingly, use of fungicidal products have decreased significantly from 1944 (136 million kg year^{-1}) to 2002 (49 million year^{-1}) due to the increased efficacy and selectivity (Morton & Staub, 2008) of newer products

compared to older chemistries. Despite the development of many fungicide active ingredients (AI) and modes of action, fungicide use in midwestern row-crop agriculture is usually limited to products in three modes of action: demethylation inhibiters (DMI), succinate dehydrogenase inhibitors (SDHI) and quinone outside inhibitors (Qol). Routine overuse of single-site fungicides has led to the selection for fungicide-resistant strains in many cropping systems. Development of fungicide-resistant strains spurred many pesticide manufacturers to commercialize pre-mixed products with multiple effective sites of action and/or types (e.g. a systemic plus a barrier/protectant) to reduce selection pressure for fungicide-resistance (J. A. Lucas, Hawkins, & Fraaije, 2015). However, as with other classes of pesticides, cost of registration and discovery has led to a reduction of new commercializations (J. A. Lucas et al., 2015). As such, use of IPM programs to control plant pathogens is required to safeguard the efficacy of existing fungicide products.

The importance of knowledge of the biology of plant pathogens and the epidemiology of the diseases they cause must be reiterated. It is only through understanding the biology of a pathogen and its life cycle that disease management can be optimized. Cultural methods to avoid and reduce plant disease is often the first line of defense (and most effective) for most plant diseases (Vicent & Blasco, 2017). Genetic resistance serves as the second line of defense. Once infected, crop protectant products for the treatment of viral and bacterial diseases or nematodes are limited. Management options for fungal diseases are not always economical, and delays in applications can result in significant grain quantity or quality reductions. As such, optimized GxExM

programs must focus on proactive management built on the tenets of IPM, rather than reactive management.

Weed Science – Mitigating Plant Competition

The first definition of the term ‘weed’ in the Oxford English Dictionary describe it as “a herbaceous plant not valued for use or beauty, growing wild and rank, and regarded as cumbering the ground or hinder the growth of superior vegetation” (Harlan & deWet, 1965). Harlan goes on to provide <20 definitions proposed by various sources from 1912 to 1963 from professional “weeds men”, where phrases such as “plant out of place”, “unwanted plant”, and “introduced plants which take possession of the soil” are frequently used (Harlan & deWet, 1965). Common attributes often added to these are the ability to outcompete native vegetation and spread and/or reproduce rapidly (Daehler, 1998). Regardless of which definition is used, weeds are capable of inflicting direct economic damages through competition with crop species.

Interplant competition is comprised of direct resource competition for soil resources or light and interference (including allelopathic competition) (Grace & Tilman, 2012). Depending on weed density, environmental factors, and emergence timing, this interspecific competition results in reduced crop yield. Weeds are one of the most significant and yet, controllable threats to crop production in North America (Soltani et al., 2017).

In most weed science research where yield is a variable being evaluated, field trials are normalized with a nontreated control, which represents the growth, development, and subsequent yields associated with no weed control practices being

implemented. Potential for yield losses was illustrated in a soybean meta-analysis of these comparisons conducted by Soltani et al. (2017). From 2007 to 2013, weeds reduced soybean yield in nontreated control plots by 52% in experiments conducted in the US and Canada (Soltani et al., 2017). These results are supported by a similar meta-analysis conducted in 2016 in corn which recorded an averaged 50% yield loss in non-treated controls (Soltani et al., 2016). When scaled across all of North America, yield losses reported in these meta-analyses would equate to 42.9 billion US dollars, a staggering value serving to indicate yet again the importance of weed control.

From a GxM perspective, management of agronomic cropping systems to control weeds follows the models of entomology and plant pathology in which the genetics placed within the field can affect management options and needs. Cultivars and crop species often differ in terms of their competitiveness with weeds. Likewise, differential metabolisms across different crop species and crop cultivars vary in their ability to process pre-emergence (PRE) herbicides. Referred to as selectivity, the crop species selected to be planted in a field influence the herbicides available for use due to risk of crop injury (Carvalho et al., 2009). In several agronomic crops, pesticide manufacturers have commercialized "ready-to-use" premixed formulations of soil-applied residual herbicides with multiple sites of action (SOAs) (Norsworthy et al., 2012). These mixtures are designed to provide more robust weed control and mitigate selection pressure for herbicide-resistant (HR) weeds; however, even these popular pre-mixed products are subject to GxM interactions.

Development and commercialization of HR cultivars of corn and soybean in the late 1990s led to widespread adoption of glyphosate-resistant crops across the United

States and in many other countries (Dill et al. 2008). In keeping with GxM interactions, adoption and use of HR crops provides novel weed management options which would have previously caused crop injuries (Beckie & Harker, 2017). With most conventional POST herbicides limited to active ingredients which have limited to no activity on the crop at the given growth stage, control of weed species which are similar to the crop (i.e. grass weeds in sweet corn) is challenging and often not without risks in terms of inflicting crop injury (Monks, Mullins, & Johnson, 1992). Adoption of HR crops is not without risk however, with some cultivars reporting a yield drag associated with the HR trait in comparison to conventional counterparts (Knezevic & Cassman, 2003). Likewise, HR crops often have increased seed costs in comparison to conventional cultivars (Striegel et al., 2020). Despite these economic concerns surrounding HR crops, adoption of HR crops remains high in the United States and in Nebraska (Beckie, Ashworth, & Flower, 2019; Werle et al., 2018).

From an ExM perspective, integrated weed management (IWM) serves to address growing concerns regarding the development of HR weeds. IWM programs, like IPM, advocate for the combination of preventative, cultural, mechanical and chemical tools to keep weed pressures below threshold levels (Knezevic & Cassman, 2003). Management changes such as decreasing row spacing, increasing population density, and altering planting date can have significant effects of weed pressure (Knezevic & Cassman, 2003), as can the use of cover crops such as cereal rye (*Secale cereale*) to suppress a variety of different weed species, including winter annuals (Werle, Burr, & Blanco-Canqui, 2017). Use of varying levels of tillage has historically been used to control weeds (Derksen, Lafond, Thomas, Loeppky, & Swanton, 1993), with emphasis recently on

reduced/conservation and interrow/strip tillage in lieu of conventional tillage (Moyer, Roman, Lindwall, & Blackshaw, 1994).

The importance of herbicide stewardship and IWM principles cannot be understated as it pertains to GxExM interactions. Even with the use of best management practices (herbicide rotation and tank-mixing multiple effective SOA), development of new HR weed biotypes isn’t diminished, but merely delayed (Beckie et al., 2019; Busi et al., 2019; Gage et al., 2019). Herbicide discovery efforts have plateaued since the 1980s (Dayan, 2019), indicating the discovery pipeline will not be providing the needed management options for HR weeds when relying primarily on herbicide control. Redirected industry focus onto IWM tactics used in combination with comprehensive GxExM evaluation may serve as one possible solution to meeting future production needs (Hatfield & Walthall, 2015).

Animal Science– Safeguarding Animal Health and Productivity

Across livestock production systems, specific nutritional requirements can vary significantly depending on species and thus, type of digestion (i.e. monogastric, avian, ruminant, pseudo-ruminant) (Pond, Church, Pond, & Schoknecht, 2004). Furthermore, nutritional requirements increase or decrease as livestock move across different life stages: growth, reproduction, lactation (within mammalian species), environmental conditions, and maintenance (Drackley, Donkin, & Reynolds, 2006; Kenyon et al., 2009; Kim, Weaver, Shen, & Zhao, 2013). Despite these complexities, nutritional requirements of domesticated livestock are predominantly met and addressed by the production of

high-quality grain and forage crops, and this production is inherently affected by GxExM interactions.

Within the United States, cereal crops such as corn, grain sorghum (*Sorhum bicolor*), barley and oats (*Avena sativa*) are commonly used as a source of carbohydrate in feed rations, with an estimated 48.7% of US corn production in 2013 used as livestock feed (USDA, 2015a; USDA-ERS, 2020). Likewise, pulse crops such as soybeans, field peas (*Pisum sativum*), and other pulse legume crops are commonly used as a source of crude protein in feed rations. In fact, livestock feed is the primary consumer of soybeans in the United States, with over 70% of soybeans produced in the United States in 2013 used in feed rations (USDA, 2015b).

Across the globe, the diversity of forage crop species is extremely large with several hundred different species of grasses, legumes, forbs, and sedges (C. J. Nelson & Moser, 1994). In this great diversity that direct connections exist between agronomic management and animal nutrition. Across the wide variety of different forage crop species, nutritional compositions can range widely (Minson, 2012). Forage production is further complicated due to additional factors such as growing environment, soil fertility, stage of growth, presence of pests, and management practices. In combination, these factors can result in significant effects on both nutritional quality and the overall quantity of forage produced (Minson, 2012).

As it pertains to forage quality, plant components can be separated into two main groups (Collins, Nelson, Moore, & Barnes, 2017): cell contents that are nearly 100% digestible for most livestock species, and cell wall components (cellulose, hemicellulose, lignin) that can range between 20 to 60% digestible (Putnam, 2012). For both

mechanically harvested forages (e.g. greenchop, hay, haylage, silage) and naturally harvested forages (e.g. grazing), considerations such as species composition, time of year, and time of harvest are critical (e.g. GxE, GxM and GxExM interactions). Regardless of harvest method, as forage species grow, the overall quantity (dry biomass) of the forage increases. But this often occurs to the detriment of reducing the forage quality (digestibility). Along with persistence of the forage stand (for biennial and perennial species), these three factors must be balanced for optimal forage management to be achieved.

However, the significance of GxExM interactions is best illustrated in situations where mismanagement creates livestock health concerns. Four examples are discussed in this chapter: mycotoxin contaminations, grass tetany, prussic acid poisoning, and the fungal endophyte found within tall fescue (*Festuca arundinacea).*

With the majority of corn and soybean grain used for livestock feed, end-use suitability is a critical consideration as it pertains to animal health. Secondary metabolites produced by many fungal ear rots in corn can have determinantal effects on livestock if they contaminate feed rations. For example, aflatoxin can result in liver damage and intestinal bleeding in swine, sheep, and cattle. Likewise, fumonisins can also result in liver damage and reduced growth of horses and cattle. The fungal mycotoxin zearalenone has similarly been linked to significant reproduction disruptions, resulting in fetal abortions in both swine and dairy cattle (Schmale & Munkvold, 2009). From a management perspective, the only effective methods of reducing mycotoxins is preventative in nature. Agronomic practices such as crop rotation, tillage, reduction of nitrogen fertilizer, avoidance of late maturing varieties, and harvesting at the proper

moisture concentration are all used to reduce the risk of mycotoxin production. Likewise, proper storage conditions (humidity and temperature) can also play a critical role in reducing the development of mycotoxins (Jouany, 2007).

Grass tetany (hypomagesemia) is a major metabolic disorder afflicting ruminant livestock species, most notably beef cattle and sheep in the United States (Grunes, Stout, & Brownell, 1970). More pronounced in female livestock especially those pregnant or lactating, grass tetany is primarily caused by a deficiency of utilizable magnesium, although interactions with high nitrogen and potassium concentrations can also contribute to symptom severity (Grunes et al., 1970). Grass tetany is commonly observed when livestock graze on lush spring growth of cool-season (C_3) grasses, although several instances have been observed in the fall (Sleper, Vogel, Asay, & Mayland, 1989). Grass tetany can be managed in a three-fold approach: the application of magnesium fertilizers to the soil (Grunes et al., 1970), use of a dietary magnesium supplements to circumvent deficiencies (Robinson, Kappel, & Boling, 1989), and the continued breeding efforts to improve or bio-fortify magnesium concentrations found naturally in forage species (Kumssa et al., 2020).

Prussic acid (hydrocyanic acid, HCN) is a poison that can cause livestock to die due to asphyxia. While all livestock species are susceptible, ruminate species are more sensitive due to the enzymatic activity within their forestomach. Within ruminate species, cattle (dairy and beef) are the most vulnerable (Robson, 2007). Regardless of livestock species, HCN poisoning can occur when livestock are grazed on stressed plants most notably plants stunted due to drought, or damaged due to frost-events (Stoltenow & Kardy, 1998). This is caused when plants exposed to these adverse environmental

conditions accumulate cyanogenic glycoside, which is readily converted to HCN. HCN poisoning can also occur in forages which are harvested and dried (e.g. hay or haylage). Ensilaging contaminated forages can be used to reduce HCN concentrations to safe levels (Stoltenow & Kardy, 1998). Several GxM strategies exist to reduce the likelihood of HCN poisoning. For example, selecting lower prussic acid forage species can be effective. Species such as sudangrass (*Sorghum* × *drummondii*), forage sorghum, and sorghum-sudangrass hybrids are notorious for high HCN concentrations (Vough & Cassel, 2006). An ExM approach is to follow fertilizer recommendations to balance nitrogen, phosphorous, and potassium concentrations in the soil/plant (Vough & Cassel, 2006).

The last animal nutrition concern discussed occurs in tall fescue, a popular forage grass grown across the United States. If alfalfa (*Medicago sativa*) has the honor of being the "queen of forages" due to high nutritional quality and widespread cultivation, tall fescue is a strong contender for "king of cool-season grasses" with over 14 million hectares produced in the United states for forage, turf grass, and erosion control (Ball, Lacefield, & Hoveland, 1991). Its prevalence impacts animal nutrition due to the extensive presence of a fungal endophyte (*Acremonium coenophialum*). This endophyte occurs naturally in "wild-type" fescue populations that were established in the early 1940s. It symbiotically inhabits tall fescue, providing increased resistance to abiotic and biotic stresses. As such, when tall fescue is exposed to adversely warm weather conditions (e.g. mid-to-late summer), the fungal endophyte produces high concentrations of a toxic alkaloid (ergovaline) as a secondary metabolite. When consumed, these alkaloids can negatively impact livestock, ranging from aberrant reproductive

efficiencies, reduced weight gain, and reduced milk production in cattle, sheep, and horses (Porter & Thompson, 1992). From a management perspective, adjustment of grazing schedules in tall fescue pastures to avoid the mid-to-late summer season can reduce the occurrence of fescue toxicosis. Likewise, planting certified endophyte-free or varieties with novel-endophytes (improved pest resistance with no alkaloid production) are agronomic options to consider (Ball, Lacefield, Schmidt, Hoveland, & Young, 2015).

Ultimately, there needs to be a connection between animal science and agronomy in the management of grain and forage crops. Agronomic management decisions and the timing of management decisions, such as variety selection, planting density, fertility programs and harvest date, can have both positive and negative effects on the nutritional quality and margin of feed safety (Brink & Marten, 1989; Buxton, 1996; L. A. Thompson et al., 2018). As the historically largest end-market consumer for feed grains (Lawrence, Mintert, Anderson, & Anderson, 2008) and the largest consumer of forages, agronomic management must ensure benchmarks for crop quality and crop safety are met to safeguard the productivity of livestock production systems.

GxExM: A Call for Action

Throughout this chapter, management considerations for GxExM were presented separated by discipline, for ease of introducing these discipline areas. However, agronomic management rarely is so simplistic. Decisions made in one facet, can directly and indirectly effect other areas. Consider the following:

Decisions made on determining soil fertility for a given field of corn result in excess nitrogen and reduced potassium levels. Research has shown incorrect N/K values

can result in increased severity of plant diseases such as fungal stalk rot, as well as increased risk for the production and subsequent contamination with certain mycotoxins (Blandino, Reyneri, & Vanara, 2008; WenJuan, Ping, & JiYun, 2010). These effects are exacerbated if planting density is excessively high (Pfordt, Ramos Romero, Schiwek, Karlovsky, & von Tiedemann, 2020). The excessive nitrogen now within this corn system can result in increased insect fecundity as well, as improved reproduction of herbivorous insects with high nitrogen levels has been reported in the literature (Awmack & Leather, 2002; Wang, Tsai, & Broschat, 2006). If a producer opted to utilize a synthetic pyrethroid (imidacloprid) to control these insect pests with two-spotted spider mite (*Tetranychus urticae*) present in this corn system, the negative effect of the insecticide on natural enemies could result in resurgence of mite populations and an increase in their fecundity as well (Gerson & Cohen, 1989). Low potassium levels and excessive nitrogen in turn increase susceptibility to mid-to-late season lodging, which often results in increase harvest loss, leading to volunteer corn populations the following year (Jeschke & Doerge, 2008; WenJuan et al., 2010). If rotating into soybeans, volunteer corn can act as a competitive weed and an alternative host for corn disease and insect pests (C. Krupke, Marquardt, Johnson, Weller, & Conley, 2009; P. Marquardt, Krupke, & Johnson, 2012; P. T. Marquardt, Terry, & Johnson, 2013). If at any time, incompatible crop protectant products are tank-mixed together (e.g. fungicides, herbicides and insecticides) significant crop injury and yield loss can occur (Stewart, Steckel, & Steckel, 2013).

As this example illustrates, the complexity present within agronomy and optimizing agronomic management requires an assimilation of knowledge from many

disciplines and subdisciplines. It is with this call to action emphasizing the need for a well-rounded agronomic training that we explore agronomic training at the University level in the next chapter.

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CHAPTER 2: AGRONOMY EDUCATION IN THE MIDWEST

Historical Perspectives on American Collegiate Education

In 1980, iconic American astronomer, scientist, and science communicator Dr. Carl Sagan said: “You have to know the past in order to understand the present” (Malone, Kennard, McCain, Oyster, & Wells, 1980). It is with this underlying missive a brief recount of the college educational systems in the United States is provided. Collegiate education in the United States has undergone large transformations since colonial times from both a philosophical and organizational standpoints. Thomas Denham (2002) summarized the history of college education prior to the modern era, splitting it into three main periods: the colonial period (1636-1789); the emergence period (1789-1865); and the reconstruction and industrialization period (1865-1900) (Denham, 2002).

During the colonial period, educational curriculum was largely limited to Bible studies and languages (Greek and Latin), with the intent of instilling propriety, civic virtue, and character (Rudolph, 1962). This classical approach to education included memorization of a large body of knowledge, rather than questioning or critique (Denham, 2002), which resulted in significant limitations in terms of content specialization.

Following America’s victory in the Revolutionary War, the nation and its educational systems began to develop during the emergence period. During this time, long-held “classical” approaches to collegiate education were abandoned in many instances for “modern” interpretations of natural law and sciences (Rudolph, 1962). These changes fragmented the academic landscape, with Harvard and Yale leading the efforts for academic reform and specializations (Denham, 2002). By the mid-1850s, the academic disciplines had expanded into what essentially constituted a “two-track”

system, one for the professions of law, medicine, and ministry, and one for all other professions (Cohen & Kisker, 1998). This flexibility led to the development of new majors and specializations as well as the establishment of many vocational training programs, leading to increased enrollment (Cohen & Kisker, 1998). This period of growth was soon challenged, as America was once again at war, this time, with itself.

Following the conclusion of the long and bloody Civil War in 1865, collegiate education began to change rapidly during the reconstruction and industrialization period. With the passing of the Morrill Land Grant College Act in 1862, promotion of vocational training in agricultural and mechanical arts had finally become a priority of the United States. In the years that followed, vocational and "non-classical" programs were developed nationwide, with enrollment increasing dramatically (Rudolph, 1962). Despite these developments, there was overall dissatisfaction with the college admission and fragmented curriculum requirements from college to college and university to university. It was in this educational landscape that many educators and external stakeholders called for national standards to be adopted (Shedd, 2003). For example, prior to educational reforms, the length of academic programs, age of eligible students, and required coursework was not consistent. Many programs blended the modern definitions of college and high school education. Despite these pressures for educational reform, no meaningful standardizations were accepted nationwide until the establishment of a pension program by the industrialist Andrew Carnegie.

Upon his retirement in 1901, Carnegie declared his intentions to design a pension program for "the poorest paid but highest professions in our nation": college professors (Silva & White, 2015). Carnegie's donation, while exceedingly large and generous

(equivalent to $250 million dollars in 2015), was not sufficient to cover every educator in the United States (Silva, White, & Toch, 2015). As such, the Carnegie Board of Trustees set forth to determine standards required for eligibility, developing a partnership with the National Education Association to serve as advisors on how to best create educational metrics for academic programs and educators. After extensive discussion, the Carnegie Unit (i.e. credit hour) was developed. Designed to standardize learning to time-based reference schedules, prevailing expectations were that students would be able to complete a comprehensive collegiate education in a period of four years, comprised of 30 credit hours each year (15 credits semester^{-1}; 10 credits trimester^{-1}; and 7.5 credits quarter^{-1}, respectively). Derivatives of the Carnegie Unit are widely used in primary, secondary, and post-secondary education programs. To this day, the 120-credit hour requirement still serves as a benchmark requirement for students in most four-year degree programs, although derivations of 121 to 128 credit hour requirements are also common.

With these academic requirements in mind, the remainder of this chapter is focused on agronomy undergraduate education in the Midwest. Required "academic compromises" as they pertain the depth and breadth of specific content areas are highlighted and discussed. Potential mitigation strategies are proposed and expanded examples and discussion of these are included in the next chapter.

Agronomy Education Programs

At most four-year universities, undergraduate students are required to complete 120 to 128 credits of academic coursework for a baccalaureate degree. These credits are targeted to be completed during a four-year period. Within a degree program, a large

proportion of the total credit hours is focused on the selected major, which represents a concentration or content area the student has identified as a career interest. To be eligible for graduation, students are required to complete pre-determined coursework which has been designed to prepare students for their future careers.

In addition to the coursework students are required to complete for a given major, students are also required to complete coursework in other non-related areas. These courses are referred to as general education. General education courses are included to establish a base level of knowledge across a diverse range of topics, thus creating a more well-rounded educational experience. General education courses range widely both in terms of content and focus, but they usually include subjects across the humanities and often some level of college mathematics, biology, and/or college chemistry.

Because many of these courses do not directly relate to a selected major, many students feel general education courses are a "waste of time". However, general education courses (and as an extension, prerequisite STEM courses) are often critical for developing "base" knowledge which is essential for building disciplinary capacities and further academic specialization. The same can be said about courses which address professional competencies such as computer skills, science communication or interpretation, as well as English composition courses.

Many programs of study are designed to provide flexibility in terms of course options, and general/free elective credits. As such, a discussion and analysis of required curriculum for undergraduate students interested in agronomic management, consulting, and production is needed. To provide a fair and accurate representation of Agronomy education in the midwestern United States, the University of Nebraska-Lincoln and ten

additional universities were selected for comparison. The objective of this comparison was to identify similarities present across universities in terms of academic strengths and weaknesses.

Survey Materials & Methods

Ten universities offering baccalaureate degrees in agronomy were selected due to state proximity to the University of Nebraska-Lincoln (Figure 2.1). In addition to geographical location, these universities were selected due to similarity of cropping systems within the state, with a focus on corn and soybean production. Campus selection was usually limited to the main "flagship" institution. However, satellite locations were selected for two universities (the University of Minnesota and the University of Wisconsin) in order to select the campus with the largest emphasis on agriculture and agronomy education.

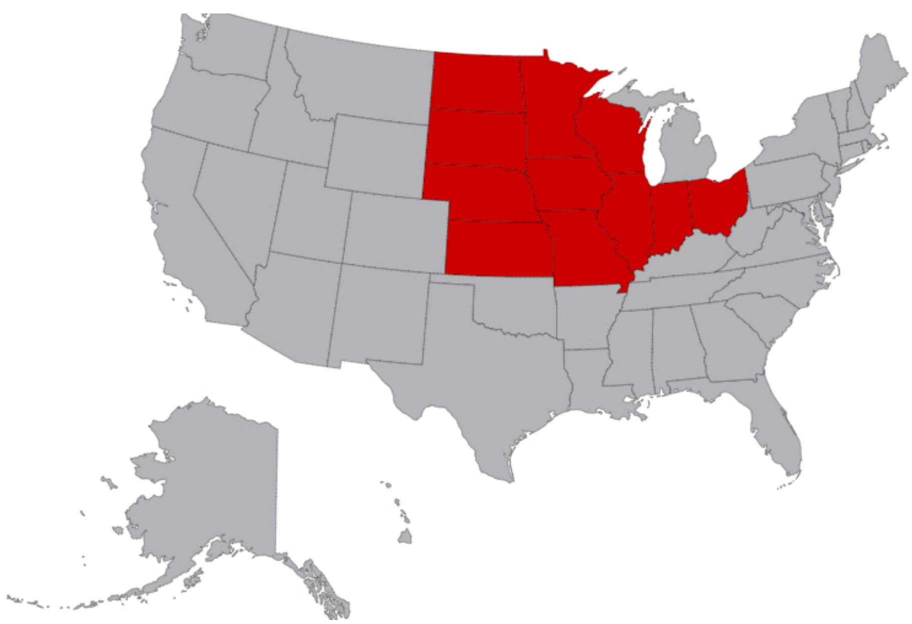

Figure 2.1. Geographical map depicting the states of selected universities. (AMCHARTS, 2014).

For each university, department programs of study from 2020-2021 were obtained from official university websites (Iowa State University, 2021; Kansas State University, 2021; North Dakota State University, 2021; Purdue University, 2021; South Dakota State University, 2021; The Ohio State University, 2021; University of Illinois at Urbana-Champaign, 2021; University of Minnesota Crookston, 2021; University of Missouri, 2020; University of Nebraska-Lincoln, 2021; University of Wisconsin-Platteville, 2021). At each university, undergraduate majors were selected that most directly included agronomic management. Following major selection, the most appropriate major option was selected for universities which offered degree options (eight of 11 universities). In most cases, this "major option" equated to some form of further specialization (e.g. specialization, emphasis, concentration), but in some instances, further specialization (e.g. subplans) was possible (Table 2.1). Regardless of these differences in nomenclature, the most appropriate major option and agronomy specialization was selected for students focused on agronomic management, crop consulting, and crop production.

Table 2.1. Universities and degree options selected for comparing baccalaureate program of study in agronomy.

University Information		Degree Information	
Name (Abbreviation)	Location	Options Offered [a]	Major – Major Option[b]
Iowa State University (ISU)	Ames, IA 50011	1	Agronomy
Kansas State University (KSU)	Manhattan, KS 66506	6	Agronomy – Consulting & Production
University of Missouri (MU)	Columbia, MO 65211	3	Plant Science – Crop Management
North Dakota State University (NDSU)	Fargo, ND 58105	4	Crop & Weed Science – Agronomy
Ohio State University (OSU)	Columbus, OH 43210	4	Sustainable Plant Systems – Agronomy

Table 2.1. (continued)

Purdue University (PU)	West Lafayette, IN 47907	3	Agronomy – Crop & Soil Management
South Dakota State University (SDSU)	Brookings, SD 57007	1	Agronomy
University of Illinois at Urbana-Champaign (UIUC)	Champaign, IL 61820	7	Crop Science – Crops
University of Minnesota-Crookston (UM-C)	Crookston, MN 56716	1	Agronomy – Agronomic Science
University of Nebraska-Lincoln (UNL)	Lincoln, NE 68511	4	Agronomy – Integrated Crop Management
University of Wisconsin-Platteville (UW-P)	Platteville, WI 53818	3	Soil & Crop Science – Agronomy

[a] Information provided within this column represent the total number of major options available for selection at each university.
[b] Verbiage used for major options varied widely from university-to-university including but not limited to: concentration, emphasis, option, specialization, and subplan. Information provided within this column represents the foremost specialization within each program of study following each respective major.

Following selection of majors and options, each program of study was further surveyed to determine the respective curriculum requirements separated into the degree components of general education, major requirements, and option requirements (Table 2.2). Due to the inherent differences in how each program reported degree requirements, programs of study were examined on a case-by-case basis to allocate general education and prerequisite courses. General education credits were defined as any required coursework within the humanities. Likewise, all science, technology, engineering, mathematics (STEM)-related coursework which did not directly relate to plant science, botany, or agronomy were also included in the general education category. After separation and removal of these courses, the preliminary number of credits available for agronomic training in each program was calculated. However, students are also allowed a certain number of free elective courses. In some academic programs, the number elective credits was directly specified, but for many instances, the total and/or range of free

elective credits reported in this chapter were calculated by subtracting the sum of all degree components from the reported credit requirements for graduation.

For the agronomy majors, most universities provided a direct estimate of required coursework (data not shown). These self-reported values were often “inflated” by prerequisite courses, seminar and orientation classes, and other general education courses. In order to provide a consistent comparison between universities, all self-reported major credit requirements were adjusted prior to analysis. Whenever a range of credits was provided, an averaged value ((MIN+MAX) ÷ 2) was used for analysis.

Similar to major requirements, universities which offered major options within a given major usually provided a direct estimation of required coursework. In general, this component did not include as many credits which might be more appropriately aligned with another component although in some instances, courses more befitting general education or prerequisite courses were removed.

Table 2.2. Required curriculum for a baccalaureate degree in agronomy at 11 universities separated by general degree components.[a]

General degree component	University											
	ISU	KSU	MU	NDSU	OSU	PU	SDSU	UIUC	UM-C	UNL	UW-P	AVG
	no. credits											
General Education[b]	43	42	40	64	57-58	48	57	46	47	44-45	44-49	48.7 ± 2.3
Avg. Agronomy Subtotal[d]	**85**	**77**	**80**	**56**	**64**	**73**	**67**	**82**	**73**	**76**	**75**	**73.5 ± 2.5**
Agronomy Major	52	48	40	37	42-43	33	44-46	47	54	17-19	28-31	40.5 ± 3.2
Agronomy Option	15	21	20-22	13-14	15-18	27	18-19	--	11	63-64	42	25.0 ± 5.2
Free Electives[c]	18	7-9	18-20	5-6	2-7	12-13	3-6	35	8	0-7	0-6	11.0 ± 2.9
Total Degree Requirements	**128**	**120**	**120**	**120**	**121**	**120**	**125**	**126**	**120**	**120**	**120**	**121.8 ± 0.9**

[a] Abbreviations: (Avg, Average; ISU, Iowa State University; KSU, Kansas State University; MU, University of Missouri; NDSU, North Dakota State University; OSU, Ohio State University; PU, Purdue University; SDSU, South Dakota State University; UIUC, University of Illinois at Urbana-Champaign; UM-C, University of Minnesota-Crookston; UNL, University of Nebraska–Lincoln; UW-P, University of Wisconsin-Platteville)

[b] Across universities, required curriculum load was separated and reported differently for general education courses, major, and option/emphases, resulting in a wide range of values for each general degree component. Programs of study were examined on a case-by-case bases, with general education courses including the fields of social sciences, humanities, oral and written communication courses as well as college chemistry, biology, physics, college algebra, etc.

[c] Average agronomy subtotals are equal to the sum of the averaged agronomy major requirements, plus agronomy option, plus free electives.

[d] Free elective credits were either directly stated within curriculum programs, or calculated by subtracting the total number of credits in each degree component from the required total.

Following separation into degree components, each program of study was examined on a course-by course basis and further separated into six general focus categories: plant, soil, electives, crop protection, technology, and other for the presentation of results. These six subcategories were subsequently separated into a total of twenty subcategories corresponding to the various disciplines and subdisciplines and grouped accordingly within the six focus categories (Table 2.3, 2.4). Special care was taken to ensure consideration of course flexibility to properly highlight programs that allow students to specialize and select classes they are interested in or find relevant toward their future careers. A common situation across universities that best illustrates this flexibility is academic programs providing a list of approved courses to select from (i.e. pick two of the following four courses). Whenever this was encountered, these credits were included in the "Agronomy Selective" subcategory. It is important to note that some reclassification of credits previously classified as "general education," was conducted due to the development of new subcategories. For example, coursework in economics is required at nine of the 11 selected universities. While economic courses may have counted towards the general education category (Table 2.2), a sound understanding of economics is required for many agronomic management practices. Thus, the business and economics subcategory was added (Table 2.3). Once subcategorized, averaged values for universities requiring coursework in each subcategory were determined, ranked and presented with standard errors (Table 2.4).

Table 2.3. Required curriculum separated by discipline and subdiscipline categories for a baccalaureate degree in agronomy at 11 universities.[a]

Category/Subcategory	University Abbreviation										
	ISU	KSU	MU	NDSU	OSU	PU	SDSU	UIUC	UM-C	UNL	UW-P
	no. credits (no. courses)										
PLANT FOCUS											
Agroecology/Ecology	--	--	--	3 (1)	3 (1)	3 (1)	--	--	--	6 (2)	3 (1)
Botany	--	--	5 (1)	--	--	8 (2)	4 (1)	4 (1)	--	4 (1)	5 (1)
Crop Production & Crop Sciences	6 (2)	3 (1)	3 (1)	6 (2)	9 (3)	3 (1)	5 (2)	4 (1)	18 (5)	10 (4)	9 (3)
Forage Production	--	--	--	3 (1)	--	--	--	--	3 (1)	3 (1)	3 (1)
Plant Breeding & Plant Genetics	3 (1)	--	6 (2)	7 (3)	3 (1)	3 (1)	3 (1)	--	4 (1)	--	3 (1)
Plant Physiology	6 (2)	3 (1)	6 (2)	3 (1)	--	--	4 (1)	--	6 (2)	4 (1)	3 (1)
SOIL FOCUS											
Soil Science & Soil Fertility	13 (4)	9 (3)	8 (3)	6 (2)	7 (3)	6 (2)	7 (3)	10 (3)	7 (2)	11 (3)	13 (4)
ELECTIVES											
Agronomy Elective/Selective	21	21	9	4	16-20	27	18-19	12	5	6	9
General/Free Electives	18	7-9	18-20	5-6	2-7	12-13	3-6	35	8	0-7	0-6
CROP PROTECTION FOCUS											
Entomology	--	5 (2)	3 (1)	3 (1)	1 (1)	--	3 (1)	3 (1)	3 (1)	3 (1)	--
Integrated Management Systems	--	3 (1)	--	--	2 (1)	--	--	--	3 (1)	--	3 (1)
Plant Pathology	--	5 (2)	4 (1)	3 (1)	5 (2)	--	2 (1)	--	3 (1)	3 (1)	3 (1)
Weed Science	--	3 (1)	3 (1)	4 (2)	3 (1)	--	3 (1)	3 (1)	6 (2)	3 (1)	3 (1)
TECHNOLOGY FOCUS											
Precision Agriculture	--	--	--	--	2 (1)	--	3 (1)	3 (1)	3 (1)	3 (1)	3 (1)
OTHER											
Animal Science	--	--	--	--	--	--	--	3 (1)	--	--	--
Business & Economics	--	12 (4)	6 (2)	3 (1)	3 (1)	3 (1)	3 (1)	6 (2)	--	10 (3)	3 (1)
Capstones	3 (1)	3 (1)	--	--	3 (1)	--	--	--	Req.	3 (1)	3 (1)
International Agriculture	6 (2)	--	--	3 (1)	--	3 (1)	--	--	--	--	--
Internship[b]	Req.	3 (1)	3 (1)	--	Req.	--	1-2 (1)	--	3 (3)	1 (1)	3-6 (1)
Meteorology	3 (1)	--	--	--	--	--	--	--	--	--	--
REMOVED	6 (4)	1 (1)	4 (2)	3 (3)	1 (2)	3 (4)	2 (2)	1 (1)	1 (1)	1 (1)	1 (1)
AVERAGE TOTAL	**79**	**78**	**75**	**54**	**64**	**70**	**62**	**83**	**72**	**74**	**74**

[a] Abbreviations: (ISU, Iowa State University; KSU, Kansas State University; MU, University of Missouri; NDSU, North Dakota State University; OSU, Ohio State University; PU, Purdue University; SDSU, South Dakota State University; UIUC, University of Illinois at Urbana-Champaign; UM-C, University of Minnesota-Crookston; UNL, University of Nebraska–Lincoln; UW-P, University of Wisconsin-Platteville)

[b] Programs with designated internship courses and/or requirements to complete internship experiences were listed in this row, with the exception of Iowa State University which requires an internship experience, but does not designate a credit value towards graduation.

Table 2.3. (continued)

[a] Abbreviations: (ISU, Iowa State University; KSU, Kansas State University; MU, University of Missouri; NDSU, North Dakota State University; OSU, Ohio State University; PU, Purdue University; SDSU, South Dakota State University; UIUC, University of Illinois at Urbana-Champaign; UM-C, University of Minnesota-Crookston; UNL, University of Nebraska–Lincoln; UW-P, University of Wisconsin-Platteville)
[b] Programs with designated internship courses and/or requirements to complete internship experiences were listed in this row, with the exception of Iowa State University and Ohio State University which require internship experiences, but does not designate a credit value towards graduation.

Table 2.4. Ranked curriculum separated by discipline and subdiscipline subcategories for a baccalaureate degree in agronomy averaged across 11 universities.

Rank	Subcategory	–no. Credits–	–no. Universities–
PLANT FOCUS			
4	Crop Production & Crop Sciences	6.9 ± 1.4	11
6	Botany	5.0 ± 0.6	6
7	Plant Physiology	4.4 ± 0.5	8
8	Plant Breeding & Plant Genetics	4.0 ± 0.6	8
10	Agroecology/Ecology	3.6 ± 0.6	5
14	Forage Production	3.0	4
SOIL FOCUS			
3	Soil Science & Soil Fertility	8.8 ± 0.8	11
ELECTIVES			
1	Agronomy Electives/Selective	13.7 ± 2.3	11
2	General/Free Electives	11.0 ± 2.9	11
CROP PROTECTION FOCUS			
11	Plant Pathology	3.5 ± 0.4	8
12	Weed Science	3.4 ± 0.3	9
13	Entomology	3.3 ± 0.7	8
16	Integrated Management Systems	2.8 ± 0.3	4
TECHNOLOGY FOCUS			
15	Precision Agriculture	2.8 ± 0.2	6
OTHER			
5	Business & Economics	5.4 ± 1.1	9
9	International Agriculture	4.0 ± 1.0	3
14	Animal Science	3.0	1
14	Capstones	3.0 ± 0.0	6
14	Meteorology	3.0	1
17	Internship[a]	2.8 ± 0.5	8
TOTAL		**71.4 ± 8.4**	**11**

[a] Programs with designated internship courses and/or requirements to complete internship experiences were listed in this row, with the exception of Iowa State University and Ohio State University which requires an internship experiences, but do not designate a credit value towards graduation.

Survey Results & Discussion

Across universities, the total credit requirements were similar for most programs. Total degree requirements ranged from 120 credits at KSU, MU, PU, UM–C, UNL, and UW–P, to 128 credits at ISU. Despite the overall similarities for total coursework required, differences were identified across the general degree categories of general education, major and major options, as well as electives.

General Educational Requirements

General education requirements set by each respective university ranged from a low of 40 credits at MU to a high of 64 credits at NDSU, with an averaged value of 48.7 ± 2.3 credits (Table 2.2). It is important to note that the value of 48.7 credits constitutes a sum of all non-agronomy related coursework, including coursework in (but not limited to) college chemistry, physics, college algebra, economics, biology, and microbiology courses. This category also includes all communication and public speaking, English and writing, and all liberal arts courses. The intention of presenting this total was to illustrate the significant time constraints educators must operate within when setting curricula. With programs requiring 120 total credits and a course workload of 15 credits semester^{-1}, general education requirements equate to a total of 3.2 semesters, or 1.6 years of education. This equates to roughly 41% of the possible coursework during a four-year degree program assigned to meet general education requirements.

Agronomic Training – Major, Options, & Subtotals

Across all universities, the direct agronomic coursework required for a major in Agronomy ranged from a low of 18 credits at UNL to a maximum of 54 credits required

at UM-C (Table 2.2). This range did vary in terms of degree classification, as programs with options or concentrations often separated components of coursework into different categories. As such the decision was made to combine major coursework with option/concentration as well as free elective credits to best capture the total opportunities for agronomic training and present these results prior to component analysis. To better normalize the data, range of course requirements were averaged within each program (e.g. minimum and maximum) prior to averaging the full survey.

Overall, surveyed universities required an average of 40.5 ± 3.2 academic credits for a major of agronomy. However, all surveyed universities require additional coursework in a given major option, with the exception of UIUC which did not offer the selection of major options within the major. This was similar to the program of study at ISU, with the exception in that students are required to select 15 credits of supporting science courses to best fit in with their specialization. Across universities, additional specializations for degree options ranged from a minimum of 11 credits at UM-C to a substantial maximum of 42 credits at UW-P, and 64 credits at UNL. Overall, the survey-wide average for agronomy specialization was 25.0 ± 5.2 credits.

In most academic programs, students are provided flexibility to take courses not required by their program of study. Elective credits can serve as a potential opportunity to increase the amount of agronomic training provided to students. Many universities did not directly list the amount of elective credits, but when calculated from the total number of credits required minus the existing category totals, students on average had the opportunity to take 11.0 ± 2.9 credits of electives.

When the agronomy option and free electives were added to the major requirements, the subtotal for agronomy training was obtained. In this survey, the agronomy subtotal for each university ranged from a low of 56 credits at NDSU to a high of 82 and 85 credits at UIUC and ISU, respectively (Table 2.2). Overall, the average subtotal across all 11 universities was 74.3 ± 2.8 credits, for a total of 4.95 semesters or 2.48 years of academic study. While not all of the free elective credits listed within each program will be used for agronomic coursework, it is important to identify the total opportunities available for students to pursue coursework related to the agronomic sciences.

Category and Subcategory Analysis

Separation of required coursework into categories and subcategories by discipline helps illustrate subtle differences from one program of study to another. For example, students enrolled at ISU, NDSU, OSU, and PU are required to complete three to six credits in international agriculture, whereas UIUC requires an animal science class (Table 2.3). Despite unique requirements in each program of study, survey-wide averages of these subcategories identified similarities present at most universities.

For the plant focus category, the largest credit requirement was in crop production and crop sciences (6.9 ± 1.4 credits). This requirement ranked fourth among the subcategories, and credits in this subcategory were required at all universities (Tables 2.3 and 2.4). At six universities, (MU, PU, SDSU, UIUC, UNL and UW-P) general biology courses were replaced with botany courses (5.0 ± 0.6 credits), and at eight universities,

students were required to complete courses in plant physiology as well as plant breeding and genetics (4.4 ± 0.5 and 4.0 ± 0.6 credits, respectively).

For the soil category, all universities required an average of 8.8 ± 0.8 credits of coursework, which was ranked third for total credit requirements behind the agronomic and general elective categories. This credit requirement indicates an emphasis and expectation across all universities that students will be required to provide significant training in soil science and soil fertility, as well as other soil-related areas (Table 2.4).

For the elective category, agronomy elective and general elective credits ranked first and second in total number of credit requirements (13.7 ± 2.3 and 11.0 ± 2.9 credits, respectively). Emphasis on selective and elective credits within agronomy found across all programs indicated the importance universities are placing on allowing students flexibility to select the most relevant coursework from a given list of approved classes. It is worth noting values for general/free electives were slightly skewed due to ISU allowing students to submit "custom" programs of study to address a requirement for supporting science courses to best meet the following goals: "keeper of the land," "builder of genetic diversity," "explorer of plant life," "developer of bio-energy," "confronter of world hunger," and "designer of sustainable systems.". Likewise, another outlier was present due to data availability at UIUC. The 35 credit hours of free electives reported in this study for UIUC was calculated manually after subtracting all listed degree requirements (46 + 47) from the 128 total credit hours required.

Similarly, averages for agronomy selective were also skewed by degree requirement at specific universities. For example, KSU and PU students are required to complete 21 and credit hours of agronomy selective, respectively. It is worth noting in the

case of PU, the agronomy selective value was inflated due to the inclusion of writing and composition courses within that subcategory. Due to the inability of this survey to completely account for the variable of student choice, agronomy selective at PU is presented including non-agronomic coursework.

For the crop protection category, required coursework within the disciplines of plant pathology (3.5 ± 0.4), weed science (3.4 ± 0.4), entomology (3.3 ± 0.7) indicates a reduced emphasis for this subcategory in comparison to others (Table 2.4). Ranked 11th to 16th for overall credit requirements, students are typically completing one, potentially two courses within each of these disciplines. However, in many cases, students must select one crop protection related course over another (e.g. field entomology vs. integrated pest management). Despite these limitations, a weed science course was required at 10 of the 11 universities surveyed. Similarly, nine of the 11 universities surveyed required courses in plant pathology and entomology courses. Only three universities (KSU, OSU, and UW-P) required standalone integrated pest management courses, and only one program required an integrated weed management course (UM-C). In many cases, several universities didn't even have a standalone integrated management course offered within the program of study.

For the technology category, eight of the 11 surveyed universities required some level of precision agriculture or remote sensing coursework, for an average of 2.8 ± 0.2 credits (Table 2.4). This followed the trend identified within the crop protection category in which students have a single required course within the given concentration.

The 'other' category encompasses several subcategories including, animal science, business and economics, capstone courses, international agriculture, internships,

and meteorology. Of these, eight programs required business and/or economics courses, for an average of 5.4 ± 1.1 credits. This requirement is identified specifically to relate to the trend observed within the categories of crop protection and technology in which students were required to complete a single class for each discipline. At five universities (NDSU, OSU, PU, SDSU, and UW-P) this trend is identical, with students completing one course of business and/or economics. At MU and UIUC, this requirement was increased to two courses equating to six credit hours, and at KSU and UNL requirements are further increased to 12 and 10 credit hours, respectively. For perspective, this pointed and deliberate emphasis on business and economics at KSU and UNL surpassed the individual requirements in soil science and soil fertility (seven and eight credits, respectively). At UNL, the 10 credit-hour requirement in economics also surpasses the combined total for all crop protection disciplines (nine credits, Table 2.3).

A relatively new requirement within most programs is experiential learning through internship experiences. The total number of credits varied from program to program, but seven of the 11 surveyed universities had specified requirements for undergraduate students to obtain and report back on an internship experience. Similarly, six programs required students to complete a capstone course (three credits) which would ideally incorporate multiple components of the program of study. Both internships and capstone courses will be discussed further in the following chapter.

Survey Limitations

The survey of these 11 universities was limited primarily due to differences in how the programs of study were reported online. Further limitations of this survey are

due to the prevalence of large agronomy elective and elective credit requirements. With students able to select any given combination of courses within each list, courses listed in these categories were difficult to assign to specific subcategories (Table 2.3, 2.4). Furthermore, the subcategory course emphasis will be modified for each student by how a student fills their elective options. Further limitations in accounting for individual student choice as it pertains to general/free electives were also identified as students could opt to utilize these credits to increase their academic training in a given agronomic discipline or in other non-related area.

Survey Conclusions

Averaged across the 11 programs of study for an agronomy majors, significant emphasis was placed within the areas of plant sciences, soil sciences, and business and economics. Most programs provided flexibility for students to select coursework of interest through agronomy elective and general elective credits. Across these universities, general education and prerequisite STEM courses comprised 41% of the average program. While some universities paired general education requirements with plant science-focused coursework (e.g. botany instead of biology, organic compounds in plants and soils instead of organic chemistry), most universities did not. In many cases, this creates limitations on time provided for academic training within each of the disciplines found within agronomy. Due to these time limitations, faculty are forced to prioritize specific courses within each discipline. Some programs of study are also forced for a variety of reasons to eliminate entire disciplines or subdisciplines from their respective curriculum.

In this survey one such prioritization was identified: reduced academic training found within the crop protection disciplines. As presented within Chapter 1, the scientific disciplines of entomology, plant pathology and weed science are immensely complex. In most cases, students are only required to complete one course within each of these disciplines. The reduced emphasis on crop protection observed within this survey is concerning. However, it is important to note these programs of study denote the absolute minimum requirements of undergraduate students. Students can (and often do) utilize some elective credits to take additional courses within the crop protection disciplines.

Another prioritization issue was the widespread lack of interdisciplinary requirements. As presented in Chapter 1, the intricacies of GxExM requires robust understanding of how the various disciplines interact with one another. To some extent, these intricacies are likely discussed and taught within the agroecology, plant ecology or soil ecology courses required at five of the 11 surveyed universities. However, based on the programs of study acquired for this survey, no university had a designated standalone course solely focused on holistic or interdisciplinary systems management. Some universities did require capstone courses, but based on course descriptions within several programs of study these capstone courses ranged widely in terms of focus and scope (data not shown). With the intricacy of GxExM programs, robust education with an increased focus on the interdisciplinary content knowledge and systems perspective is essential to ensure the success of students upon graduation.

Lastly, students on average received only one class on integrated management, which was only required at four of the 11 universities present in this survey. As presented in Chapter 1, integrated management is a tenet and arguably a requirement of sustainable

and ecologically friendly management not only for the discipline of entomology where IPM is most well-known, but also in the disciplines of plant pathology and weed science. The deemphasis on these content areas for students who are specializing in agronomic management, crop consulting and crop production is alarming, even with the previous caveat on these survey results representing the “minimal standards”.

Based on the conclusions presented within this chapter, it is clear further exploration about potential mitigation strategies and opportunities for students to address these concerns is needed. Three such opportunities are presented in the following chapter. The first opportunity is to increase, expand, and highlight internship experiences in roles or positions which require students to integrated multiple discipline-specific areas together (i.e. crop scouting and crop consulting). The second opportunity is to promote use of elective credits on co-curricular classes structured to provide experiential opportunities or intensive academic training on one or more disciplines through enjoyable and competitive experiences (i.e. crops judging, soil judging, weed science contest). Finally, the third opportunity to address these concerns is to reemphasize and integrate interdisciplinary knowledge in capstone courses focused on GxExM programs. These opportunities are addressed at length in the following chapter.

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CHAPTER 3: REINFORCING INTERDISCIPLINARY EDUCATION

Introduction

Over the last few decades, there has been many calls for the agriculture industry to improve the overall sustainability of food production systems. These calls have increased as the effects of climate uncertainty move from theoretical to observable. For example, over the last few decades the migration of soybean (*Glycine max*) and corn (*Zea mays*) into northern growing regions has been reported (Cusick, 2020). Some of this shift is due to plant breeders selectively developing cultivars specifically for these northern latitudes. However, a significant component of these migrations is due to changes in precipitation patterns and temperature ranges that makes these regions more conducive to corn and soybean production. For example, optimal planting dates of corn has steadily changed towards earlier planting by 0.13 days/year from 1980 to 2015 in the US Corn belt (Baum, Licht, Huber, & Archontoulis, 2020). These examples represent changes in agriculture production systems that are already underway.

In a recent report by National Academies of Sciences, Engineering, and Medicine (NAS) on feeding the world sustainably, significant mitigation strategies were proposed. Societal shifts on eating and buying habits were suggested, as were agronomic considerations such as implementing IPM programs and reducing synthetic fertilizer use (NAS & The Royal Society, 2021). In the same report, NAS also identified a gap between discoveries from fundamental research and the practical application of that research. This has resulted in valuable research being lost before reaching the farm or end user (NAS & The Royal Society, 2021). In a separate NAS report on technology advancements in food production systems, the authors identified the dire need to

transition from disciplinary silos toward systems-level management in order to best address the interconnections and linkages among multiple disciplines (NAS, 2019).

These NAS reports illustrate the need to modify agricultural research and production systems to meet their intended goals while striving towards improved sustainability. It is logical that the gaps identified between agricultural research and crop production constituents exist as well between academic training and required skillsets. These educational gaps can impact the training required for agronomists to identify and subsequently optimize genetics-by-environment-by-management (GxExM) programs. GxExM programs expand traditional GxE models for crop productivity to account for the critical role comprehensive management has on crop productivity and sustainability (Hatfield & Walthall, 2015).

Curriculum surveys across several Midwestern universities (see Chapter 2) showed a reduced emphasis on the disciplines within crop protection (entomology, plant pathology, weed science) and little emphasis on integrated management (i.e. integrated weed management, integrated pest management, integrated disease management). Likewise, courses that emphasize holistic, integrated crop management were absent from most of the programs. To meet the industry-level recommendations proposed by the NAS (NAS, 2019) increased emphasis in these content areas is warranted.

Many of the shortfalls identified are likely caused by time constraints present in most four-year degree programs. Potential mitigation strategies must build upon existing course requirements or utilize the flexibility present within agronomy electives and general/free elective credits. However, the majority of courses are taught as disciplinary courses (e.g. Entomology 101). Thus, a redoubling of emphasis on diverse internship

experiences, capstone courses, and co-curricular activities could improve interdisciplinary content knowledge, as well as systems level thinking. Opportunities for reinforcing interdisciplinary content knowledge also exist following graduation, and will be discussed following mitigation strategies at the undergraduate level.

Internship Experiences

In Chapter 2, the trend of incorporating external educational experiences into academic training was identified with most universities requiring internship experiences. This highlights the shift found across higher education toward the promotion of experiential learning opportunities. In formal education, students are initially taught new content as abstract concepts and theories. These abstract concepts and theories need to be reinforced by real world case studies or examples in the classroom in order to transfer concepts and theories into concrete systems.

In experiential learning settings, students must take the concepts and theories they have learned in other courses (or on the job) and actively experiment and implement them in the real world. In these scenarios, it is the students who must realize their own educational transformation. Failure to do so can result in concepts and theories remaining as abstract ideas in the student's mind (Kolb, 2015). In experiential learning, concrete "real world" experience is necessary to transform ideas into understandings.

The incorporation of experiential learning opportunities into agronomy curriculum is similar to their integration within other academic programs. According to a National Association of Colleges and Employers (NACE), an increasing number of

colleges, universities, and companies promote internship experiences to undergraduate students, and an increasing number of students are pursing internships (NACE, 2018).

Despite the positive support internships have received at many universities, internship experiences can vary between internships and students as nearly all internships are externally controlled and designed by the various organizations or companies that offer them. Lack of academic control on internship experiences in agronomy has been identified previously as a problem which can limit the academic value they provide students (Herring, Gantzer, & Nolting, 1990). This is further exacerbated by a lack of consistency in how internships are reported in different programs. In some programs, internships are “taught” or reviewed in accredited courses ranging from one to three credits. These internship courses often require presentations to peers about educational experiences, key learnings, and self-reflection. Conversely, in other programs, these requirements are non-existent, with internship experience being simply “required” or discussed in existing courses without accreditation. In some programs, internship requirements only exist as a mere box to check on the degree audit program. The former more structured approach offers a much more meaningful academic experience than the latter because self-reflection and internalization are key components to the experiential learning cycle (Kolb, 2015).

Capstone Courses

One change that has emerged in many agronomy programs is the promotion and integration of capstone courses into curriculum plans. Synonymous with other educational terms such as “senior thesis” and “culmination project”, capstones are usually

designed with multiple components which include oral presentations and written objectives (Tophatmonocle Corp., 2021). Within agronomy, instructors of capstone courses report they are designed to “put all the pieces together,” often with extended effort on the part of the instructor (Grabau, 2008). For example, in a whole-farm nutrient management course designed for students majoring in crop and soil science, as well as dairy science at Cornell University, students reported high satisfaction with learning objectives and course curriculum, but overall dissatisfaction in the initial amount of field trip experiences provided and limited contact with farmers and nutrient management specialists (Albrecht, Ketterings, Czymmek, van Amburgh, & Fox, 2006). Cornell’s whole-farm nutrient management program is similar to one at Iowa State University (ISU) for students majoring in agricultural production (AG450 Farm). This is a 450-acre farm utilized as a student laboratory to simulate real world farming decisions (hybrid/variety, planting population, marketing plan, livestock decisions, etc.). AG450 has received positive feedback from most students (Steiner, 2004).

As the student feedback from Cornell’s capstone course suggests, capstone courses must continue to adapt to meet the needs of undergraduate students. Multi-level (e.g. consecutive) integrated capstone courses were promoted in the late-1990s within agribusiness curriculum programs in order to address limitations within agribusiness curriculum (Collins & Dunne, 1996). In contrast, senior level interdisciplinary capstone courses have been evaluated at Massey University in New Zealand for students majoring in agricultural production related fields. Massey University’s capstone program carried robust prerequisite requirements including internship experience (30 weeks total) and academic coursework (two courses of agronomy, animal production, farm economics,

and soil science each) before students were eligible to enroll (Wright, 1992). This capstone course was considered very successful and a worthwhile educational experience by students.

These examples illustrate two significant considerations for capstone courses. The first consideration is that from university-to-university, capstone courses range significantly in terms of depth, breadth, and content focus, especially as it relates to interdisciplinary knowledge. These differences make assigning value to capstone courses across universities and majors challenging as not all capstone courses are created "equal". The second consideration is the student's grade level when completing these capstone courses. A vast majority of capstone courses are only offered to senior-level students. Collins and Dunne (1996) propose that a multi-leveled approach would provide significantly more benefits. This would increase the responsibilities of instructors to adjust expectations in lower-level capstone courses to account for the amount of agronomy coursework completed and subsequently, agronomy content knowledge. Due to time limitations present in most curriculum programs, the addition of more coursework in the form of new capstone courses for freshman, sophomore, or junior students is likely unrealistic and would not be palatable for many students.

Students who have completed capstone courses (regardless of depth, breadth, or degree level) usually rate their experiences as extremely beneficial for preparing them for their first professional position after graduation (Andreasen & Trede, 1998). As curriculum programs of study are updated within agronomy, capstone courses that integrate multiple disciplines are recommended to better prepare graduates for their future careers. Furthermore, incorporating integrated management concepts into the

capstones would directly address the lack of focus on integrated management within most programs of study.

Co-Curricular Educational Experiences

Undergraduate students have opportunities to customize their educational experiences to best fit their career interests through agronomy electives and general/free electives. One such use of elective credits are co-curricular educational experiences. According to the Great Schools Partnership, a nonprofit school-support organization promoting academic reform, co-curriculars are complementary to the content students are learning in school, thus, these experiences connect to or mirror the academic curriculum (Great School Partnership, 2013). It is this implicit connection to academic programs that separate co-curricular experiences from extracurricular activities that focus less on student learning (Great School Partnership, 2013).

As reported by the Great Schools Partnership (2013), rules constituting co-curricular experiences are not well defined. Many co-curricular activities are ungraded activities or do not offer academic credit for completion. As a general rule, co-curricular courses are often removed from "normal" academic courses either by time (e.g. offered outside of regular class hours) or organization (e.g. offered by an external teacher and/or organizer), although this can range from one activity to another (Great School Partnership, 2013).

Overall, the value of co-curricular activities should not be understated. Co-curricular activities have immense educational and practical value in gaining relevant

experience and improving student skills (Jackson & Bridgstock, 2021; Stirling & Kerr, 2015). In a blog post published on Anthology.com, Lundquist, (2020) stated:

> "When students participate in co-curricular events, they increase self-efficiency, . . . make important gains in critical thinking, . . . [and] develop marketable skills. Students engaged in experiences outside of the classroom are developing different skills . . . and developing those skills more deeply than those who do not participate."

The educational value of co-curricular activities is not isolated to only four-year institutions. In many cases, co-curricular activities are also promoted in various community college programs (Gill, 2016). Likewise, the value of co-curricular experiences is supported by research in various graduate and professional degree programs (Waryas, 2015). Co-curricular activities are incorporated into some medical school programs in efforts to better humanize the process of medical training (Senok et al., 2021). With a range of implementation strategies (e.g. free-study, extracurricular-led, accredited course), a review of major agronomy-related co-curricular activities is needed. Co-curriculars included do not represent a totally comprehensive list of those available to agronomy students, but they do represent some of the premier organizations involved in this aspect of agronomy education.

SSSA: Collegiate Soil Judging.

Collegiate Soil Judging is an intercollegiate undergraduate student contest hosted by the Soil Science Society of America (SSSA; SSSA, 2021). Collegiate soil judging is designed to promote and build student knowledge and ability to identify, evaluate,

classify, and describe soil profiles. Students from eligible universities compete in both regional and national contests that rotate locations from year to year. While primarily sponsored by SSSA and other industry sponsors, a vast majority of the planning, organization and development of content materials comes from the United States Department of Agriculture–Natural Resource Conservation Service (USDA-NRCS). In the United States, the USDA-NRCS serves as the highest authority on soil science. This provides students involved with Collegiate Soil Judging a unique, first-hand experience with the techniques and procedures utilized by the USDA-NRCS. These methodologies are used in a wide array of applications, the most important being land use classification (e.g. buildings, roads, fields) surveys. In Collegiate Soil Judging, students compete over the course of two days to judge and assess the soil within three individual soil pits, and two team pits. Within each pit, students are required to complete a total of five sections that describe and classify the soil.

The first section in each soil pit is related to soil morphology. Students are required to provide the correct designators for soil horizons (prefix, master, subordinate, and number). Boundary measurements for each horizon are also required, as are texture determinations on the percent clay and coarse fragments and soil texture classification. Students are then required to complete soil color-related information on moistened soil with soil hue, value, and chroma used to match the soil sample from each horizon to an established soil color matrix. Following color classification, students are required to identify the soil structure and grade its distinctness and overall durability. Soil consistency is also a factor to consider depending on the specific moisture level and associated rupture resistance. Lastly, students are required to identify special soil features

(e.g. redox concentrations, redox depletions, and effervescence) (Rees, Johnson, Smit, & Riddle, 2019).

The second section of the collegiate soil judging contest addresses soil profile characteristics. This is separated into five main categories. The first category is hydraulic conductivity or the soils ability to transmit water. Students must rate the soil profile on where the limiting layer is located (e.g. high, medium and low). The next category is effective soil depth, which characterizes how deep soil roots can penetrate. The third category is available water holding capacity. This takes into consideration the effect soil texture has on water retention. Following this categorization, students are required to determine the depth to the season high water table, as well as the carbonate stage of the soil profile (Rees et al., 2019).

The third section of the collegiate soil judging contest covers site characteristics. Simply put, site characterization references the placement of the soil profile on the landscape. In this section, students must determine the soil's landform and position (e.g. local soil terrain), parent material (alluvium, colluvium, residuum, etc.), and slope on a scale to 0-30%. Following this, students must classify the soil profile into risk categories for surface runoff and soil erosion (Rees et al., 2019). Properly characterizing the local site is an essential skill to describe local soil conditions and potential risks.

The forth section of the collegiate soil judging contest is soil classification. This section requires students properly identify the five levels of soil classification. This includes soil epipedons (e.g., mollic, umbric, ochric), diagnostic subsurface horizons or features, and the soil order (e.g., vertisol, inceptisol, mollisol), sub order, and great group.

Following this, students are required to specify particle-size control and family particle size classes (Rees et al., 2019).

The fifth and final section of the collegiate soil judging contest is site interpretation. Using the classifications, characterizations, and morphological features they have previously described for each soil profile, students must provide a comprehensive rating on suitability for dwellings without basements, or septic tank absorption fields. In 2019, this also included a Storie index rating that ranks land for use in irrigated agriculture in California (Rees et al., 2019). This is somewhat similar in context to the corn suitability rating (CSR) rating in Iowa (Miller, 2012). Depending on the location of the contest, new or additional suitability ratings can be added to address local points of interest.

With this review of the contest rules and requirements, it is clear that Collegiate Soil Judging has an intense focus within the science underlying the methodology of soil classification and soil characterization. This intensive focus significantly limits the ability of Collegiate Soil Judging to reinforce interdisciplinary education and address systems-level management considerations. Despite these shortcomings, for undergraduate students interested in soil science as well as soil and natural resources conservation, this co-curricular can provide invaluable experience and training. Furthermore, promotion of this disciplinary knowledge can improve student competency within soil science (Rees et al., 2019).

NCWSS/WSSA: Collegiate Weed Science Contest

The North Central Weed Science Society (NCWSS) and Weed Science Society of America (WSSA) weed science contests are hosted regionally by NCWSS on an annual basis and nationally by WSSA every four years. Often referred to as "weeds contest," the location of these contests changes each year among four-year universities with graduate programs in weed science. At both the regional and national level, the contests are designed to provide educational experience to both graduate and undergraduate students interested in weed science and provide valuable networking opportunities with university faculty, industry representatives, and fellow students (NCWSS, 2021).

The weed science contests are comprised of four main sections. The first section addresses weed identification. All students are required to identify to species 30 mature weeds, weed seedlings, plant parts, or seeds. Graduate students are required to also provide the correct spelling of the scientific name (NCWSS, 2021). This section is designed to promote the important skill of weed identification, as in nearly all management programs, correct identification of the pest is critical in creating an optimal management plan.

The second section of the weed science contest is separated into two components: a written mathematics exam over herbicide application technology and a team sprayer calibration. Students are required to complete mathematic questions related to weed science. These include spray calibration, unit conversion, active ingredient, and concentration (e.g., ppm, ppb, etc.) calculations, and students must be able to find, interpret, and apply information found within example pesticide labels. In the second component, students are required to apply the mathematical concepts to properly calibrate

a research spray boom for a given field scenario as a team (NCWSS, 2021). This real-world application of mathematical concepts reinforces the value these agronomic calculations have in the real world.

The third section of the weed science contest is the identification of an unknown herbicide. This section requires students to identify a total of 15 herbicide sites of action based on visual symptomology shown in known indicator crops with varying herbicide-resistant traits, as well as indicator weed species. Graduate students are then required to further classify the unknown herbicide to chemical family, as well as specific active ingredient based on selectivity for control/injury, from an approved list of 28 active ingredients (NCWSS, 2021). These simulated experiences are many students' first opportunity to identify the effects of unknown pesticides that represent fields where spray records were not made or retained, and the experience serves to reinforce the importance of in-field diagnostics and product knowledge.

The fourth and final section of the weed science contest involves problem solving and developing recommendations. This section is fondly referred to as the "farmer problem". In these simulations, experienced agri-professionals and weed scientists play the role of a farmer who has called in about a plant production problem. Students must then ask the "farmer" diagnostic questions and examine the assigned field scenario for evidence to support or disprove the proposed diagnosis, and determine the correct answer. While heavily focused on weed science, other disciplines and agronomic issues are also represented at the contests to provide a variety of situations for students to solve. The field simulation ends after 15 minutes, or after a student has provided effective solutions for the problem in-season and for the following year. Regarded by most (if not

all) participants as their favorite section, students demonstrate their ability to identify and diagnose agronomic problems, gain exposure to agronomic troubleshooting, and practice their "farm-side manner" when interacting with producers (NCWSS, 2021).

Students involved with the Collegiate Weeds Science contest receive deep and intensive academic training and educational experiences as they pertain to weed science and pesticide application technologies. Weed identification and in-field diagnostics are critical skills, and they are very important within agronomy and at times, direct field/farm management. There is often limited emphasis on interdisciplinary systems management; however, many of the skills developed for this contest are definitely transferrable across disciplines. Despite these limitations, the focus on diagnostics and development of "soft skills" present in the farmer problem often lead to many students promoting this co-curricular contest to their peers.

ASA: Collegiate Crops Judging.

The Agronomy Society of America (ASA) conducts Intercollegiate Crops Judging at regional (Kansas City, MO) and national (Chicago, IL) contests. These are organized primarily by the ASA with additional sponsorship from industry representatives, including the Chicago Mercantile Exchange (CME) Group (ASA, 2021b). As a co-curricular contest, Collegiate Crops Judging enjoys a great deal of prestige, with many four-year universities traveling to compete from across United States. The contest is heavily weighed on commercial grain grading, but its three main sections encompass other disciplines and segments of agronomy.

The first section of the Collegiate Crops contest is commercial grain grading. This section is essential for teaching students about crop products, their markets, and defects that can affect their worth and end market use. Students are given eight grain samples selected from approved species (e.g., corn, soybean, barley (*Hordeum vulgare)*, wheat (*Triticum aestivum*), oats (*Avena sativa*), cereal rye (*Secale cereale*), and grain sorghum (*Sorghum bicolor*), along with information on test weight, moisture percentage, dockage, damage, special grades, foreign material, and other special designations. Students must use specific rules and grading factors for each market class to provide commercial grades for the eight samples within the time limit of an hour and a half (ASA, 2019).

The second section of the Collegiate Crops contest is seed analysis. This section tests student's knowledge of important considerations behind the selection of seed for planting or market consumption. Factors such as genetic purity and seed quality are important to consider when selecting a seed source. Contamination by noxious weeds can make seed not only undesirable, but potentially illegal! Species covered within this section range from large seeded legume crops (e.g., soybean, cowpea, field pea, field beans), small grains, cultivated broadleaf crops (e.g., safflower, sunflower, daikon radish, flax), forage grasses and legumes, and traditional turfgrass species (ASA, 2019). In each of the 10 required samples, students must identify all species mixed with the marketable class of grain. They then must classify the contaminants and identify weed species (e.g., prohibited noxious, restricted noxious, common) present in the sample. This section provides students the opportunity to work with a wide variety of crops and develop seed identification skills.

The third and final section of the Collegiate Crops Judging contest addresses plant and seed identification. Students are given an hour and a half to identify 200 specimens ranging from prepared plant mounts of broadleaf species (ranging from post-bud to fruiting) and grass species at full maturity. Included in this section are disease samples common to these cultivated crop species. These 200 specimens are chosen from an approved list of 136 crop species and/or crop varieties, 21 diseases, and 74 weed species (ASA, 2019).

Collegiate Crops Judging struggles to gain traction as many students may have the misconception that if they aren't going to pursue a career in grain grading or grain merchandising, this co-curricular has no educational or "real world" value. This misconception is unfortunate. Despite being heavily focused on grain grading, grain merchandising, and seed analysis, students also get broad experiences with disease, plant, and seed identification, and this knowledge can transition well into other applications (e.g., careers). The intense focus on grain grading and seed analysis can be a significant barrier of entry for universities that do not have the teaching materials or equipment to adequately prepare for the contests. However, as with many of the other co-curricular contests, universities involved with Collegiate Crops Judging often pool their surplus resources to aid new professors and faculty who wish to lead teams to these contests.

NACTA: Crops Judging.

The North American Colleges and Teachers of Agriculture (NACTA) Crops Judging is an intercollegiate undergraduate student contest. Originally formed in 1955, NACTA is a professional society comprised of a multidisciplinary coalition of

agriculturally-related educators employed at public and private four-year universities as well as technical and vocational two-year colleges (NACTA, 2021a). As a society, they host a national judging conference comprised of multiple co-curricular events for various agriculturally related majors. Crops Judging is one of six contests at each judging conference (i.e., soils, crops, general livestock, dairy cattle, ag business, and knowledge bowl). Hosting schools can also offer additional, optional contests (NACTA, 2021c). The location of the NACTA judging conference changes, alternating between two-year and four-year institutions as hosting schools. A reformatted copy of the 2020 NACTA Crops Judging contest rules is provided in Appendix A.

Crops Judging is designed to prepare students for a career in agronomy, with an emphasis on broad and diverse crops and cropping systems. It is separated into four distinct sections: an agronomic exam, math practical, lab practical, and plant and seed identification exam.

The agronomic exam is a multiple-choice exam covering a wide variety of agronomy-related topics (NACTA, 2021b). This ranges from basic soil management and pesticide formulations to plant physiology and IPM tactics (Appendix A). The agronomic exam was created to test and evaluate students on their preparedness and knowledge base on important topic areas evaluated in the International Certified Crop Advisor and Certified Crop Advisor programs.

The math practical tests agronomically-related mathematics and calibrations. In many avenues of agronomy, math is an underlying skill that must be mastered to perform optimally. Students are required to complete various agronomic conversions, calibrations, and calculations (NACTA, 2021b). Key examples include fertilizer calculations, pesticide

calibrations, yield determinations, area or volume conversions, and simple plant breeding calculations involving heritability, homozygosity and expected genotypic and phenotypic ratios from a cross (Appendix A).

The lab practical shines as an interdisciplinary co-curricular. This section is a 75-question exam covering a wide array of agronomy topics. For plant pathology-related questions students are required to identify up to 35-40 diseases across nine crop species from symptomology, identify optimal management strategies, and provide basic background information on the disease (Table A.2). These expectations are similar for entomology-related questions where students must be able to identify up to 40-45 insect species in both larval and adult stages (Table A.3). These species range from beneficial insects to pests of nine crop species and includes expectations on understanding the effects life cycle can have on management strategies. In addition, students are required know a wide array of other content areas including weed management, pesticide formulations and identification, nutrient deficiencies, identify common field machinery or related agronomic equipment (Table A.4), recognize and discern statistical differences from tables and graphs, and knowledge on precision agriculture (Appendix A).

The final section of the NACTA Crops Judging contest involves plant and seed identification. Students are required to identify a plant species based off a live plant sample, pressed parts or photographs, and/or seed samples (Table A.1). The list is limited to 54 species and/or classes of cultivated crops, 16 species of forage grasses, 11 species of forage legumes, and typically 60-70 species of grass and broadleaf weeds (NACTA, 2021b). The specimen list is designed to provide a broad exposure to the important crop and weed species in various growing regions (Appendix A).

Students involved with NACTA Crops Judging receive one of the most multidisciplinary educational experiences of the four selected co-curricular contests, especially as they relate to direct management considerations. Robust and comprehensive identification listings in entomology, plant pathology, and weed science help target potential shortcomings in crop protection-related disciplines that occur due to curriculum time limitations. The NACTA crops judging has an interdisciplinary focus, although continued effort must be made by both coaches and instructors as well as contest developers to transform multidisciplinary content knowledge and skills into truly systems level management and interdisciplinary experiences.

Post-Graduate Pathways to Interdisciplinary Knowledge

Following graduation with a bachelor's degree in agronomy, requirements for further learning do not cease. In fact, with the intricate complexities found within agronomy and an everchanging environment, agronomists and agri-professionals are required to continuously develop their content knowledge and skills to best serve their customers and/or constituents. Two avenues for seeking interdisciplinary knowledge following a bachelor's degree include graduate studies and continuing education within professional certification.

Graduate Degrees.

Time constraints for general undergraduate education and prerequisite courses requirements often result in compromises being made in terms of both the depth and breadth of agronomic training. For undergraduate students interested in continuing their

education in graduate school to fill these knowledge gaps, many universities provide either in-person or online MS programs within agronomy as well as the other agronomy-related disciplines.

However, for most traditional MS and PhD degrees, students are required to specialize in the content area of their program. This comes in the form of intense research focus as well as some required graduate coursework. For an M.S. degree, this is limited to about 30 credits. For students continuing on to a PhD, additional coursework is available, but this coursework is often directly related to their research (e.g. statistics, bioinformatics) or within their discipline.

Plant Doctor Programs.

For students explicitly seeking multidisciplinary or interdisciplinary graduate degrees, options are quite limited compared to disciplinary programs. In the United States, two doctorate-level programs are available that provide academic training across agricultural sciences including crop protection-related (entomology, plant pathology, nematology, weed science) as well as plant- and soil-related (agronomy, horticulture, soil science, water science). Commonly referred to as "Plant Doctor" programs, these academic programs are designed to produce a highly skilled plant practitioner with broad interdisciplinary academic training (McGovern & To-anun, 2016). These include the Doctor of Plant Medicine (DPM) degree at the University of Florida and the Doctor of Plant Health (DPH) degree at the University of Nebraska-Lincoln (McGovern & To-anun, 2016). Of the plant doctor programs in the United States the University of Florida's

DPM program was the first established in 1999. Ten years later, the University of Nebraska established the DPH program in 2009 (University of Nebraska-Lincoln, 2021a).

The DPM and DPH programs are a part of a global network of plant doctor programs that extends to South Korea, Taiwan, and Japan, with additional programs in development in Egypt, China, and Taiwan (McGovern & To-anun, 2016). Each plant doctor program differs slightly in credit requirements, but all programs focus on providing both depth and breadth of interdisciplinary knowledge to their students. These include three interdisciplinary programs offered in the United States at the masters level, at Ohio State University (Masters in Plant Health Management, MPHM), University of Georgia (Masters in Plant Protection and Pest Management, MPPPM) and Washington State University (Plant Health Management, PHM) (The Ohio State University, 2021; University of Georgia, 2021; Washington State University, 2021).

As a doctoral-level degree, students enrolled in the DPM and DPH programs are required to complete 100 academic credits in entomology, plant pathology, weed science, soil science, and plant science) coupled with required internship experiences to apply that significant knowledge base. These expectations are similar for masters-level programs (e.g., MPHM, MPPPM, PHM), although credit requirements are significantly reduced (30 to 35 credits) to account for their reduced time (and effort) requirement.

Despite an array of disciplinary and interdisciplinary graduate programs available, it is clear not all students will wish to continue their academic training past the undergraduate level for a variety of reasons. As such, it is important to consider other educational opportunities that can enhance the agronomist’s knowledge base.

Promotion of Professional Accreditation/Certification.

The assimilation of knowledge required in agronomy from different scientific disciplines can be difficult to prove to local constituents. Furthermore, advancements and changes within agronomy (e.g. new pests, disorders, agronomic issues) can arise, requiring agronomists and related agri-professionals to continuously develop and expand their knowledge base and training. To facilitate the verification of the skillset and offer continuing education opportunities, ASA established the Certified Crop Advisor (CCA) program in 1992. To obtain CCA accreditation, applicants must pass two comprehensive agronomic exams (local and international) that cover four main competency areas: nutrient management, soil and water management, pest management, and crop management. Passing these exams requires content knowledge within the multiple agronomic disciplines (which includes crop protection). This requirement illustrates the value of promoting interdisciplinary education and systems management during undergraduate degrees.

However, passing the CCA exams is not the only requirement to obtaining CCA accreditation. CCA applicants must also meet education and experience requirements. To qualify, applicants must have either a bachelor’s degree in agronomy-related fields with two years of experience, an associate degree in an agronomy-related field with three years of experience, or four years of experience with no degree. While those with an associate degree or no degree are eligible to apply for CCA accreditation, ASA estimates more than 70% of the over 13,000 accredited CCAs have at least a bachelor’s degree (ASA, 2021a). Following accreditation, all CCAs must complete at least 40 hours of continuing education credits every two years to retain certification. Once a CCA has met

the requirements of five years of experience (post-degree), they may be eligible to apply to the next level of ASA certification: The Certified Professional Agronomist (CPAg).

Qualifications for the CPAg program are increased compared to the CCA program. For example, not all bachelor's degrees "related to agronomy" are eligible, with an added requirement to have completed six to nine credit hours within crop management, pest management/crop protection, and soil sciences. An additional six to nine credit hours of professional electives must also have been completed that align with these three categories. CPAg applicants are also required to provide five professional references (ASA, 2021c). In both cases, these programs are well respected by industry, academia, and governmental agencies. In obtaining CCA and CPAg accreditation, individuals illustrate that they meet minimal benchmark requirements in interdisciplinary content knowledge. (ASA, 2021a).

Conclusions

Within undergraduate agronomy programs, educators must take great efforts to reinforce multidisciplinary and interdisciplinary education. As a science, agronomy is comprised of multiple disciplinary sciences interacting with one another. These interactions are central to crop management and create a need for modern agronomists, crop consultants, and ag advisors to have sufficient depth of knowledge and breadth of knowledge as it pertains to the agronomic sciences.

Shortcomings exist in the required agronomic curriculum at universities that compromise abilities to comprehensively address crop production systems. Multiple opportunities exist within program curricula to improving the academic training students

receive across diverse disciplines, as well as their integration into systems level management. Furthermore, slight modifications to curriculum plans can help address knowledge gaps, improve the educational experiences, and enhance the ability to develop and implement more comprehensive GxExM management programs.

Emphasize Internship Experiences.

In addition to being valuable career training experiences, internships have been proven to provide valuable opportunities to develop self-confidence, problem-solving skills and professionalism (Herring et al., 1990). Despite these benefits, not all internships are created equal in terms of interdisciplinary focus. However, the multiple opportunities undergraduate students have while in school to seek new and diverse work experiences that challenge them and teach about new areas of agronomy can help address these limitations. For example, universities can leverage structured courses focused on student reflection (Kolb, 2015) to enhance the value of internship experiences (Clark, 2003). In these courses, student reflection is often coupled with 20 to 30-minute presentations on their internship experiences (Clark, 2003). This allows students to share their key learnings and expose students to other opportunities within agronomy. Universities that do not currently require internship experiences or structured review courses should incorporate these experiential learning opportunities.

Develop Capstone Courses focused on Integrated Management.

Development, promotion, and integration of interdisciplinary capstone courses is highly recommended in order to better integrate the concept of systems level management to the students. Limitations in existing capstone courses at many universities

prevent educators from leveraging these courses to their true potential. For students involved with crop consulting and crop production, opportunities to practice classroom concepts as they relate to integrated management programs are needed. With an overall lack of emphasis on integrated management systems across the several universities surveyed (see Chapter 2), it is logical to utilize existing coursework to provide valuable interdisciplinary training as it pertains to systems level management. This strategy could prove even more valuable to universities not currently requiring designated capstone courses, which have been proven to have significant educational value (Andreasen & Trede, 1998; Steiner, 2004; Wright, 1992).

Promotion of Co-Curriculars and Agronomic Electives.

Within each program of study, students receive flexibility to shape their undergraduate experience to best address their career goals through agronomy elective credits and general/free electives. While it is doubtful most undergraduate students would opt to use 100% of their elective credits on furthering their disciplinary and interdisciplinary training, educators and academic advisors should make a conscious effort to promote the selection of coursework that will improve and diversify disciplinary knowledge, as well as courses with a focus on integrated crop management. In addition to these agronomic elective courses, co-curriculars similar to those described in this chapter should be highly recommended to all students due to the educational benefits they can provide (Gill, 2016; Jackson & Bridgstock, 2021; Senok et al., 2021; Stirling & Kerr, 2015).

Development of Structured Co-Curricular Preparation Courses.

A major limitation of most, if not all collegiate co-curriculars is that by themselves, participating in co-curricular contests do not provide the complete educational value. This is unfortunate, as the non-traditional framework of a competitive intercollegiate contest presents opportunities to leverage a different learning environment – one designed with the expressed purpose to train and prepare students for contests. It is reasonable to believe the “complete” value of co-curriculars can only be obtained through organized and purposeful preparation for these co-curricular contests.

In some co-curriculars such as intercollegiate soil judging, this is well understood with accredited contest preparation courses offered by many universities (AGRO 279 at UNL, AGRY 1500 at Purdue, AGRON 415 at Kansas State University) (Kansas State University, 2020; Purdue University, 2021). In some cases, this course is required as part of curriculum for students majoring in a soil science related field (University of Nebraska-Lincoln, 2021b). Across other co-curricular contests and universities, preparation methods for co-curriculars varies significantly.

In many cases, undergraduate students compete on self-taught teams or as teams organized as part of an extracurricular club with no official coach or instructor. The student-led approach reduces student learning opportunities and contest performance because access to academic resources and teaching materials are limited. In other scenarios, students may be coached by a faculty member, but not receive academic credit via an accredited course (e.g., an unofficial course). This approach addresses many of the concerns present in non-structured/non-coached programs as students are now led by a knowledgeable and trained educator. This approach unfortunately fails to recognize the

academic value co-curriculars can offer undergraduate students by means of receiving academic credits.

Accredited courses for all relevant co-curricular contests should be developed and promoted to provide continued student access to both academic resources and facilities. Furthermore, these courses should be included on student transcripts to identify students which have chosen to utilize some of their limited elective or selective credits to pursue these learning opportunities. While peer-reviewed academic research is not available to support these recommendations, there is some evidence based on student feedback on existing preparation courses. For example, in student evaluation forms for an independent study course developed to prepare for NACTA Crops Judging contests at the University of Nebraska-Lincoln, students reported the following:

AGRO 496-004 INDEPENDENT STUDY

Question 36. What is your evaluation of this course based upon: (a) your satisfaction with what you got out of this course and (b) whether it was a valuable educational experience or a disappointment? Please comment.

- Spring 2017: Very valuable course and I learned more than I ever thought that I would.
- Spring 2017: Excellent. One of the best classes I ever took in college. Would encourage all agronomy majors to take this class.
- Spring 2017: I was extremely satisfied with the course, and would recommend it to anyone.
- Spring 2018: Great class offers a broad spectrum of Agronomic Knowledge, a course I would highly recommend to anyone going into ag.
- Spring 2018: I think this class has been one of the most helpful classes I have taken here at the University when it comes to Agronomy. There is still so much you could learn but in terms of applicable knowledge pound for pound this is a fantastic class.
- Spring 2018: I was very satisfied with this course and look forward to be in it again in the fall. It was so valuable I'm taking it again. Very satisfied with what I got out of the course. Taught me more real-world knowledge than any other class.
- Spring 2019: I learned so much from this class that I can apply to any component of the cropping system.

These selected quotes represent a mere portion of the complete 37-question evaluation form (data not shown). Averaged across all available semesters (n = 8), student evaluations strongly supported the course content, course structure, and educational value of AGRO 496-004, with many students reportedly recommending the course to their peers. These positive evaluations support further development and implementation of co-curricular preparation courses for other contests, and at other universities.

During development of preparation courses and contests, special care must be taken by educators and organizers to ensure material covered on the contest is relevant, realistic, and useful. Additional effort and care must be taken to transform disciplinary and multidisciplinary content into the level of integrated systems management required to optimize GxExM programs in the real world.

Intricacies found within agronomic management often create daunting challenges for many newly graduated students. While hindsight and learning lessons the “hard way” will ultimately be a part of every agronomist’s career, co-curricular preparation courses and contests can serve as valuable training grounds. Mistakes made in classroom, soil pit, or contest hall do not carry with them the same economic weight as mistakes made in the field. It is prudent to promote these experiential learning opportunities for students as following graduation; lessons will not be learned as easily, nor as cheaply.

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APPENDIX A: CO-CURRICULAR CONTEST RULES

Introduction

Co-curricular programs presented within this document are organized and sponsored by organizations within the field of agronomy, soil science, and education. These organizations (e.g. ASA, SSSA, WSSA, NACTA) are well-established professional societies with focus within their respective disciplines. With a proven history of providing these opportunities to students, it is reasonable to assume these contests will endure. However, in the event that online hostings, society websites, or contests in general are modified, additional documentation and references for each program presented in chapter three are provided. Furthermore, given the overall fluidity of many contests to change content from year-to-year, an example of the NACTA Crops Judging contest rulebook is provided.

SSSA: Collegiate Soil Judging

A three-page rules overview of the Collegiate Soil Judging contest can be readily obtained through the Tri-Society (ASA/CSA/SSSA) website (ASA, 2021; CSSA, 2021; SSSA, 2021). Detailed rules for each regional and national contest are released on an annual basis in the form of a guidebook by hosting universities. Examples of regional and national contests can be found on various websites, including an archive page by the undergraduate organization SASES (Students of Agronomy, Soils, and Environmental Sciences) (OSU, 2018; Rees, Johnson, Smit, & Riddle, 2019; SASES, 2019; TAMU,

2017; UNL, 2019). Example score cards are also available online for each regional and national contest.

ASA: Collegiate Crops Judging

Collegiate Crops Judging contest rules and materials are best obtained from the ASA website (ASA, 2019). The most recent national rules available online are from the Fall of 2019. Additional information on the Kansas City, MO regional contest is available at the American Royal website (American Royal, 2021). Additional information is available from the officers of the 2019 coaching committee, which includes Dr. Rob Proulx, Dr. Mindy DeVries, and Dr. Kevin Donnelly.

NCWSS/WSSA: Collegiate Weed Science Contest

An historic overview of weed contests in other regions is presented by Oliver (1991). More current information, rules, and full specimen lists are available from the North Central Weed Science Society (NCWSS) and the Weed Science Society of America (WSSA) websites (NCWSS, 2021; WSSA, 2019). This also includes answer keys from previous contests for use as student preparation material. Additional information on the NCWSS contest can be obtained by contacting members of the summer contest subcommittee of Resident Education. The current 2021 chair is Dr. Devin Hammer (Bayer Crop Science) and Dr. Debalin Sarangi (University of Minnesota). For information on the national WSSA contest which is held every four years, the 2019 contest superintendent was Dr. Dawn Refsell (Corteva Agriscience). No

information regarding a national committee or subcommittee for these contests was identified within the 2021 WSSA Manual of Operating Procedures (WSSA, 2021).

NACTA: Crops Judging

A reformatted copy of the contest rules from the 2020 Fort Hays State University Contest is provided below. The 2020 NACTA judging conference was cancelled due to health concerns from the COVID-19 pandemic. Additional resources and contest rules are available on the NACTA website (NACTA, 2021). Previous contest results, photos, and rules are available within the NACTA archive (NACTA, 2019)

2020 NACTA CROPS CONTEST DESCRIPTION

The contest will be divided into four areas with 600 total points as follows:

A. Agronomic Quiz (150 points)

B. Math Practical (150 points)

C. Lab Practical (150 points)

D. Plant and Seed Identification (150 points)

One hour will be allowed for completion of each section. Additional descriptions and specific rules for each section of the contest follow and will be considered official for the contest.

Section A: Agronomic Quiz

This section will consist of 75 written multiple-choice exam questions worth 2 points each for a total of 150 points. Both general and specific questions will be asked on production of major US grain and forage crops. The International Certified Crop Adviser (ICCA) Performance Objectives will provide an excellent outline of potential topics. They are available from the American Society of Agronomy, 5585 Guilford Road, Madison, WI53711-5801 (608-273-8080) or website at: https://www.certifiedcropadviser.org/exams/icca-performance-objectives

Topics may include:

- Crop production statistics (major world and U.S. crops) and distribution of US crop production
- Crop classification terms (botanical, growth habit, crop utilization, etc.)
- Crop physiology, growth, and development
- Crop quality and quality evaluation, including typical levels for important quality factors in variousgrain and forage crops

- Seed and plant morphology and anatomy
- Plant breeding and genetics, including biotechnology and genetic engineering tools and applications
- Seed industry/technology (seed quality, seed certification, testing, processing, treatment, intellectualproperty rights, etc.)
- Planting (cultivar selection, seeding equipment, planting practices, seed treatment, seeding dates,replanting decisions, etc.)
- Pest problems and pest control (insects, diseases, and weeds, biology/life cycle of major crop pests)
- Herbicide management (classification of herbicides, crop injury symptoms, managing herbicideresistance, herbicide programs, application timing terminology and strategies)
- Pest management alternatives (cultural and biological control practices, IPM principles, pest scoutingand monitoring, role of beneficial insects, etc.)
- Pesticide use and management (pesticide stewardship, safety, restrictions, formulations, adjuvants,trade/common names of major pesticides, etc.)
- Harvesting and storage of grain and forage crops and crop products
    - Management of forage crops, including harvest factors and effects on forage quality, comparison of tame pasture systems (grasses, legumes, mixtures), native range management, evaluating forage quality (protein, NDF, ADF, TDN), grazing management, cutting schedules
    - Cropping systems and crop rotations
- Climate and crop environment (light, temperature, and moisture effects on plants, weather and weatherpatterns, earth's energy balance, climate change, global temperature and CO_2 levels)
- Weather and climate effects on crop production and management decisions
- Basic soil properties (physical, chemical, and biological)
- Soil fertility (nutrient availability, nutrient movement, factors affecting nutrient loss, plant needs fornutrients, soil pH, organic matter, etc.)
- Nutrient management (soil testing, soil test reports/recommendations, fertilizers and fertilization,fertilizer application and nutrient stewardship, four R's - source, rate, timing, placement)
- Managing soil pH, lime and liming, description and management of saline and sodic soils
- Soil water management (irrigation, drainage, erosion, leaching, evapotranspiration, conservation, etc.)
    - Tillage and residue management (tillage systems, seedbed preparation, tillage tool selection, etc.)
    - Site specific management concepts (GPS, GIS, variable rate technology, guidance, row and boomcontrol, grid sampling, field mapping, sensing technology, UAS technology, NDVI mapping, etc.)
    - Managing temperature (effects of cover and tillage on soil temperature, frost

prevention, snow and ice)

- Biofuels and biomass production for bioenergy
- Carbon management in agriculture (greenhouse gases, carbon sequestration, carbon credits)

Section B: Math Practical

This section will include mathematical problems related to agronomy. It will be scored on the basis of 150 total points. Answers must be rounded and given in correct units as specified in the problem. Critical information will be given except for commonly known conversion factors. Possible types of problems are listed below:

- Area conversion calculations (Estimate per acre yield from harvest strips or small plots; Calculate areasand yields from irregularly shaped fields; Area covered and time required for given capacity and delivery rate of fertilizer/chemical applicator; Time to complete tillage/harvest operation given area of field, width of equipment, and speed of travel; Obtaining material and cost estimates for fencing materials for given field size; Converting units involving area to corresponding metric units, etc.)
- Pesticide application (Calibrate broadcast or band application given number of nozzles, nozzle spacing,output from one or more nozzles, and distance traveled or intended speed of travel; Find amount of chemical formulation to add to a spray tank to meet product or active ingredient label recommendationsgiven tank size and delivery rate; Calculate costs of pesticide application, etc.)
- Fertilizer/lime application (Spreader calibration given amount delivered in a distance traveled or byturning the drive wheel; Fertilizer application rates given carrier analysis and recommended rates inelemental or oxide form or replacement of nutrients removed by the crop; Prepare bulk blends fromgiven rates and available carriers; Calculate costs of fertilizer/lime application; Compare costs of different fertilizers/lime sources)
- Seeding/Planting (Calibration of row planter or grain drill given amount of seed delivered in a set distance traveled or by turning the drive wheel a certain number of revolutions; Seeding rates, plant population, and percent seed emergence calculations; Calculating PLS and adjusting seeding rates andcomparing costs based on PLS)
- Volume calculations (tank capacity, storage volume for hay, grain bin, or silo)
- Unit conversions (English to metric units and vice versa)
- Concentration (ppm, %)
  - Harvest (estimating harvest losses, harvest speed, area covered, harvest

efficiency)

  - Irrigation (application rate for given GPM and area covered, convert gallons to acre-inches)

- Tillage and field operations (time required, field efficiency, cost per acre, labor and fuel costs)
- Pasture carrying capacity (stocking rates based on animal units)
- Soil erosion loss equation
- Soil physical properties (bulk density, % soil moisture, water retention in profile):
- Plant breeding (heritability, % homozygosity, expected genotypic and phenotypic ratios from a cross)
- Water usage (day, season, species)
- Weed competition (seeds/acre, yield loss, spread of resistant weed seed)
- Yield determination and adjustment for % moisture
- Forage quality (protein content, NDF, ADF, TDN, relative feed value)
- Livestock rations (combining forages, grains, and supplements to target protein levels - Pierson square)
- Heat units/growing degree days

Section C: Lab Practical

This section will consist of 75 stations worth 2 points each for a total of 150 points. Each station will have photographs or actual samples of various plant materials, fertilizers, pesticides, seed samples, data tables, equipment, insects, diseases, etc. along with specific questions which will require identification, interpretation,calculation, or evaluation of the display material to answer correctly. These stations will represent activities commonly completed in laboratories or field trips in crop production and soil management courses. For example, contestants may have to:

- Identify common crop diseases and disease symptoms*
- Identify common crop insects and insect damage*
- Identify common field machinery and other agronomic equipment*
- Recognize classes of pedigreed seed from standard seed tags and interpret information from a seed bag(germination, purity, seed size, noxious weeds, variety or hybrid identification, genetically modified traits, refuge requirements, treatments applied, recommended seeding rates, planter adjustments, etc.)
- Write the commercial grade and grade determining factors for market grain samples given variousquality factors and official FGIS grain standards tables
- Identify specific plant and seed structures, crop growth stages, or developmental characteristics on freshor pressed plant samples
- Recognize common nutrient deficiency symptoms (N, P, K, S, Fe) on both dicot and grass crops
- Recognize common herbicide injury symptoms on weeds and crops and classify based on group number
- Use a soil textural triangle to name soil textural class
- Determine soil texture by feel, distinguish different types of soil structure, determine soil color andrelate soil color to soil properties
- Interpret information found in a soil survey or on a soil test report
- Recognize common fertilizer carriers (major nutrient supplied, typical analysis, common name)
- Interpret information on a fertilizer bag or pesticide label
- Recognize common pesticide formulations and their standard abbreviations
- Determine proper sprayer nozzle tip size and type, screens, pressure, etc. for pesticide applications
- Identify and explain the purpose of items such as ag lime, inoculum, talc, seed treatments, soil amendments, etc.
- Identify stored or processed crop products and common livestock feed ingredients made from crops(silage as to type, hay as to type, alfalfa pellets and cubes, soybean meal, cottonseed meal and hulls,wheat bran, corn meal, beet pulp, dried distillers’

grains, flaked or ground grains, etc.)

- Match various food or industrial products with the crops (or classes of a crop) from which they are made
- Evaluate crop quality by ranking two or more samples of hay, silage, seed, or cotton
- Interpret data from tables or graphs (analyze a variety trial based on the LSD mean comparison statistic,select the proper spray nozzle tip for given conditions from a manufacturer's spraying equipment manual, read a calibration monograph for a sprayer or planter, interpret crop yield response to different input levels, determine economic threshold from pest counts vs. yield response given control costs, etc.)
- Evaluate various crop production problems from photos, illustrations, or displays.
- Identify or describe common crop production and soil management practices from photos or slides.
- Apply precision ag and site-specific management concepts – identify precision ag tools (GPS unit, variable rate control, autosteer, boom and row control, UAS, etc.) assessing variability, analysis and interpretation of maps and data (grid samples, yield maps, aerial imagery, remotely sensed data, NDVI)

* A copy of the lists for the above three sections will be provided during the contest. The final five items on each list are added by the host school each year.

Section D: Plant and Seed Identification

1. A total of 75 specimens will be identified in a one-hour time limit. Each sample will be worth two points for a total of 150 points.
2. Contestants must move among stations as directed by the room monitor. Contestants must stand directly infront of the specimen being viewed and only one contestant may examine a specimen at a time.
3. Crop and weed plants will be shown either as fresh or dried and pressed samples. All seed samples will be mature. Seed may be shown either hulled, or where typical, within surrounding hulls, burs or pods (e.g. wildbuckwheat, peanut, Korean lespedeza, rice, etc.).
4. Crop and weed identification materials will be selected from the attached identification list. Items are marked with a (p) for plants that may be shown in the flowering to mature plant stage, (v) for plants that maybe shown in the vegetative stage, and (s) if seed identification is required. (The final ten plants and/or seeds on the list are added by the host school each year.)
5. Plants and seeds will be identified by common name as given on the official identification list provided eachcontestant. Contestants must fill in bubbles corresponding to the identification code for the specimen as given on the list provided.
6. Hand magnifying lenses will be allowed.
7. Sample specimens may not be moved from their stations. Live plant specimens may be touched carefully toaid in identification, but must not be broken or damaged by the contestant or disqualification may result. Dried, pressed plant specimens cannot be touched. Seeds may be rearranged in their place but may not be removed from their containers.

Table A.1. Modified plant and seed identification list from 2020 NACTA Crops Judging contest rules at Fort Hays State University in Fort Hays, KS.

	Cultivated Crops		**42**	castor	p v s
01	wheat	p v	**43**	flax	p v s
02	hard red winter wheat	s	**44**	safflower	p v s
03	hard red spring wheat	s	**45**	sesame	p v s
04	soft red winter wheat	s	**46**	potato	p v
05	soft white wheat	s	**47**	common buckwheat	p v s
06	hard white wheat	s	**48**	crambe	p v s
07	durum wheat	s	**49**	lentil	p v s
08	barley	p v	**50**	sugarbeet	p v s
09	six-rowed barley	s	**51**	tobacco	p v s
10	two-rowed barley	s	**52**	sunflower	p v
11	rye	p v s	**53**	confectionary sunflower	s
12	oat	p v s	**54**	oilseed sunflower	s
13	triticale	p s		**Forage Grasses**	
14	rice	p v s	**55**	big bluestem	p s
15	corn	p v	**56**	little bluestem	p s
16	dent corn	s	**57**	blue grama	p
17	flint corn	s	**58**	sideoats grama	p
18	sweet corn	s	**59**	buffalograss	p s
19	pop corn	s	**60**	Indiangrass	p s
20	grain sorghum	p v s	**61**	switchgrass	p s
21	sudangrass	s	**62**	Kentucky bluegrass	p v s
22	foxtail millet	p s	**63**	orchardgrass	p v s
23	proso millet	p s	**64**	tall fescue	p v s
24	pearl millet	p s	**65**	smooth bromegrass	p v s
25	soybean	p v s	**66**	bermudagrass	p v s
26	fieldbean	p v	**67**	perennial ryegrass	p v s
27	great northern fieldbean	s	**68**	reed canarygrass	p v s
28	red kidney fieldbean	s	**69**	timothy	p v s
29	pinto fieldbean	s	**70**	crested wheatgrass	p v s
30	navy fieldbean	s		**Forage Legumes**	
31	black turtle fieldbean	s	**71**	alfalfa	p v s
32	cowpea	p v	**72**	sweetclover	p v s
33	blackeye cowpea	s	**73**	red clover	p v s
34	purplehull cowpea	s	**74**	white clover	p v s
35	fieldpea	p v s	**75**	crimson clover	p v s
36	Austrian winter fieldpea	s	**76**	arrowleaf clover	p v s
37	peanut	p v s	**77**	alsike clover	p v s
38	green mungbean	p v s	**78**	Korean lespedeza	p v s
39	guar	p v s	**79**	birdsfoot trefoil	p v s
40	canola	p v s	**80**	crownvetch	p v s
41	cotton	p v s	**81**	hairy vetch	p v s

Table A.1. (continued)

	Weeds			**Weeds (cont.)**	
82	barnyardgrass	p v s	**118**	Pennsylvania smartweed	p s
83	blackseed plantain	p s	**119**	perennial sowthistle	p v s
84	buckhorn plantain	p s	**120**	prickly sida	p v s
85	buffalobur	p v s	**121**	puncturevine	p v s
86	Canada thistle	p v s	**122**	quackgrass	p v s
87	cheat	p s	**123**	redroot pigweed	p v s
88	chickweed	p v s	**124**	rescuegrass	p s
89	cocklebur	p v s	**125**	Russian thistle	p v s
90	common lambsquarters	p v s	**126**	shepherdspurse	p s
91	common ragweed	p v s	**127**	sicklepod	p v s
92	curly dock	p v s	**128**	silverleaf nightshade	p
93	dandelion	p v s	**129**	spotted knapweed	p s
94	dodder	p v s	**130**	tall morningglory	p v s
95	downy brome	p v s	**131**	tall waterhemp	p v
96	eastern black nightshade	p s	**132**	velvetleaf	p v s
97	field bindweed	p v s	**133**	Venice mallow	p v s
98	field pennycress	p s	**134**	wild carrot	p v s
99	field sandbur	p s	**135**	wild buckwheat	p v s
100	giant foxtail	p v	**136**	wild mustard	s
101	giant ragweed	p v s	**137**	wild oat	p s
102	goosegrass	p s	**138**	wild sunflower	p s
103	greenflower pepperweed	p s	**139**	yellow foxtail	p v s
104	green foxtail	p s	**140**	yellow nutsedge	p v
105	hedge bindweed	p		**Additional Selection for 2020**	
106	henbit	p v s	**141**	tumble pigweed	p v
107	hoary cress	p s	**142**	devil's claw	p v s
108	horsenettle	p s	**143**	fall panicum	p
109	horseweed	p v	**144**	windmill grass	p v
110	jimsonweed	p v s	**145**	common onion	p v
111	johnsongrass	p s	**146**	prickly lettuce	p v
112	jointed goatgrass	p s	**147**	sericea lespedeza	p v
113	kochia	p v s	**148**	stinkgrass	p
114	leafy spurge	p s	**149**	hemp	p v s
115	large crabgrass	p v s	**150**	teff	p s
116	musk thistle	p v s			
117	Palmer amaranth	p v			

[a] Life cycles required: p, flowering to mature stage plant (live or dry mount); v, vegetative plant (live); s, seed

Table A.2. Modified disease identification list from 2020 NACTA Crops Judging contest rules at Fort Hays State University in Fort Hays, KS.

	Small Grain			**Cotton**	
01	powdery mildew	any small grain	**24**	bacterial blight	
02	stem rust	wheat, oat	**25**	Verticillium wilt	
03	leaf rust	wheat, oat		**Peanut**	
04	loose smut	wheat, barley, oat	**26**	Cercospora leaf spot	
05	barley yellow dwarf mosaic	wheat, barley	**27**	Sclerotinia blight	
06	ergot	any small grain		**Sorghum**	
07	black point of wheat	seed	**28**	charcoal rot	
08	common bunt	seed	**29**	gray leaf spot	
09	wheat scab	seed	**30**	maize dwarf mosaic	
	Corn			**Alfalfa**	
10	common corn smut		**31**	bacterial wilt	
11	ear rot		**32**	leaf spot	
12	gray leaf spot		**33**	Phytophthora root rot	
13	northern corn leaf blight			**Additional Selection for 2020**	
14	southern corn leaf blight		**34**	sudden death syndrome	soybean
15	Gibberella stalk rot		**35**	bacterial streak	corn
16	Fusarium stalk rot		**36**	Goss's wilt	corn
	Soybean		**37**	stripe rust	wheat
17	bacterial blight		**38**	wheat streak mosaic	wheat
18	brown stem rot				
19	Phytophthora root rot				
20	pod and stem rot				
21	bean pod mottle	seed			
22	purple stain	seed			
23	Asian rust				

Table A.3. Modified insect identification list from 2020 NACTA Crops Judging contest rules at Fort Hays State University in Fort Hays, KS.[a]

	Alfalfa			**Stored Grain**	
01	alfalfa weevil	a l	**25**	granary weevil	a
02	blue alfalfa aphid	a l	**26**	sawtoothed grain beetle	a
03	pea aphid	a l	**27**	lesser grain borer	a
04	spotted alfalfa aphid	a l	**28**	red flour beetle	a
05	potato leaf hopper	a l	**29**	Indian meal moth	a l
	Cotton			**Miscellaneous**	
06	boll weevil	a	**30**	black cutworm	l
07	cotton bollworm	l	**31**	blister beetle	a
08	lygus bug	a	**32**	Colorado potato beetle	a l
	Corn		**33**	fall armyworm	l
09	European corn borer	a l	**34**	grasshopper	a
10	Southwestern corn borer	l	**35**	spider mite	a
11	corn earworm	l	**36**	thrips	a
12	corn rootworm	l	**37**	white grub	a l
13	northern corn rootworm	a	**38**	wireworm	l
14	southern corn rootworm	a		**Beneficials**	
15	western corn rootworm	a	**39**	lady beetle	a l
	Soybean		**40**	lacewing	a
16	green stinkbug	a	**41**	parasitic wasp	a
17	soybean cyst nematode	a		**Additional Selection for 2020**	
18	green cloverworm	l	**42**	bird cherry oat aphid (small grains)	a
19	bean leaf beetle	a	**43**	Dectes stem borer (sunflower, soybean)	a
	Sorghum		**44**	Japanese beetle (soybean)	a
20	chinch bug	a	**45**	sunflower head moth (sunflower)	l
21	corn leaf aphid	a	**46**	yellow sugarcane aphid (sorghum)	a
	Sorghum				
22	greenbug	a			
23	Russian wheat aphid	a			
24	Hessian fly	l			

[a] Life cycle stages required, a, adult stage; l, larval stage

Table A.4. Modified equipment identification list from 2020 NACTA Crops Judging contest rules at Fort Hays State University in Fort Hays, KS.

01	anhydrous ammonia applicator	**27**	rod weeder
02	bale wrapper	**28**	rotary hoe
03	bermudagrass sprigger	**29**	rotary mower
04	Boerner divider	**30**	rotary tiller
05	broadcast fertilizer spreader	**31**	row crop cultivator
06	broadcast seeder	**32**	row crop planter
07	Carter dockage tester	**33**	self-unloading forage wagon
08	chisel plow	**34**	soil probe
09	combine yield monitor system	**35**	spiketooth harrow
10	cotton picker	**36**	subsoiler
11	cultipacker seeder	**37**	swather/windrower
12	drainage tile installation system	**38**	tandem disk
13	field cultivator	**39**	variable rate control system
14	field sprayer	**40**	Winchester bushel weight apparatus
15	forage chopper	**41**	offset disk
16	forage probe	**42**	peanut digger/shaker
17	global positioning system	**<u>Additional Selections for 2020</u>**	
18	grain combine	**43**	bale accumulator
19	grain drill	**44**	hoe drill
20	grain moisture tester	**45**	stripper header
21	grain trier	**46**	sweep plow
22	hay baler	**'47**	vertical tillage implement
23	hay moisture tester		
24	hay rake		
25	laser land plane		
26	moldboard plow		

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