PLANT GROWTH REGULATORS AND BIOSTIMULANTS FOR USE IN VARYING MANAGEMENT SYSTEMS TO IMPROVE CORN GRAIN YIELD

BY

CONNOR NELSON SIBLE

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Crop Sciences
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2019

Urbana, Illinois

Master's Committee:

Professor Frederick E. Below, Chair
Research Assistant Professor Carolyn J. Butts-Wilmsmeyer
Assistant Professor Nicolas Federico Martin

ABSTRACT

Plant growth regulators (PGRs) and biostimulants are product chemistries that have recently become popular in the agricultural market. There is no concrete evidence however, for their best place in a management system to optimize their return on investment and crop yield potential. The objective of this study was to evaluate the responses of corn (*Zea mays* L.) grain yield to in-furrow and foliar applications of PGRs and biostimulants, and to determine if PGRs and biostimulants impact yield differently under varying management systems. Field studies were conducted in the 2017 and 2018 growing seasons across three locations: Harrisburg, Champaign, and Yorkville in Illinois. Corn was grown under two different management conditions, a standard or an intensive input system. The standard management was implemented with a standard planting population, fertility based on soil test values, and with no foliar fungicide. The intensive input system used an increased plant population, added fertility through nitrogen side-dress and foliar micro fertilizer applications, and provided a fungicide application at the VT growth stage.

The PGRs (Ascend SL or Optify/Stretch) were applied in-furrow at planting, and either Ascend SL, or a biostimulant (Toggle or Voyagro) was applied to the foliage at the V5 growth stage. Corn plants grown in the intensive input system out-yielded those grown in the standard system by 1 kilogram hectacre^{-1} (15 bushels acre^{-1}) on average, showing that grain yield can be increased through management. Plant growth regulators and biostimulant applications resulted in few significant impacts on yield and yield components, with responses being both positive and negative. Therefore, PGRs and biostimulants can influence corn grain yield, but these responses vary and their effects were greatest when applied in an intensive input system.

ACKNOWLEDGEMENTS

The research opportunities and education from the Crop Physiology Lab at the University of Illinois has been very rewarding during my Master's program. This journey could not have been possible without the help of the many individuals who helped with these projects. A special thanks to my advisor Dr. Fred Below for the chance to join the Crop Physiology Lab to continue my education with engaging projects and opportunities. I would further like to thank Juliann Seebauer, Dr. Tryston Beyrer, Brad Bernhard, and Alison Vogel for their guidance and endless patience.

None of the work would have been possible without the help from my fellow Master's students Scott Foxhoven, Eric Winans, Vitor Rampazzo Favoretto, Ben Wiegmann, Logan Woodward, and the many undergraduate students and visiting scholars who helped through the years. Advice from my committee members Dr. Carolyn J. Butts-Wilmsmeyer and Dr. Nicolas Federico Martin has had a large influence in my work, and I greatly appreciate their support and guidance. Also, thanks goes to Winfield United for the generous support in funding this research.

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LITERATURE REVIEW

Corn Production and Management

With the current world population of 7.6 billion people expected to grow to 9.8 billion people by 2050 (United Nations, 2017), crop yields need to double in the next 30 years to meet population needs (Ray et al., 2013). Corn (*Zea mays* L.) is one of the most important crops in the world, and in 2018 the United States planted 36 million hectares (89 million acres) of corn (USDA NASS, 2018a). Climate, soil, and the weather vary by location, and each producer has their own strategy for producing their crop through various agronomic management practices, including hybrid selection, crop nutrition, and pest management strategies. Corn has twice the grain yield potential of other cereal crops (Tollenaar and Lee, 2002), and research has revealed that it is a system of crop management factors working together that leads to the greatest corn grain yields (Ruffo, 2015). While there are many management factors that contribute to producing high yields, five have been identified as having the largest impacts on grain yield: hybrid, planting population, nitrogen fertility, additional nutrient fertility, and foliar protection (Ruffo, 2015).

Hybrid

Hybrid selection is one of the first things a grower considers in preparation for their growing season. Each hybrid varies in its genetic make-up, and therefore interacts differently with all other management and environmental factors (Castleberry et al., 1984). Corn yields have greatly increased since the introduction of double-cross hybrids in the 1930's, and then single-cross hybrids in the 1960's (Crow, 1998). Among the various management practices, hybrid genetics strongly influence crop response to greater planting populations (Tokatlidis and Koutroubas, 2004). Thus, it is important to use the appropriate hybrid to maximize the yield potential of the given management system.

Planting Population

While hybrid genetics have changed greatly in the last century, planting population has been the management factor that producers have changed the most. The average planting population for corn grown in Illinois was 55,000 plants hectare^{-1} (22,200 plants acre^{-1}) in 1982, and has since risen to 79,000 plants hectare^{-1} (32,000 plants acre^{-1}) in 2018; an average increase of 670 plants hectare^{-1} year^{-1} (270 plants acre^{-1} year^{-1}) (USDA NASS, 1982; USDA NASS 2018b). Understanding the impacts of deficient or excessive plant populations is key to optimizing corn growth and yield, as too high of a population can increase barren stalks and kernel abortion, while too low of a population can limit grain yield potential (Hashmei et al., 2005). Establishing the correct planting population is a key management decision for optimizing yield (Jiang et al., 2013). After the hybrid is planted at the appropriate population, the next management factors of concern involve in-season applications of plant nutrition and plant protection products.

Nitrogen Fertility

There are sixteen essential mineral nutrients needed for plant growth and development (Taiz, 2015a). An essential nutrient has to meet the following criteria to be classified as "essential": (a) a deficiency of the element makes it impossible for the plant to complete its life cycle; (b) the deficiency is specific for the element as the function of the element is not replaceable by another element; and (c) the element is directly involved in the metabolism of the plant (Arnon and Stout, 1939). Of the essential elements, nitrogen is often the most limiting to corn growth due to the high levels of nitrogen accumulated by the crop (Ciampitti and Vyn, 2012). A 14.5 T hectare^{-1} (230 bushel acre^{-1}) corn crop will take up 287 kg nitrogen hectare^{-1} (256 lbs nitrogen acre^{-1}), and 75% of this nitrogen uptake occurs after the V10 growth stage (Bender et al., 2013). The season-long uptake of nitrogen implies that nitrogen availability is necessary throughout the crop's growth and development. Although nitrogen availability is highly influenced by weather conditions, the use of urease inhibitors and side-dress applications can help mitigate nitrogen loss and increase season-long availability.

Foliar Micronutrients

The essential nutrients can be classified as macro- or micro-nutrients. The difference in nomenclature is not based on being more or less essential than the other nutrients, but rather refers to the quantity of each nutrient that is needed to support growth. Macronutrients are needed in larger quantities by the plant, while micronutrients are needed in much smaller quantities. There is increasing interest in mitigating micronutrient deficiencies as limiting factors for crop growth and yield due to a multitude of reasons. Current crop yields are greater and therefore require larger quantities of all nutrients. Topsoil loss through erosion removes nutrients present in the surface layers of soil. Furthermore, land management such as terracing can change nutrient availability across fields, and long term cropping systems are removing these nutrients with the grain (Bell and Dell, 2008). To determine if micronutrient deficiencies exist, in-season leaf tissue is typically analyzed for nutrient concentrations and compared to pre-determined critical levels. Any nutrients that are shown to be deficient can then be corrected with a foliar spray application. Often it is the micronutrients Boron (B) and Zinc (Zn) that are deficient and targeted for in-season foliar nutrient management. Boron and Zn play key roles in seed set and pollination processes, whereby their deficiency can decrease seed set and lower grain yield (Ziaeyan and Rajaie, 2009). Boron plays an important role in photosynthesis, accumulation of carbohydrates, cell wall synthesis, cell wall structure, lignification, membrane transportation, vegetative growth and retention of flowers and fruits, as well as phenol and indole acetic acid metabolism. A deficiency of B leads to browning of plant tissues along with stunting of young plants (Takano et al., 2007; Miwa et al., 2008;

Dordas et al., 2007). Zinc plays a key role in many plant metabolic processes as a regulatory co-factor of a wide range of different enzymes and proteins, or as a structural constituent in many important biochemical pathways relating to carbohydrate metabolism, auxin metabolism, protein metabolism, pollen formation, the integrity of biological membranes, and disease resistance (Alloway, 2004). Sulfur (S) is a micronutrient that has shown more frequent deficiencies in recent years due to new environmental laws creating greater filtration requirements on factories, leading to less sulfur in the atmosphere to be deposited in crop fields (Husain et al., 1998). Sulfur is essential to many plant functions as it is an important factor in protein structures, in fragrance for attracting pollinators, and can be utilized as a source of energy for soil bacteria (Hawkesford and Kok, 2007). Manganese (Mn) is another micronutrient often found to be deficient in plant tissues, with various crop species showing varying levels of Mn requirements (Reuter et al., 1988).

Foliar Protection

Greater planting populations and adequate fertility programs can result in rapid plant growth that leads to greater risk of disease pressure as the decreased plant to plant spacing and greater above-ground biomass reduces airflow, leading to a moist environment conducive to fungal growth. Strobilurin fungicides inhibit mitochondrial respiration and are effective at controlling disease-causing mycelium and spores (Bartlett et al., 2002; Vincelli, 2012). While increased disease control keeps plants healthy, another advantage to strobilurin fungicides is their ability to induce the “stay green” effect. The “stay green” effect is a delay in plant senescence as a result of a decrease in the rate at which chlorophyll is degraded (Thomas and Howarth, 2000). Longer chlorophyll duration can lead to greater photosynthetic output during grain fill, leading to heavier kernel weights and greater yields.

Biological Products

In addition to ensuring that sufficient levels of nutrients are available, the use of biological products is one of the newest solutions to help growers increase corn grain yields. The average yield for corn in the United States in 2017 was 11.11 T hectare^{-1} (176.6 bushels acre^{-1}), setting a new national record. The average in 2018 was close to breaking that record with an average of 10.97 T hectare^{-1} (174.4 bushels acre^{-1}) (USDA NASS, 2018c). These records are broken more frequently each subsequent year as growers learn to better manage their crops and increase their yields. Recently, the biological product market available to producers has exploded with new technologies. This biological management category is relatively undefined, and there are many different products that can be classified as biological management factors. The vast majority of these products can be grouped in a variety of ways: application methods, intended use (bio-pesticides, fertility enhancement, growth alteration, etc.), as well as by their active ingredients or modes of action. Two such categories are plant growth regulators and biostimulants.

Plant Growth Regulators (PGRs)

Plant growth regulators have many different purposes and uses in agriculture. One of the most ambiguous concepts in the agricultural industry is what a PGR actually is. One definition of a PGR is as follows: "an organic compound, either natural or synthetic, that modifies or controls one or more specific physiological processes within a plant. If the compound is produced within the plant, it is called a plant hormone" (Lemaux, 1999). For the most part, the various definitions are similar and focus on the concept that PGRs are compounds that influence plant growth. The inconsistency among a large number of definitions comes between the terms regulator and hormone, as well as whether these compounds can be either natural and synthetic. A common definition of a hormone is "a product of living cells that circulates in body fluids (such as blood) or sap and produces a specific often stimulatory effect on the activity of cells usually remote from its point of origin; *also* a synthetic substance that acts like a hormone" (Merriam-Webster, 2019). This definition would imply that a hormone is either naturally derived from cells, or can be a synthetic compound that acts as a natural hormone. However, this definition only refers to the compounds themselves, and does not account for other compounds that interfere with hormones or hormone signaling. Interference with hormones and hormone signaling still affects plant growth by either accelerating or delaying the signaling process, and as such would still be included under the definition of a plant growth regulator. Therefore, all hormones can be considered plant growth regulators, but not all plant growth regulators can be classified as hormones. Thus, it is essential to understand the known plant hormones so one can differentiate between the natural plant hormones and the PGRs designed to interact with hormone signaling.

Plant Hormones

In the last century, nine major classes of plant hormones have been discovered and classified (Taiz, 2015b). These nine classes include auxins, cytokinins, gibberellins, abscisic acid, ethylene, brassinosteroids, jasmonates, salicylic acid, and strigolactones. While all classes of plant hormones are key to plant growth and development, auxins, gibberellins, and cytokinins are the most common hormones to be concentrated into agricultural products and labeled as PGRs. These products may be applied as seed treatments, in-furrow at planting, or at multiple vegetative and early reproductive stages during the corn growth cycle. Two such product examples are Ascend SL (Winfield Solutions LLC., St. Paul, MN) (containing auxins, gibberellic acids, and cytokinins) and Optify/Stretch (United Suppliers, Eldora, IA) (containing cytokinins). The hypothesis is that exogenous applications of these three hormones (or synthetic versions of them) will increase cell growth through enlargement, elongation, and division. Seed treatments and in-furrow applications primarily target the root system, while foliar applications are designed to impact leaf growth. This upregulation in cell growth and maturation is expected to lead to more extensive root systems, quicker emergence, and faster light interception, all of which are assumed to positively influence grain yield.

Auxins

Auxins were the first group of hormones to be identified and studied. Charles Darwin made the observations that plants bend towards light and termed this phenomenon as "phototropism." The first appearance of auxin in the plant sciences was with the discovery of an unknown phytohormone in plants that were the result of Darwin's observations (Peterson, 1967). F. W. Went took Darwin's original work further and is credited with identifying and extracting auxin in 1926. There are many different pathways for auxin synthesis. The most common natural forms of auxin in plants is indole-3-acetic acid (IAA) and indole-3-butyric acid (IBA) (Moore, 1989a). Many theories exist regarding auxin synthesis in plants. Most proposed pathways for auxin synthesis start with the amino acid tryptophan, and it is theorized that IAA is a coincidental by-product of tryptophan degradation through transamination, as opposed to being produced through a specific product pathway (Sheldrake, 1973). Recent studies suggest that in addition to the degradation of tryptophan, IAA can be synthesized independently of tryptophan as a reactant in an enzymatic process (Wang et al., 2015). Auxins are involved in many cellular processes, are predominately produced in meristematic tissue, and are key to cell enlargement, apical dominance, root initiation, leaf and fruit abscission, and flowering (Taiz, 2015b). Ascend SL contains IBA as an active ingredient and is labeled to be applied either in-furrow or as a foliar application. When IBA was applied to maize seedling roots, there was an increase in lateral root formations (Schlicht et al., 2013). Direct application of IBA to the roots of an early seedling plant indicates that in-furrow applications of IBA can also increase lateral root growth in field scenarios. Foliar applications of IBA have been shown to increase stem diameter, plant height, number of leaves per plant, leaf area index, total leaf area, total biomass, and increased corn yields (Amin et al., 2006).

Gibberellic Acids

The second class of hormones to be extensively studied are the gibberellic acids (GAs). Their first discovery was theorized through observations of "foolish seedling" disease in rice. The disease is caused by the fungus *Gibberella fujikuroi*. In 1926, Kurosawa was able to grow the fungus on growth medium, and used filtrates from the medium the fungus was grown on to induce "foolish seedling" disease in rice seedlings (Moore, 1989b). The first successful isolation of GAs from fungal filtrates occurred in 1938, by Yabuta and Simuki (Yabuta, 1938) in Japan, and extensive research on GAs did not start in the United States until the 1950's. By the end of the decade pure isolates of GAs had been extracted from fungal colonies, and the term gibberellic acid was officially coined in 1954 (Stodola et al., 1955). Further research showed the discovery of natural gibberellins in plants, proving their production was not just isolated to fungus. Many of the first studies of exogenous applications of GA's to plants was on dwarf varieties of peas and maize. Applications of GA's on dwarf cultivars was able to increase internode length of the dwarf plants, but showed no influence on standard cultivars (Leopold and Kriedemann, 1975). Initial studies demonstrated that GA's could enlarge fruits, specifically grapes (Weaver, 1958), while more recent research shows increases in cereal crop yields (Hedden, 2003). In addition to IBA, Ascend SL contains gibberellic acid as an active ingredient, and mesocotyl elongation was shown to be increased in maize seeds that had been soaked with GA_3 (Pan et al., 2017). Greater mesocotyl elongation during germination can lead to quicker emergence and reduced time spent in the soil. When applied in-furrow at planting, there is the opportunity for increased cell elongation of the roots and emerging shoots to lead to greater emergence rates. This increased emergence and early growth is especially important when seedlings are planted too deep, where there is a greater advantage to exogenous applications of GA's (Zhao and Wang, 2008). While in-furrow applications have the potential to influence crop growth and yield, foliar applications of IBA and GA at early vegetative leaf stages (V4-V6), and at flowering (VT/R1) have also been shown to enhance the rate of crop development and yield in corn by increasing kernel number per area (Ghodrat et al., 2012). This positive interaction of IBA and GA give the possibility of blending these hormones into agricultural products designed for foliar applications in agricultural systems.

Cytokinins

The third class of hormones is cytokinins, which, like auxins and gibberellins are essential to numerous plant growth processes. Like the other hormones, the effects of cytokinins were first visually observed, and the idea of specific compounds being involved was theorized long before their isolation and extraction. Folke Skoog officially isolated kinetin in 1955, and showed that exogenous applications of kinetin led to growth in tobacco cultures of mature cells which would not normally be actively dividing (Miller et al., 1955). Since then, different cytokinins have been shown to actively influence mitosis and cell division in plants (Moore, 1989c). There are many different cytokinins, and they are developed in living systems as N^6-substituted adenine derivatives. The first plant-natural cytokinin to be isolated was zeatin, found in corn seed (Letham et al., 1964). Cytokinins are not just active in plant systems, but can be used to induce growth of fungi, protozoans, and bacteria (Taiz, 2015b). In addition to cell division, cytokinins have been shown to prevent senescence in aging leaves (Richmond and Lang, 1957) and release axillary buds from the control of apical dominance (Brown et al., 1967). Since then, various formulations of cytokinins have been developed for agriculture production systems for use in increased root growth and development and increased leaf area. The third active ingredient in Ascend SL is kinetin, a form of cytokinin. Foliar applications of kinetin can cause increased biomass, chlorophyll content, and proline concentrations of maize seedlings (Xu et al., 2010). Optify/Stretch also contains kinetin, and it is the cytokinin effects of kinetin that can be advantageous with in-furrow applications.

Abscisic Acid, Ethylene, Brassinosteroids, Strigolactones, Jasmonates, and Salicylic Acids

The remaining six classes of PGRs contain the abscisic acids (ABA), ethylene, brassinosteroids, strigolactones, jasmonates, and salicylic acid. While these hormones are key to plant growth and development, they are less extensively utilized as active ingredients in commercial products.

The first isolation of ABA was from mature cotton burs as reported by Liu and Carnsdagger in 1961. In addition to its initial discovery in the ability to induce dormancy of buds, ABA has been shown to function in seed dormancy (Sondheimer et al., 1968), leaf and fruit abscission (Davis and Addicott, 1972), and seed maturation (Williamson et al., 1988). Abscisic acid production is upregulated during times of stress, and has been shown to play a key role in stomata closure (Honour, 1995). Ethylene is a simple gas and found in many different environments and living systems, and D. N. Neljubow was the first scientist to discuss the impacts of ethylene on plants (Moore, 1989e). Earlier work with auxin showed that ethylene production was increased in conjunction with IAA (Zimmerman and Wilcoxon, 1935). Agricultural uses of ethylene were primarily targeted to reduce stem elongation in small grains by interfering with auxin stimulation, leading to less lodging and higher yields (Simmons et al., 1988). Brassinosteroids were first isolated from rape (*Brassica napus*) pollen (Grove et al., 1979). They appear to interact with other hormones, primarily auxin and GAs, and have multifaceted influences on plant growth. Strigolactones were observed and isolated from witchweed (*Striga* spp.) species and broomrapes (*Orobanche* and *Phelipanche* spp.) and shown to initiate root growth from parasitic plants (Seto et al., 2012). Jasmonates are key in protein synthesis and tissue repair (Wasternack and Strnad, 2019). Salicylic Acid is reactive when plants are stressed and mitigates reactive oxygen species damage in plants (Jahan et al., 2019). It is the interactions of all plant hormones that determine crop growth patterns, and it is key to understand these interactions for beneficial use of plant hormones as commercial products in agricultural production systems.

Biostimulants

The newest category of products that are used to increase yield production is biostimulants. The distinction of a biostimulant from what would be considered a PGR or fertilizer is vague, but typically biostimulants have a role in stress reduction or nutrient accumulation in plants (Harpen et al., 2015). A definition used by the European Union is as follows: plant biostimulants are substances or materials, with the exception of nutrients and pesticides, which, when applied to plants, seeds, or growing substrates in specific formulations, have the capacity to modify physiological processes in plants in a way that provides potential benefits to growth, development, or stress response" (du Jardin, 2012). These products are assumed to up-regulate plant or microbe activity with the goal of increasing growth. Ordinarily, these types of products are targeted for stress relief, especially drought stress. Biostimulant products are designed to upregulate innate processes by providing the crop with similar substrates that it produces naturally in response to drought tolerance, such as amino acids, betaines, and sugars. Many biostimulants are manufactured through microbial extract processes with amino acids or sugars being the primary filtrates utilized. Many other products are derived from marine seaweed extracts.

Amino Acids

Amino acids (AAs) influence a multitude of plant processes. As protein building blocks, they can be directly utilized for crop growth and enzyme upregulation. Additional interactions involve gene regulation, ion transport and chelation, and heavy metal detoxification (Rai, 2002). Proline specifically has been shown to have higher accumulations in plants under drought stress (Sing et al., 1972). In addition to proline, glycine betaine has been shown to increase in concentration under drought stress, which translates to greater crop growth and yield (Ashraf and Foolad, 2005). Voyagro (Winfield Solutions, St. Paul, MN) (containing proline and glycine betaines) is one such amino acid product currently utilized in cropping systems. Exogenous applications of proline and glycine betaine together reduced the negative effects of salt stress in canola (Sakr et al., 20120). Under controlled drought scenarios, the foliar application of proline to corn was able to increase potassium, calcium, nitrogen, and phosphorus uptake leading to greater levels of drought tolerance (Ali et al., 2008).

Marine Extracts

In addition to AA products, the use of marine extracts as active ingredients for foliar biostimulants is a common approach for drought tolerance and enhanced plant growth (Spinelli et al., 2010). The use of seaweed extracts in commercial products has been around since 1912 (Booth, 1969). A product example available in today's market is Toggle (Acadian Plant Health, Dartmouth, Nova Scotia, Canada). Marine extracts act similarly to AAs, in that they interact with a multitude of plant metabolic processes and are the most commonly used products to mitigate drought stress. Marine extracts have also been shown to increase chlorophyll levels as a result of their interactions with betaines (Whapham et al., 1993). The most prominent method of marine extract applications is as foliar sprays during times of stress, and they are often tank mixed with herbicide and fungicide applications to reduce the cost. Foliar applications in sweet corn have been shown to increase total nutrient uptake, crop growth, and yield (Pal et al., 2015). The marine extract products vary in the species that they are derived from, and different compositions of extracts can result in a variety of responses across management systems.

INTRODUCTION

While there are many studies looking into the impacts of individual management factors or PGR and biostimulant effects on corn grain yield, there is little research assessing the interactions that these biological products have with the degree of crop management. The genetic makeup of different hybrids can lead to varying microbe interactions and growth patterns (Picard and Bosco, 2006), which in turn can influence the effectiveness of PGRs and biostimulant applications. Increasing the planting population creates a more competitive environment between individual plants within the row and can affect the potential treatment responses as compared to lower population systems (Sangoi, 2001). Fertility levels also affect both plant and soil microbe community growth. As fertility management varies across environments (Vanlauwe et al., 2010), understanding how varying levels of fertility interact with PGRs and biostimulant applications is key to maximizing their potential in a grower system. Foliar protection with fungicide applications has shown a positive influence on leaf area duration of corn, which can, in turn, lead to greater grain fill. Keeping the plant active for a longer period of time further influences the impact of biological products introduced into the system.

While each grower varies in their individual crop management decisions, they grow their crops based on the entire system rather than changing a single factor at a time. Recent low grain commodity prices have hampered the ability of growers to purchase inputs and have led to more farms being managed at a standard or base level with fewer inputs, and planting populations are kept lower to maximize the yield potential of each planted seed with fewer inputs. Base rates of nitrogen are applied, and any additional fertilizer or foliar protection is based on soil test values and pest thresholds. A majority of the state of Illinois has naturally fertile soils, and pre-plant soil test values often indicate that phosphorus and potassium are adequately present for crop needs.

Thus, many growers use a base rate of pre-plant nitrogen as the only fertilizer addition, and the only in-season treatments are herbicide applications for weed control; unless insect and disease thresholds are met and justify the need of insecticide and/or fungicide applications.

In contrast, intensive input systems will utilize management responsive hybrids that are planted at greater populations with more comprehensive fertilizer applications and with foliar protection regardless of disease thresholds to maximize the influence of the other factors on yield potential. Utilizing all of these management practices would be charactersitic of a progressive grower working to optimize the yield potential of all management factors of population, fertility, and foliar protection. These standard and intensive management systems differ greatly in their total inputs, and the addition of PGRs and biostimulants to these systems is likely to result in different responses.

While PGRs and biostimulants have been shown to increase corn grain yields in individual studies, there is limited research on how they interact with other management decisions. Studies comparing PGRs and biostimulants are often conducted in the greenhouse, and as a result, treatment differences observed may not reflect those observed in a field setting. Additionally, when these products are tested in field studies, they typically only use a single hybrid and plant population, with either no fertilizer added or base rates of nitrogen, phosphorus, and potassium. More research is needed comparing products across management factors, as well as product blends for optimal yield increases (Calvo et al., 2014).

The first objective of this research was to compare the impact of individual PGRs and biostimulants applied either in-furrow, foliar at V5, or in combination on the growth and yield of corn. The second objective was to evaluate these products under two varying levels of crop management, a standard and an intensive input system, to determine if they are best recommended in a lower input system, or if they are best utilized in an intensive system where population, fertility, and foliar protection are managed to be non-limiting factors.

MATERIALS AND METHODS

In-Season Pesticide Applications and Location Soil Parameters

The experiment was implemented during the 2017 and 2018 growing seasons, at three locations across the state of Illinois: the Crop Sciences Research and Education Center in Champaign, IL and two offsite locations at Harrisburg, IL, in the southern part of the state, and Yorkville, IL, in the northern part of the state.

In 2017, these locations were maintained weed-free with a pre-emergence herbicide application of S-metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide] + atrazine (1-chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine) + mesotrione (2-[4-(methylsulfonyl)-2-nitrobenzoyl] cyclohexane-1,3-dione), known as Lumax (Syngenta, Basel, Switzerland) at a rate of 7.6 L hectare^{-1} (3.25 qt acre^{-1}) at all three locations, and with glyphosate (N-phosphonomethyl glycine, in the form of a potassium salt), known as RoundUp PowerMax (Monsanto, St. Louis, MO) included in Harrisburg at a rate of 2.33 L hectare^{-1} (1 qt acre^{-1}). Field sites provided relatively even distributions of soil fertility, pH, soil organic matter, and water availability. Soil samples 0-15 cm (0 – 6 in) deep were obtained from plot areas prior to planting and analyzed for significant constituents by A&L Great Lakes Laboratories (Ft. Wayne, IN) to confirm fertility levels. Plots were planted with an ALMACO Seed Pro 360 planter (ALMACO, Nevada, IA) on 9 May 2017 in Harrisburg, 18 May 2017 in Champaign, and 16 May 2017 in Yorkville.

In 2018, these locations were maintained weed-free with a pre-emergence herbicide application of Lumax at a rate of 7.6 L hectare^{-1} (3.25 qt acre^{-1}) in Harrisburg; Bicyclopyrone (Bicyclo[3.2.1]oct-3-en-2-one, 4-hydroxy-3-[[2-[(2-methoxyethoxy)methyl]-6-(trifluoromethyl)-3-pyridinyl]carbonyl] + mesotrione + S-Metolachlor + atrazine, known as

Acuron (Syngenta, Basel, Switzerland) at a rate of 7 L hectare^{-1} (3 qt acre^{-1}) in Champaign; and pyroxasulfone (3-[[[5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl)-1H-pyrazol-4-y]methyl]sulfonyl]-4,5-dihydro-5,5-dimethylisoxazole), known as Zidua (BASF Corporation, Research Triangle Park, NC) at a rate of 219 ml hectare^{-1} (3 oz acre^{-1}), flumioxazin (2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propynyl)-2H-1,4-bensoxazin-6-y]-4,5,6,7-tetrahydro-1H-isoindole-1,3(2H)-dione) + pyroxasulfone, known as Fierce (Valent, Walnut Creek, CA) at a rate of 36.5 ml hectare^{-1} (0.5 oz acre^{-1}), and atrazine, known as AAtrex 4L (Syngenta, Basel, Switzerland) at a rate of 1.1 kg hectare^{-1} (1 lb acre^{-1}) in Yorkville. Plots were planted on 1 May 2018 in Harrisburg, 28 April 2018 in Champaign, and 18 May 2018 in Yorkville.

In both years, all plots received an in-furrow soil insecticide application of [tefluthrin:(2,3,5,6-tetrafluoro-4-methylphenyl)methyl-(1α,3α)-(Z)-(±)-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate], known as Force 3G (Syngenta, Basel, Switzerland) at a rate of 0.1134 kg hectare^{-1} (4 oz acre^{-1}) and soybean was the previous crop with conventional tillage used at all three locations.

The 2017 in-season weed control was applied at the V8 growth stage in Harrisburg with topramezone [3-(4,5-dihydro-isoxazolyl)-2-methyl-4-(methylsulfonyl)phenyl](5-hydroxy-1-methyl-1H-pyrazol-4-yl)methanone, known as Armezon (BASF Corporation, Research Triangle Park, NC) at a rate of 54.8 ml hectare^{-1} (0.75 oz acre^{-1}), RoundUp Powermax at a rate of 2.33 L hectare^{-1} (1 qt acre^{-1}), ammonium sulfate (AMS; 21-0-0-24S) at a rate of 1.87 L hectare^{-1} (0.2 gal acre^{-1}), and Interlock (Winfield Solutions LLC, St. Paul, MN) surfactant at a rate of 292.3 ml hectare^{-1} (4 oz acre^{-1}). In Champaign, in-season weed control was applied at the V5 growth stage with Armezon at a rate of 54.8 ml hectare^{-1} (0.75 oz acre^{-1}), RoundUp Powermax at a rate of 2.33 L hectare^{-1} (1 qt acre^{-1}), AAtrex 4L at a rate of 1.1 kg hectare^{-1} (1 lb acre^{-1}), and Class Act Ridion

(Winfield Solutions LLC, St. Paul, MN) water conditioner at a rate of 1.4 L hectare^{-1} (19.2 oz acre^{-1}). In Yorkville, in-season weed control was applied at the V7 growth stage with Armezon at a rate of 54.8 ml hectare^{-1} (0.75 oz acre^{-1}), RoundUp Powermax at a rate of 2.33 L hectare^{-1} (1 qt acre^{-1}), and Class Act Ridion water conditioner at a rate of 2.33 L hectare^{-1} (1 qt acre^{-1}).

In-season weed control in 2018 was applied at the V5 to V6 growth stages with AAtrex 4L at a rate of 1.1 kg hectare^{-1} (1 lb acre^{-1}), RoundUp Powermax at a rate of 2.33 L hectare^{-1} (1 qt acre^{-1}), and AMS at a rate of 1.87 L hectare^{-1} (0.2 gal acre^{-1}) at all three sites, with Armezon at a rate of 54.8 ml hectare^{-1} (0.75 oz acre^{-1}) added at Harrisburg and Yorkville.

Management Specifics

A corn hybrid responsive to management practices (Croplan 6594VT2P; 113-day relative maturity, in 2017 and Croplan 6594SS; 113-day relative maturity, in 2018) was used at all locations. These two hybrids have the same base genetics, but differ in their degree of transgenic insect protection. Two management systems were assessed, a standard system and an intensive input system. All plots across both managements received 179 kg hectare^{-1} (160 lbs acre^{-1}) pre-plant nitrogen (28% urea ammonium nitrate at Champaign in 2017 and 2018, and Yorkville in 2018; dry urea in Harrisburg in 2017 and 2018, and Yorkville in 2017) and 47 L hectare^{-1} (5 gal acre^{-1}) ammonium polyphosphate (10-34-0) with 2.3 L hectare^{-1} (1 qt acre^{-1}) Ultra-Che Zinc 9% EDTA (7-0-0-9Zn) (Winfield Solutions LLC, St. Paul, MN) applied in-furrow at planting. The standard management plots were planted at 79,000 plants hectare^{-1} (32,000 plants acre^{-1}) and received no additional fertility or foliar protection. The intensive input system was planted at 94,000 plants hectare^{-1} (38,000 plants acre^{-1}) and received an additional 89 kg hectare^{-1} (80 lbs acre^{-1}) nitrogen [urea coated with urease inhibitor, known as Limus (BASF, Research Triangle Park, NC)] at side-dress (V5-V7), a single foliar application of micro-nutrient product Max-In

Ultra ZMB (3.6% Sulfur, 0.1% Boron, 3.0% Manganese, and 4.0% Zinc) (Winfield Solutions LLC, St. Paul, MN) at 2.3 L hectare^{-1} (1 qt acre^{-1}) within the V5-V7 growth stages, and a foliar application of fungicide [pyraclostrobin (carbamic acid, [2,-[[[1-(4-chlorophenyl)-1H-pyrazol-3-y]oxy]methyl]phenyl]methoxy-,methylester) + metconazole (5-[4-chlorophenyl)methyl]-2,2-dimethyl-1-(1H-1,2,4-triazol-1-ylmethyl)cyclopentanol)], known as Headline AMP (BASF Corporation, Research Triangle Park, NC) at a rate of 1 L hectare^{-1} (14.4 oz acre^{-1}) with MasterLock (Winfield Solutions LLC., St. Paul, MN) surfactant at a rate of 468 ml hectare^{-1} (6.4 oz acre^{-1}) at the VT/R1 growth stage.

Treatment Applications

Applications were designed to supply products to the corn plants either in-furrow at planting and/or as a foliar application at the V5 growth stage (Table 1). In-furrow applications included the PGRs Ascend SL (containing cytokinins, gibberellic acids, and indolebutyric acid) (Winfield Solutions LLC., St. Paul, MN) at a rate of 387 ml hectare^{-1} (5.3 oz acre^{-1}) or Optify/Stretch [containing cytokinins and complex polymeric polyhydroxy acids (CPPA)] (United Suppliers, Eldora, IA) at a rate of 730 ml hectare^{-1} (10 oz acre^{-1}). The in-furrow treatments were applied at planting to all plot rows with a planter-attached liquid starter applicator system (Surefire Ag Systems, Atwood, KS). Foliar applications included Ascend SL at a rate of 490 ml hectare^{-1} (6.7 oz acre^{-1}), the biostimulant Toggle (containing marine extracts) (Acadian Seaplants Limited, Dartmouth, Nova Scotia, Canada) at a rate of 2.9 L hectare^{-1} (40 oz acre^{-1}), or the biostimulant Voyagro (containing proline, glycine betaine, and glutamic acid) (Winfield Solutions LLC., St. Paul, MN) at a rate of 585 ml hectare^{-1} (8 oz acre^{-1}) at approximately the V5 growth stage. All foliar treatments were applied with MasterLock surfactant at a rate of 468 ml hectare^{-1} using a pressured CO_2 backpack sprayer with water as a carrier for a total spray volume of 140 L hectare^{-1} (15 gal acre^{-1}) application rate, providing full coverage across the center two plot rows. Flat fan nozzles (TeeJet XR1002) with 110º spray pattern were used. In the first year, foliar treatments were applied 5 June 2017 (V6 PGR), 9 June 2017 (V7 Max-In Ultra ZMB) and 10 July 2017 (VT/R1 Fungicide) at Harrisburg. Champaign foliar treatments occurred on 16 June 2017 (V5 PGR and Max-In Ultra ZMB) and 21 July 2017 (VT/R1 Fungicide), and Yorkville foliar applications were accomplished on 14 June 2017 (V5 PGR and Max-In Ultra ZMB) and 25 July 2017 (VT/R1 Fungicide). In the second year, Harrisburg treatments were sprayed 25 May 2018 (V5 PGR and Max-In Ultra ZMB), and 29 July 2018 (VT/R1 Fungicide). Champaign foliar sprays occurred 24 May 2018 (V5 PGR), 25 May 2018 (Max-In Ultra ZMB) and 27 June 2018 (VT/R1 Fungicide). Yorkville foliar treatments were supplied 8 June 2018 (V5 PGR and Max-In Ultra ZMB) and 18 July 2018 (VT/R1 Fungicide).

Experimental Design and Statistical Analysis

Treatments (660 total plots; 336 in 2017 and 324 in 2018) were arranged using a split-split-plot experimental design with six replications. Plots were split first by management system as the main-plot, second by in-furrow products as the sub-plot, and third by foliar applications as the sub-sub-plot. Each experimental unit consisted of four 11.4 meter long rows spaced 76 centimeters apart with a 0.76 meter walk alley between each range of plots. All data were analyzed in PROC MIXED of SAS (SAS 9.4) (SAS Institute Inc., Cary, NC). The initial analysis was run as a single data set composed of all three locations, with location as a random factor in the model. All random factors were assumed to be independent of each other and follow a normal distribution (NID). PROC GLM of SAS was used to conduct the Brown-Forsythe modification of the Levene test for homogeneity of variance on the errors, with significance declared at $P \leq 0.05$ (Table 30). PROC UNIVARIATE of SAS was used to determine potential outliers and assess the normality of the errors, with significance declared at $P \leq 0.01$ (Table 30). In addition to the Shapiro-Wilk test, QQ plots and histograms were utilized to assess normality of the errors in situations where the Shapiro-Wilk tests were significant. With homogeneity of variance and normality assumptions met, the data were analyzed as a single set across all three locations.

The 2017 experimental design was asymmetrical, with unequal balance between the foliar and in-furrow applications such that not all foliar applications occurred in combination with every in-furrow application. This design inhibited the use of a factorial analysis to describe the individual products of the foliar and in-furrow applications. To properly obtain estimates of treatment effects and LSMEANS, the initial analysis was performed with the in-furrow and foliar treatments as a treatment combination, using the following model.

$$y_{ijkl} = \mu + L_i + B_{(i)j} + M_k + LM_{ik} + \epsilon_{1ijk} + T_l + LT_{il} + MT_{kl} + LMT_{ikl} + \epsilon_{2ijkl}$$

Where:

y_{ijkl} is the individual observation at the ith location, jth block, kth management, and lth treatment combination,

μ is the grand mean of all individual observations,

L_i is the random effect of the ith location, NID (0, σ_L^2),

$B_{(i)j}$ is the random effect of the jth block, NID (0, σ_B^2),

M_k is the fixed effect of the kth management level,

LM_{ik} is the random interaction between the ith location and the kth management level, NID (0, σ_{LM}^2),

ϵ_{1ijk} is the random error associated with the whole plot experimental unit, NID (0, σ_{e1}^2),

T_l is the fixed effect of the lth treatment combination,

LT_{il} is the random effect of the interaction between the ith location and the lth treatment combination NID (0, σ_{LT}^2),

MT_{kl} is the fixed effect of the interaction between the kth management level and the lth treatment combination,

LMT_{ikl} is the fixed effect of the interaction between the ith location, kth management level, and lth treatment combination,

ϵ_{2ijkl} is the random error associated with the sub-plot experimental unit, NID (0, σ_{e2}^2)

For further analysis, a second data set was created with the removal of the control treatments (no in-furrow additives or foliar sprays, both for standard and intensive input systems), leaving only the two in-furrow products and their corresponding foliar applications. Analysis of variance assumptions of normality of the errors and homogeneity of variance were re-assessed for the new data set (Table 31). Removal of the control treatment allowed the individual products to be analyzed separately as a factorial, as opposed to a treatment combination in order to better examine the additive and non-additive effects of in-furrow and foliar applications. This analysis utilized the following model:

$$y_{ijklm} = \mu + L_i + B_{(i)j} + M_k + LM_{ik} + \epsilon_{1ijk} + I_l + LI_{il} + MI_{kl} + LMI_{ikl} + \epsilon_{2ijkl} + F_m + LF_{im} + MF_{km} + LMF_{ikm} + IF_{lm} + LIF_{ilm} + MIF_{klm} + LMIF_{iklm} + \epsilon_{3ijklm}$$

Where:

y_{ijklm} is the individual observation at the ith location, jth block, kth management level, lth in-furrow, and mth foliar,

μ is the grand mean of all individual observations,

L_i is the random effect of the ith location NID (0, σ_L^2),

$B_{(i)j}$ is the random effect of the jth block NID (0, σ_B^2),

M_k is the fixed effect of the kth management level,

LM_{ik} is the random interaction between the ith location and the kth management level, NID (0, σ_{LM}^2),

ϵ_{jk} is the random error associated with the whole plot experimental unit, NID (0, σ_{e1}^2),

I_l is the fixed effect of the lth in-furrow product,

LI_{il} is the random effect of the interaction between the ith location and the lth in-furrow NID (0, σ_{LI}^2),

MI_{kl} is the fixed effect of the interaction between the kth management level and lth in-furrow,

LMI_{ikl} is the random effect of the interaction between the ith location, kth management level, and the lth in-furrow, NID (0, σ^2_{LMI}),

$\epsilon_{2(i)jkl}$ is the random error associated with the sub-whole-plot experimental unit, NID (0, σ^2_{e2}),

F_m is the fixed effect of the mth foliar,

LF_{im} is the random effect of the interaction between the ith location and the mth foliar, NID (0, σ^2_{LF}),

MF_{km} is the fixed effect of the interaction between kth management level and mth foliar,

LMF_{ikm} is the random effect of the interaction between the ith location, kth management level, and mth foliar, NID (0, σ^2_{LMF}),

IF_{lm} is the fixed effect of the interaction between lth in-furrow and mth foliar,

LIF_{ilm} is the random effect of the interaction between the ith location, lth in-furrow, and mth foliar, NID (0, σ^2_{LIF}),

MIF_{klm} is the fixed effect of the interaction between the kth management level, lth in-furrow, and mth foliar applications,

$LMIF_{iklm}$ is the random interaction between the ith location, kth management level, lth in-furrow, and mth foliar, NID (0, σ^2_{LMIF}),

ϵ_{3ijklm} is the random error associated with the sub-plot experimental unit, NID (0, σ^2_{e3})

All random three- and four-way interactions resulted in ANOVA p-values greater than 0.6, and therefore were removed from the model for final analysis.

In 2018, the trial was redesigned to equally balance the in-furrow and foliar interactions, allowing in-furrow and foliar interactions to be separated into their individual effects through a factorial design. Therefore, only one analysis was run, using the second model outlined above. Due to differences in treatment responses and weather patterns, years were not analyzed together across the replicated treatments. Analysis of variance assumptions for the 2018 data were also checked for normality of errors and homogeneity of variance (Table 32).

Measured Parameters

In 2018, total plant biomass was recorded at the V4 growth stage, and above-ground biomass was recorded at the V8 growth stage. For the V4 sampling, three plants were dug from plot border rows (i.e., rows one and four of each plot). The soil was removed from the roots using pressurized water, and plants were dried and weighed for root biomass, shoot biomass, and shoot:root ratios. The V8 sampling was done by excising six plants at the soil surface from plot rows two and three (three plants from each row). Samples were then dried and weighed for total shoot biomass. In both years, stand and lodging counts of all plots were conducted prior to harvest to determine the final plant population. At physiological maturity, the center two rows of each plot were mechanically harvested with an ALMACO SPC40 combine (ALMACO, Nevada, IA) for determination of grain yield, with values adjusted to 15.5% moisture. Harvest in 2017 was on 9 September at Harrisburg, 30 September at Champaign, and 31 October at Yorkville. Harvest in 2018 was 14 September at Harrisburg, 22 September at Champaign, and 12 October at Yorkville. Subsamples of harvested grain were analyzed for grain quality (starch, protein, and oil concentrations at 0% grain moisture) by near-infrared transmittance spectroscopy using a Foss Infratec 1241 grain analyzer (Eden Prairie, WI). Subsamples of harvested grain were also used to determine individual kernel weight based on a representative sub-sample of 300 kernels and adjusted to 0% moisture. Kernel number on a per-area basis was calculated algebraically by dividing total grain weight by the individual kernel weight.

2017 RESULTS AND DISCUSSION

Soil Characteristics

Prior to planting, a soil sample was taken at each field site to measure organic matter (%), pH, CEC (meq/100g), phosphorus (ppm), and potassium (ppm) (Table 2). Values of these characteristics varied across the field sites, with the general trend that the native soil organic matter and CEC increased from south to north, with greater pH at Harrisburg, and the greatest native phosphorus and potassium levels at Yorkville (Table 2).

Weather

Weather conditions across the three sites showed similar trends when compared to the 30-year averages at each respective site (Table 3). Individual months varied slightly in temperature compared to the 30-year average, but the average temperature for the entire 2017 growing season was the same as the 30-year average at Yorkville and Champaign, and only 0.6 degrees Celsius lower in Harrisburg (Table 3). The month of May had about average rainfall followed by 6.6, 4.5, and 6.3 cm less rainfall in June when compared to the 30-year averages at Harrisburg, Champaign, and Yorkville, respectively (Table 3). The months of July and August had variable precipitation across the three locations, but no extremes of either excess or limiting rainfall. In September, during grain fill, there was 5.4, 5.9, and 7.6 cm less rainfall than the 30-year average at Harrisburg, Champaign, and Yorkville, respectively (Table 3). These seasonal trends led to seasonal total precipitation that was 14.5, 19.3, and 10.4 cm less than the 30-year average at Harrisburg, Champaign, and Yorkville, respectively (Table 3), which led to moderate drought stress during early vegetative growth, and again during grain fill, impacting both seedling emergence and final grain yields.

Final Plant Population

The target planting populations were 79,000 and 94,000 plants hectare^{-1} for the standard and intensive input systems, respectively. Across the three locations, the final plant population for the control treatments of the standard and intensive input systems averaged 76,869 and 86,467 plants hectare^{-1}, respectively (Table 4). This represents a loss of 2,131 plants hectare^{-1} (-2.7% of the target population) in the standard management compared to a loss of 7,533 plants hectare^{-1} (-8.0% of the target population) in the intensive input system. The percentage of target population lost was 3 times greater under the intensive input system, suggesting that wet conditions during planting followed by dry soils during emergence and early season growth had a greater negative effect on the final population when the planting rate, and plant to plant competition, was greater. There was a significant interaction of management and treatment, indicating that the final plant population responses to the treatments were different between the two crop management systems (Table 4). Final plant populations were unchanged by any of the biological treatments of Ascend SL or Optify/Stretch in-furrow and Ascend SL, Toggle, or Voyagro foliar under standard management at any location (Table 5). In contrast, all combinations of PGR and/or biostimulant treatments in combination with the intensive input system led to significant increases in plant population at Harrisburg, and tended to increase plant population at Champaign and Yorkville (Table 4). When averaged across the three locations the treatments of Ascend SL applied in-furrow with no V5 foliar application, Ascend SL applied in-furrow followed with a foliar application of Ascend SL at V5, and Optify/Stretch applied in-furrow followed with a foliar application of Toggle at V5 each led to significant increases in final plant populations of 4,146, 5,869, and 4,529 more plants hectare^{-1}, respectively over the corresponding intensive management control (Table 4). The application of PGRs and biostimulants had a positive effect on final plant populations at the higher target population of the intensive system, especially at Harrisburg, similar to previous reports of foliar PGR applications reducing crop lodging (Cao et al., 2016). Final plant population resulted in no significant effects of PGR or biostimulant supplementation when plants were grown in a standard management system, although, foliar applications of Voyagro tended to decrease final stand (Table 4).

Grain Yield and Yield Parameters

Comparison of All Treatment Combinations

All grain yield, yield components, and grain quality results and discussion are in reference to the average of the three locations unless otherwise noted. Grain yields, yield components, and grain quality for each treatment at individual locations are listed in Appendix B (Tables 33-35). The average grain yield was 14.5 and 15.4 metric tons (T) hectare^{-1} for corn grown in the standard and intensive input systems, respectively (Table 6). Additionally, all treatments promoted significantly higher yields when plants were grown with intensive inputs than when grown in the standard management system (Table 7). Different yields can be characterized via a yield gap, which is the difference between the final yield and the yield potential of the crop with no limiting factors. Closing this yield gap involves better management to achieve greater yields (Dobermann et al., 2003). The intensive input system was better able to close the yield potential gap and maximize yields of the hybrid compared to the standard management. Yield responses varied significantly when plants were grown with intensive inputs but not when grown under standard management, resulting in a significant interaction of management with biological treatments (Table 8). While there were statistically no significant differences in the plant yield response to treatments under the standard management system, there were consistent patterns in yield response when averaged across the locations. Ascend SL applied in-furrow tended to promote the greatest yields when followed by a V5 foliar application of either Ascend SL, Toggle, or Voyagro, compared to no response or a negative response to Ascend SL applied in-furrow with no foliar follow-up (Table 9). Corn grown under the intensive input system with Optify/Stretch applied in-furrow and followed by a foliar application of Toggle at V5 increased yield over the respective control (Table 6 and 9). Toggle is a marine extract, and foliar applications of marine extracts have been shown to increase grain yield of corn in other studies (Basavaraja et al., 2018). The other yield responses to treatments in combination with the intensive input system tended to be inconsistent, except that the foliar application of Toggle led to a yield increase at all three sites when following Optify/Stretch applied in-furrow, but a yield decrease when following Ascend SL applied in-furrow (Table 9). Overall, the treatment combinations had non-significant impacts on yield under a standard management system, but led to inconsistent yield responses under an intensive input system.

In-furrow and Foliar Main Effects

With the removal of the control treatment from the analysis, the remaining treatments were balanced between in-furrow and foliar products and individual product comparisons could be made. In either management system, supplementation with either in-furrow product resulted in similar grain yields (Table 10). Additionally, the main effect of the foliar application was also non-significant, regardless of the management system, indicating that all foliar applications were equal to each other as well as to no foliar product application (Table 11). However, all foliar products tended toward greater yields compared to plants without the foliar application, and had an even greater effect in combination with the intensive input system (Table 11).

Yield Components

There was a significant effect of crop management on final kernel number (Table 6), likely because the intensive input system had an *a priori* greater plant population, and therefore more ears per unit area (Table 4). The intensive input system also received a fungicide application at VT, reducing disease pressure and stress, which has been shown to increase kernel set during pollination (Andrade et al., 1999). However, specific biological treatment combinations did not affect kernel number (Table 6). Overall, the management system did not affect kernel weight either, but there was an interaction between the level of crop management and the treatments (Table 6). Notably, Ascend SL applied in-furrow and followed by a foliar Toggle application at V5 resulted in a slight increase in kernel weight with standard management, but a decrease of 6 mg $kernel^{-1}$ with the intensive input system; the latter is reflective of the 0.3 T $hectare^{-1}$ decrease in yield (Tables 6 & 12).

Grain Quality

Neither the level of crop management nor PGR and biostimulant treatment combinations significantly affected the concentrations of grain oil, protein, or starch (Table 6). Most PGR and biostimulant treatments tended to result in equal or greater concentrations of grain protein and starch. However, Optify/Stretch applied in-furrow, and followed by a foliar application of Toggle at V5, in combination with the intensive input system decreased grain protein concentration (Table 6).

2017 Conclusions

With wet planting conditions in May followed by a dry June, supplying PGRs and biostimulants was the most beneficial to plant growth and stand count when applied in combination with the intensive input system that had more stress due to a higher planting population and greater plant to plant competition. Continued dry conditions throughout the growing season, especially during grain fill, led to additional, but moderate, in-season stress (Table 3). However, yields in these trials were still above the state average (12.6 T hectare^{-1}, or 201 bu acre^{-1}) (USDA NASS, 2017) and there was little effect of the PGRs and biostimulant treatments on grain yields. There was a tendency of PGR and biostimulant combinations to increase yields for plants grown under standard management, but results under intensive management were inconsistent. Interestingly, yield differences due to PGR and biostimulant supplementation in 2017 were a result of differences in kernel weights, suggesting that the products maintained leaf area duration and extended grain filling.

2018 RESULTS AND DISCUSSION

Trial Redesign

As the original experimental design in 2017 was unbalanced with an unequal distribution of foliar applications to in-furrow products, the treatment combinations were redesigned in 2018 to balance in-furrow and foliar applications. These treatment combinations are outlined in Table 13.

Soil Characteristics

As in 2017, soil samples were taken at each location prior to planting and analyzed for significant constituents by A&L Great Lakes Laboratories (Ft. Wayne, IN) (Table 14). Organic matter (%), CEC (meq/100g), and phosphorus (ppm) concentrations all increased from the southern to the northern testing sites, while pH was highest at the southern location (Harrisburg) and lowest at the northern one (Yorkville). Potassium (ppm) levels were high at all three locations, with Yorkville having the greatest native potassium soil levels (Table 14).

Weather

Weather trends in 2018 were similar across the three locations (Table 15). The month of May experienced 3.9, 5.0, and 3.3 degrees Celsius greater than average temperatures in Harrisburg, Champaign, and Yorkville, respectively, compared to the 30-year averages (Table 15). The temperatures for the rest of the growing season were more similar to the 30-year averages at all three sites. The month of May had close to average precipitation at Harrisburg and Champaign, but 5.6 cm more rainfall at Yorkville than the 30-year average, while June led to 4.1, 7.6, and 7.1 cm greater precipitation at Harrisburg, Champaign, and Yorkville, respectively (Table 15). Rainfall for July and August varied at each location, but the differences from the 30-year average were not great enough to lead to drought or excess water stresses. The month of

September had 1.8 cm less rainfall than average at Yorkville, while Champaign and Harrisburg had 4.0 and 11.9 cm greater rainfall than the 30-year averages (Table 15). The above average temperatures in May and consistent rainfall into June led to excellent conditions for seedling emergence at all three locations, followed by relatively seasonal precipitation and temperature in July and August. The month of September was slightly warmer than average at all three sites, with excess rainfall in Champaign and Harrisburg leading to favorable conditions for grain fill.

Final Plant Population

The target planting populations were 79,000 and 94,000 plants hectare^{-1} for the standard and intensive input systems, respectively. When averaged across the three locations, the final plant population for the control treatment of the standard management system was 79,978 (+1.2% of the target population) and for the intensive input system was 90,949 plants hectare^{-1} (-3.2% of the target population) (Table 16). Planter settings are designed to plant the crop at a greater population than the final target population to ensure final populations are near to the final target. The weather conditions in 2018 were ideal with minimal emergence issues, and early season growth was fostered with adequate rainfall and temperatures leading to synchronous emergence and greater observed plant stand in the standard management treatment. Conversely, the subpar population tallied in the intensive input system indicates that plants grown at the greater planting population had greater competition for resources required for emergence and continued growth. Management, the management by foliar interaction, and the in-furrow by foliar interaction all exhibited significant effects on the final plant population (Table 16). The management by foliar interaction indicated that the three foliar treatments led to significantly different final plant populations in combination with intensive inputs, but not when combined with standard management (Table 17). Under the more stressful intensive input system, applications of Toggle led to higher plant populations than when Voyagro was applied (Table 16). The in-furrow by foliar interaction indicates that foliar applications did not cause variations in plant populations when there was no product applied in-furrow, or when following Optify/Stretch, but did affect plant populations when following in-furrow Ascend SL (Table 18). Similarly, the in-furrow treatments generated similar final plant populations when followed with Voyagro or no foliar application, but the in-furrow treatments did differ when followed by an application of Toggle (Table 18). When plants were grown under standard management, final plant population was decreased when applications of Toggle followed no in-furrow application or when they followed Optify/Stretch, but increased when Toggle applications followed Ascend SL (Table 16). Overall, the additions of PGRs and/or biostimulants as a combination of either in-furrow, foliar, or both had no individual effect on final plant populations in either management system (Table 16). With adequate weather conditions for emergence and early vegetative growth in 2018, there was no benefit from applying PGR and/or biostimulant combinations for increasing the final plant population, but individual products interacted differently under varying application combinations.

In-Season Plant Biomass – Champaign Location Only

V4 Plant Biomass

Total plant biomass was measured at the V4 growth stage to assess the influence of the in-furrow applied Ascend SL or Optify/Stretch. Foliar applications had not yet been made, so the analysis was limited to just the in-furrow and management system factors. The only significant influence on V4 plant biomass was from the management system (Table 19). On a per plant basis, there was no difference in shoot or root weights across the two management systems. Greater total biomass per land area, but the same biomass per plant, indicates that at the V4 growth stage the difference between the managements in total biomass was directly related to the intensive system having more plants per hectare (Table 16). There was also no difference in the shoot:root ratio for any treatment combination, further emphasizing that all measured plants at the V4 growth stage were growing at the same rates regardless of treatment applications, and that any observable differences resulted from greater plant populations (Tables 16 and 19).

V8 Plant Biomass

The foliar treatments were applied at the V5 growth stage and plant shoots were sampled at the V8 growth stage to determine foliar product impact on above-ground biomass. Roots were not dug at this stage as the plants were too large to dig individual roots without damaging neighboring plants and potentially negatively influencing final plant population and grain yield. The three-way interaction of management by in-furrow by foliar applications was not significant, and there were no differences in above-ground biomass at the V8 growth stage due to any in-furrow by foliar treatment combinations (Table 20). However, the individual main effects of in-furrow or foliar treatments were significant, and both Ascend SL and Optify/Stretch significantly increased above-ground biomass over the no-in-furrow application control (Table 21). Additionally, a foliar application of Toggle at the V5 growth stage also led to increased total above-ground biomass compared to the no-V5 foliar treatment (Table 22). Also by V8, foliar applications affected above-ground biomass differently depending on the level of crop management (Table 23). Notably, the application of Voyagro led to increased shoot biomass under standard management, while the application of Toggle resulted in greater biomass in the intensive input system (Table 22). Surprisingly, the V8 biomass per area was similar, regardless of the crop management system, even with the greater plant populations in the intensive input system. Therefore, at the V8 growth stage, individual plants in the standard system had greater shoot biomass than individual plants in the intensive input.

In summary, plant biomass was unaffected by treatment applications at the V4 growth stage, but was changed by in-furrow and foliar products by the time plants attained the V8 growth stage. In-furrow treatments did not affect plant biomass at V4, but did by V8, indicating that the plant response to in-furrow applications was delayed. Presumably, at the V4 growth stage the plant is just exhausting the seed reserves and the plant roots had not yet depleted the readily-available levels of soil nutrients, but additional research is needed to confirm this hypothesis.

Grain Yield and Yield Parameters

Comparison of All Treatment Combinations and Individual In-furrow and Foliar Main Effects

All grain yield, yield components, and grain quality results and discussion are in reference to the average of the three locations unless otherwise noted. Grain yields, yield components, and grain qualities at each location are listed in the Appendix B (Tables 36-38). The overall grain yield, averaged across the three locations, was 14.5 metric tons (T) $hectare^{-1}$ using the standard management system, and this increased to 15.4 T $hectare^{-1}$ when plants were grown in the intensive input system (Table 24). All in-furrow and foliar treatments led to significantly higher yields when grown with intensive inputs when compared to their corresponding application in a standard management system (Table 25). Individual biological treatment combinations did not significantly change grain yield under either management system, when compared to the respective management controls (Table 26). However, there was an observable tendency across the three locations of the PGR and biostimulant treatments to reduce yields in a standard management system, but increase yields in an intensive input system (Table 26). The only exception to this negative yield tendency with standard management was at Yorkville, where some positive yield responses to PGRs and biostimulants were recorded. The difference in responses to the treatments between the two management systems can likely be attributed to the weather. Weather patterns in 2018 were conducive to high-yielding systems and overall yields were above the state average at all three locations. The start of the season provided adequate precipitation and temperature, resulting in good conditions for crop growth and development. The standard management received no additional management factors after planting, whereas the intensive input system received side-dress nitrogen, foliar micronutrients, and foliar protection at the VT growth stage. The standard system was able to set a high yield potential early in the season, but the lack of additional inputs for the remainder of the season limited the assimilate supply needed to adequately fill all of the kernels that were originally set early in the season. In contrast, the intensive input system was able to set a higher yield potential early in the season with the additional PGRs and biostimulants, and the additional in-season nutrients and foliar protection provided the assimilates needed to fill the kernels and lead to the greater yields (Table 24). As cytokinins can positively influence root growth and nutrient acquisition from the soil, leading to greater photosynthetic activity (Werner and Schmülling, 2009), the expectation would be for PGRs having a greater influence in the intensive input system where there was greater nutrient availability through both foliar and side-dress nitrogen applications. The Yorkville location contained the highest levels of native potassium and phosphorus levels with values well over the recommended thresholds for fertilizer input needs, and this high native soil fertility was able to supplement those few treatments in the standard management that did show a positive yield response to PGRs and biostimulants (Tables 14 and 26). The main effects of in-furrow and foliar treatments were non-significant, indicating that no product was better able to increase yields over another, nor over the untreated plots at each respective timing (Tables 27 and 28).

Yield Components

There was a significant effect of crop management system on final kernel number per area (Table 24), presumably due to the fact that the intensive input system had a greater final plant population and therefore more ears per unit area (Table 16). While the individual biological treatment combinations did not affect kernel number per area (Table 24), the main effect of in-furrow, and the in-furrow by foliar interaction, did lead to significant differences in final kernel number (Table 24). Neither Ascend SL nor Optify/Stretch in-furrow applications changed kernel number per area compared to the treatment of no in-furrow application, but Ascend SL supplementation did result in significantly more kernels per square meter than Optify/Stretch, and this same trend resulted in the significant interaction of in-furrow treatments with the foliar applications (Table 24). Toggle applied at the V5 growth stage following either Optify/Stretch, or no in-furrow application, resulted in significantly fewer kernels than Toggle following Ascend SL, of which the latter interaction led to the greatest number of kernels per square meter of any in-furrow by foliar treatment combinations (Tables 24 and 29). There was a tendency for the PGR and biostimulant treatments to generate fewer kernels per square meter compared to the standard management control, which corresponded to the observed yield decreases when plants were grown with the standard management. Corn will tentatively set the number of kernel rows around the ear at the V5-V6 growth stages, and the number of kernel ovules per row around V9-V10 (Stevens, 1986). As both crop management systems received upfront nitrogen applications and starter in-furrow, it is unlikely that the plants experienced stress early in the season, leading to the observed greater kernel set and yield potential. The standard management-grown plants did not have the supplemental full season treatments to fill all of those kernels (resulting in the decrease in kernel number), whereas the intensive system with additional fertility and foliar protection filled a greater proportion of those potential kernels.

The only factor leading to changes in individual kernel weight was the crop management system (Table 24). Lighter kernels were produced in response to the PGR and biological treatments with standard management, compared to kernels receiving the same PGR and biological treatments in the intensive input system. All PGR and biostimulant treatments in combination with the intensive input system resulted in slightly heavier individual kernels, resulting in the observed yield increases for the intensive input system.

Grain Quality

No in-furrow or foliar treatments affected the concentrations of grain oil or protein (Table 24). The crop management system did significantly alter the concentration of grain starch, with the standard system resulting in grain with a higher starch concentration than those grown in the intensive input system (Table 24).

2018 Conclusions

With good early season weather patterns, there was no effect of PGRs and/or biostimulants on final plant population. Individual plant growth and development was relatively unaffected by varying agronomic management or PGRs and/or biostimulant treatments through the V4 growth stage, with the only factor influencing plant biomass on a per area basis being planting population. By V8, the plant had expended its seed reserves and started to use resources from the surrounding soil environment. Therefore, there was increased shoot biomass as a result of PGR and biostimulant applications, with those plants growing in the standard management system showing greater shoot biomass per plant when compared to the ones grown in the intensive input system. Combining PGRs and biostimulants with a standard management system tended to decrease yield as a result of fewer kernels per square meter, but tended to increase yields in an intensive system by producing heavier kernels.

TWO-YEAR SUMMARY

Weather

The greatest difference in precipitation in 2018 compared to 2017 occurred during the months of June and September. There was 13.4, 12.1, and 10.7 cm greater rainfall in the month of June in 2018 than in 2017 at Yorkville, Champaign, and Harrisburg, respectively (Tables 3 and 15). This contrast led to a minor drought stress in 2017 compared to adequate rainfall and limited early season crop stress in 2018. While temperatures in 2017 were average, in 2018 the crop experienced above-average temperatures in May from planting through emergence. Mid-season temperature and rainfall were reasonably close to the 30-year averages in both years. The month of September led to 5.8, 9.9, and 17.3 cm greater rainfall in 2018 than 2017 at Yorkville, Champaign, and Harrisburg, respectively (Tables 3 and 15). These weather patterns likely resulted in vastly different growing conditions between the two years, leading to the different responses to the PGR and biostimulant treatment combinations.

Final Plant Population

In 2017, the emergence conditions were slightly wet and cool followed by a dry period that led to PGRs and biostimulants increasing final plant population under the greater planting population stress with the intensive input system. This benefit from supplementations was not present in 2018, as the emergence and early season growth conditions were ideal and there was no need of external factors to increase emergence rate and early growth when plants were grown under either the standard or intensive input systems.

Grain Yield and Yield Parameters

In both years, the intensive input system led to higher grain yields than the standard management system as a direct result of greater planting populations and greater kernel numbers in 2017 and significantly greater kernel numbers and weights in 2018. Individual PGR and biostimulant treatments led to variable responses in combination with the management systems in 2017. In 2018, PGR and biostimulant treatments tended to decrease yield in a standard system as a result of fewer kernels per unit area, but increase yield in an intensive system as a result of heavier individual kernels. Precipitation in 2017 was less than average, and biological treatments were able to potentially alleviate this stress in the standard management under some biological treatment combinations, while the intensive input system led to more variability in treatment responses. With the greater planting populations, it is likely that the water needs of the individual plants was not met and precipitation was the yield-limiting factor overcoming any potential advantage of added PGRs and biostimulants to increase yield. In contrast, 2018 weather conditions were conducive to high yields, and plants grown under both management systems experienced good conditions for setting early yield potential. The early season greater biomass of the standard system plants became limited during the later stages of crop growth and hindered yield, whereas the intensive system plants with the additional management factors were able to fulfill their additional yield potential as a result of the PGR and biostimulant applications. Therefore, we found that PGRs and biostimulants were best suited to an intensive grower system where the management factors of population, fertility, and foliar protection were non-limiting and yield potential could be increased and realized with the addition of biological products.

TABLES

2017 Tables

Table 1. Nine in-furrow and foliar treatment combinations used in the evaluation of the effect of plant growth regulators (Ascend SL, Optify/Stretch) and biostimulants (Toggle, Voyagro) on corn grain yield tested under two different management systems, standard and intensive, at three locations in Illinois, in 2017.

In-furrow Treatment †	Foliar Treatment ‡
None	None
Ascend SL	None
"	Ascend SL
"	Toggle
"	Voyagro
Optify/Stretch	None
"	Ascend SL
"	Toggle
"	Voyagro

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.
‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Ascend SL at 490 ml ha^{-1}, Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.

Table 2. Soil test values for the three field sites used for the testing of plant growth regulators and biostimulants under two different management systems at Harrisburg, Champaign, and Yorkville, IL in 2017.

Soil Characteristics	Harrisburg	Champaign	Yorkville
Organic Matter, %	2.5	3.7	3.2
pH	6.3	5.6	5.6
CEC, meq/100g	13.1	20.8	20.5
P, ppm	23	13	56
K, ppm	127	96	175

Table 3. Precipitation and temperature during the production season at Harrisburg, Champaign, and Yorkville, IL in 2017 compared to the 30-year average. Values obtained from the Illinois State Water Survey.

	Precipitation (cm)		**Temperature (°C)**	
Month	**2017**	**30-Year Average**	**2017**	**30-Year Average**
		Harrisburg		
May	14.7	13.7	18.9	18.9
June	4.8	11.4	23.3	23.9
July	5.1	9.4	26.1	25.6
August	9.1	8.4	22.2	25.0
September	2.5	7.9	20.6	20.6
Total/Average	36.3	50.8	22.2	22.8
		Champaign		
May	14.2	12.4	16.1	17.2
June	6.4	10.9	22.8	22.2
July	5.6	11.9	25.0	23.9
August	5.6	9.9	22.2	22.8
September	2.0	7.9	20.6	18.9
Total/Average	33.8	53.1	21.1	21.1
		Yorkville		
May	11.9	10.9	14.4	16.1
June	4.6	10.9	22.2	21.1
July	17.8	11.9	23.3	23.3
August	7.1	10.4	21.1	22.2
September	0.3	7.9	20.0	18.3
Total/Average	41.7	52.1	20.0	20.0

Table 4. Effect of management and in-furrow plant growth regulators (Ascend SL, Optify/Stretch) and foliar plant growth regulator (Ascend SL) or biostimulants (Toggle, Voyagro) treatments on final plant population and tests of fixed effects at Harrisburg, Champaign, and Yorkville, IL in 2017.

Management †	In-Furrow	Foliar	Locations			
			Harrisburg	Champaign	Yorkville	All
			plants / hectare			
Standard	None	None	78,631	74,248	77,117	76,869
	Ascend SL	None	79,014	75,011	78,839	77,826
		Ascend SL	79,205	74,631	76,926	77,070
		Toggle	78,058	71,873	76,926	75,809
		Voyagro	79,014	68,888	76,543	75,019
	Optify/Stretch	None	79,751	73,672	78,839	77,660
		Ascend SL	78,631	72,525	78,456	76,741
		Toggle	79,780	73,022	80,178	77,875
		Voyagro	79,205	68,888	75,011	74,653
Intensive	None	None	87,144	81,517	88,983	86,467
	Ascend SL	None	94,414	83,050	92,617	90,613
		Ascend SL	94,990	87,067	93,191	92,336
		Toggle	92,773	80,371	91,085	88,476
		Voyagro	90,396	79,988	92,808	88,318
	Optify/Stretch	None	90,969	83,240	90,705	88,891
		Ascend SL	93,663	81,517	91,851	89,511
		Toggle	95,370	81,710	94,147	90,996
		Voyagro	91,740	81,354	92,427	89,155
Management*Treatment LSD (α = 0.10)			2,454	NS	NS	3,961

Source of Variation	*p-value*			
Management	<0.0001	<0.0001	<0.0001	0.1543
Treatment	0.0016	0.0091	0.2281	0.0212
Management*Treatment	0.0077	0.7511	0.5236	0.0369

† Standard management planting population target was 79,000 plants/hectare and intensive management planting population target was 94,000 plants/hectare.

Table 5. Slice effects of the management by treatment interactions on final plant population averaged over three locations in Illinois in 2017.

	Management †	***p-value***
	Standard	0.0820
	Intensive	0.0019*

Treatment Combination ±		
In-Furrow	**Foliar**	***p-value***
None	None	0.2039
Ascend SL	None	0.1542
	Ascend SL	0.1281
	Toggle	0.1558
	Voyagro	0.1483
Optify/Stretch	None	0.1738
	Ascend SL	0.1533
	Toggle	0.1491
	Voyagro	0.1343

*Significant at $\alpha = 0.05$.

† Comparisons of treatment combinations when managements are held constant.

± Comparisons of managements when treatment combinations are held constant.

Table 6. Effect of management and in-furrow plant growth regulator and foliar plant growth regulator or biostimulant treatment on corn grain yield, yield components (kernel number and kernel weight), and grain quality (oil, protein, and starch concentrations), and test of fixed effects averaged over three locations in Illinois in 2017. Grain yield is presented at 15.5% moisture, and kernel weight and grain qualities are presented at 0% moisture.

Management	In-Furrow †	Foliar ‡	Yield	Yield Components		Grain Quality		
				Kernel Number	Kernel Weight	Oil	Protein	Starch
			T/ha	kernels/m^2	mg/kernel	g/kg		
Standard	None	None	14.5	4447	276	40.5	65.5	713
	Ascend SL	None	14.2	4378	275	40.5	66.8	717
		Ascend SL	14.7	4444	281	41.1	66.8	714
		Toggle	14.7	4454	279	40.5	66.8	715
		Voyagro	14.7	4395	283	40.6	67.3	715
	Optify/Stretch	None	14.7	4402	282	40.0	65.9	719
		Ascend SL	14.6	4446	278	40.3	66.3	716
		Toggle	14.3	4382	278	40.4	67.2	715
		Voyagro	14.4	4408	279	41.2	67.0	714
Intensive	None	None	15.4	4782	273	39.0	66.5	714
	Ascend SL	None	15.4	4816	270	39.0	66.5	716
		Ascend SL	15.4	4806	271	39.0	66.9	717
		Toggle	15.1	4765	267	39.6	67.4	715
		Voyagro	15.7	4794	272	38.8	67.1	716
	Optify/Stretch	None	15.2	4691	274	39.3	67.4	716
		Ascend SL	15.5	4767	274	39.1	66.5	719
		Toggle	15.8	4846	274	39.4	66.3	717
		Voyagro	15.5	4782	275	39.9	67.0	716
Management*Treatment LSD (α = 0.10)			0.4	NS	6	NS	NS	NS

Source of Variation				*p-value*		
Management	0.0002	0.0006	0.2321	0.2243	0.6785	0.4107
Treatment	0.2634	0.8152	0.1213	0.7618	0.3693	0.4684
Management*Treatment	0.0165	0.4506	0.0829	0.9342	0.4697	0.8566

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.
‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Ascend SL at 490 ml ha^{-1}, Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.

Table 7. Yield differences of corn grown under the intensive management system compared to standard management-grown corn due to nine different plant growth regulator and/or biostimulant treatments at Harrisburg, Champaign, and Yorkville, IL in 2017.

		Location			
In-Furrow †	**Foliar ‡**	**Harrisburg**	**Champaign**	**Yorkville**	**All**
		Tons / hectare			
None	None	+ 1.3	+ 0.4	+ 1.3	+ 0.9
Ascend SL	None	+ 1.3	+ 0.7	+ 1.6	+ 1.2
	Ascend SL	+ 1.3	- 0.4	+ 1.3	+ 0.7
	Toggle	+ 0.8	- 0.1	+ 0.8	+ 0.4
	Voyagro	+ 1.3	+ 0.3	+ 1.6	+ 1.1
Optify/Stretch	None	+ 1.3	- 0.3	+ 0.8	+ 0.4
	Ascend SL	+ 1.0	+ 0.3	+ 1.5	+ 0.9
	Toggle	+ 1.4	+ 1.3	+ 1.7	+ 1.4
	Voyagro	+ 2.0	+ 0.1	+ 1.3	+ 1.1
Management LSD ($\alpha = 0.10$)		0.3	0.3	0.3	0.3

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.

‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Ascend SL at 490 ml ha^{-1}, Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.

Table 8. Effects of the management by treatment interactions on corn grain yield averaged over three locations in Illinois in 2017.

	Management †	*p-value*
	Standard	0.0948
	Intensive	0.0127*

Treatment Combination ±		
In-Furrow	**Foliar**	***p-value***
None	None	0.0004*
Ascend SL	None	<0.0001*
	Ascend SL	0.0077*
	Toggle	0.0953
	Voyagro	0.0002*
Optify/Stretch	None	0.0757
	Ascend SL	0.0010*
	Toggle	<0.0001*
	Voyagro	<0.0001*

*Significant at $\alpha = 0.05$.

† Comparisons of treatment combinations when managements are held constant.

± Comparisons of managements when treatment combinations are held constant.

Table 9. Effects of in-furrow plant growth regulator and/or foliar plant growth regulator or biostimulant treatments on corn grain yield differences compared to the respective management control at Harrisburg, Champaign, and Yorkville, IL in 2017. Grain yield is presented at 15.5% moisture.

			Location			
Management	**In-Furrow †**	**Foliar ‡**	**Harrisburg**	**Champaign**	**Yorkville**	**All**
			Tons / hectare			
Standard	None	None	15.3	13.3	14.4	14.5
	Ascend SL	None	+ 0.0	- 0.3	- 0.4	- 0.3
		Ascend SL	+ 0.3	+ 0.2	+ 0.1	+ 0.3
		Toggle	+ 0.3	+ 0.1	+ 0.3	+ 0.2
		Voyagro	+ 0.2	+ 0.1	+ 0.3	+ 0.2
	Optify/Stretch	None	- 0.3	+ 0.3	+ 0.4	+ 0.3
		Ascend SL	+ 0.1	- 0.1	+ 0.1	+ 0.1
		Toggle	+ 0.0	- 0.6	+ 0.2	- 0.1
		Voyagro	- 0.6	+ 0.1	+ 0.3	- 0.1
Intensive	None	None	16.7	13.6	15.7	15.4
	Ascend SL	None	+ 0.0	+ 0.1	- 0.1	+ 0.0
		Ascend SL	+ 0.3	- 0.6	+ 0.1	+ 0.0
		Toggle	- 0.3	- 0.4	- 0.3	- 0.3
		Voyagro	+ 0.3	+ 0.0	+ 0.6	+ 0.3
	Optify/Stretch	None	- 0.3	- 0.4	- 0.2	- 0.2
		Ascend SL	- 0.2	- 0.2	+ 0.3	+ 0.1
		Toggle	+ 0.1	+ 0.3	+ 0.5	+ 0.4*
		Voyagro	+ 0.1	- 0.1	+ 0.3	+ 0.1

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.
‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Ascend SL at 490 ml ha^{-1}, Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.
* Significant difference from respective management control.

Table 10. Effect of management and in-furrow plant growth regulator treatment on corn grain yield and tests of fixed effects averaged over three locations in Illinois in 2017. Grain yield is presented at 15.5% moisture.

Management System	In-Furrow Treatment †	Grain Yield
		Tons / hectare
Standard	Ascend SL	14.6
	Optify/Stretch	14.6
Intensive	Ascend SL	15.3
	Optify/Stretch	15.5
Management*In-Furrow LSD (α = 0.1)		NS

Source of Variation	*p-value*
Management	0.0070
In-Furrow	0.7182
Management*In-Furrow	0.3510

† Both in-furrow treatments applied at planting; Ascend SL at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.

Table 11. Effect of management and foliar plant growth regulator or biostimulant treatment on corn grain yield and test of fixed effects averaged over three locations in Illinois in 2017. Grain yield is presented at 15.5% moisture.

Management System	Foliar Treatment †	Grain Yield
		Tons / hectare
Standard	None	14.5
	Ascend SL	14.7
	Toggle	14.6
	Voyagro	14.6
Intensive	None	15.3
	Ascend SL	15.4
	Toggle	15.4
	Voyagro	15.6
Management*Foliar LSD ($\alpha = 0.1$)		NS

Source of Variation	———— *p-value* ———— -
Management	0.0070
Foliar	0.3367
Management*Foliar	0.6340

† All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Ascend SL at 490 ml ha^{-1}, Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.

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Table 12. Slice effects of the management by treatment interactions on kernel weights averaged over three locations in Illinois in 2017.

	Management †	*p-value*
	Standard	0.0584
	Intensive	0.0830

Treatment Combination ±		
In-Furrow	**Foliar**	***p-value***
None	None	0.5343
Ascend SL	None	0.2837
	Ascend SL	0.0658
	Toggle	0.0314*
	Voyagro	0.0553
Optify/Stretch	None	0.1141
	Ascend SL	0.4900
	Toggle	0.4783
	Voyagro	0.3166

*Significant at α = 0.05.

† Comparisons of treatment combinations when managements are held constant.

± Comparisons of managements when treatment combinations are held constant.

2018 TABLES

Table 13. Nine in-furrow and foliar treatment combinations used in the evaluation of the effect of plant growth regulators (Ascend SL, Optify/Stretch) and biostimulants (Toggle, Voyagro) on corn grain yield tested under two different management systems, standard and intensive, at three locations in Illinois, in 2018.

In-furrow Treatment †	Foliar Treatment ‡
None	None
"	Toggle
"	Voyagro
Ascend SL	None
"	Toggle
"	Voyagro
Optify/Stretch	None
"	Toggle
"	Voyagro

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.
‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.

Table 14. Soil test values for the three field sites used for the testing of plant growth regulators and biostimulants at Harrisburg, Champaign, and Yorkville, IL in 2018.

Soil Characteristics	Harrisburg	Champaign	Yorkville
Organic Matter, %	2.3	4.5	7.0
pH	6.5	6.3	5.8
CEC, meq/100g	17.1	25.1	28.7
P, ppm	20	50	248
K, ppm	143	137	180

Table 15. Precipitation and temperature during the production season at Harrisburg, Champaign, and Yorkville, IL in 2018 compared to the 30-year average. Values obtained from the Illinois State Water Survey.

	Precipitation (cm)		**Temperature (°C)**	
Month	**2018**	**30-Year Average**	**2018**	**30-Year Average**
		Harrisburg		
May	12.7	13.0	22.8	18.9
June	15.5	11.4	25.6	23.9
July	7.9	9.7	25.6	25.6
August	12.7	7.6	24.4	25.0
September	19.8	7.9	22.2	20.6
Total/Average	68.6	49.5	23.9	22.8
		Champaign		
May	10.7	12.4	22.2	17.2
June	18.5	10.9	23.9	22.2
July	8.1	11.9	23.9	23.9
August	10.2	9.9	23.9	22.8
September	11.9	7.9	21.7	18.9
Total/Average	59.4	53.1	23.3	21.1
		Yorkville		
May	16.5	10.9	19.4	16.1
June	18.0	10.9	21.7	21.1
July	4.8	11.9	22.2	23.3
August	7.1	10.4	21.7	22.2
September	6.1	7.9	18.9	18.3
Total/Average	52.6	52.1	20.6	20.0

Table 16. Effect of management and in-furrow plant growth regulators (Ascend SL, Optify/Stretch) and/or foliar biostimulants (Toggle, Voyagro) treatments on final plant population and tests of fixed effects at Harrisburg, Champaign, and Yorkville, IL in 2018.

			Location			
Management †	**In-Furrow**	**Foliar**	**Harrisburg**	**Champaign**	**Yorkville**	**All**
			plants / hectare			
Standard	None	None	76,558	77,883	84,836	79,978
		Toggle	69,916	79,222	81,391	76,818
		Voyagro	72,155	81,977	82,731	79,074
	Ascend SL	None	73,605	79,032	83,114	78,073
		Toggle	79,101	81,900	81,391	80,233
		Voyagro	73,934	79,988	84,068	78,703
	Optify/Stretch	None	76,138	78,075	85,219	79,770
		Toggle	71,547	78,762	82,157	77,107
		Voyagro	78,626	81,517	83,497	80,915
Intensive	None	None	84,399	91,392	94,888	90,949
		Toggle	82,293	92,617	95,163	90,641
		Voyagro	79,808	91,278	96,502	89,810
	Ascend SL	None	81,505	92,044	94,587	89,620
		Toggle	85,523	92,541	97,841	92,301
		Voyagro	80,546	92,617	95,546	89,810
	Optify/Stretch	None	84,861	93,000	98,224	91,404
		Toggle	88,498	92,044	96,309	91,661
		Voyagro	82,182	93,383	93,631	89,109
LSD Management*In-Furrow*Foliar (α = 0.10)			NS	NS	NS	NS

Source of Variation	——— *p-value* ———			
Management	0.2253	<0.0001	<0.0001	<0.0001
In-Furrow	0.5143	0.7151	0.6973	0.7256
Management*In-Furrow	0.8251	0.6511	0.8682	0.9406
Foliar	0.3268	0.1371	0.2819	0.7789
Management*Foliar	0.0485	0.2647	0.0423	0.0083
In-Furrow*Foliar	0.0361	0.6141	0.1275	0.0236
Management*In-Furrow*Foliar	0.2271	0.6080	0.3202	0.3541

† Standard management planting population target was 79,000 plants hectare^{-1} and intensive management planting population target was 94,000 plants hectare^{-1}.

Table 17. Slice effects of the management by foliar interactions on final plant population averaged over three locations in Illinois in 2018.

Management †	***p-value***
Standard	0.1365
Intensive	0.0435*
Foliar ±	***p-value***
None	<0.0001*
Toggle	<0.0001*
Voyagro	<0.0001*

*Significant at α = 0.05.

† Comparisons of foliar products when managements are held constant.

± Comparisons of managements when foliar products are held constant.

Table 18. Slice effects of the in-furrow by foliar interactions on final plant population averaged over three locations in Illinois in 2018.

In-Furrow †	***p-value***
None	0.2068
Ascend SL	0.0281*
Optify/Stretch	0.4640
Foliar ±	***p-value***
None	0.1358
Toggle	0.0259*
Voyagro	0.7218

*Significant at α = 0.05.

† Comparisons of foliar products when in-furrow products are held constant.

± Comparisons of in-furrow products when foliar products are held constant.

Table 19. Effect of management and in-furrow plant growth regulator treatment on V4 plant biomass and tests of fixed effects at Champaign, IL in 2018.

Treatment Factor	Treatment	Growth Parameter			
		Root Weight	Shoot Weight	Total Weight	Shoot:Root Ratio
		kg dry wt / hectare †			
Management	Standard	46	146	192	3.1
	Intensive	53	172	225	3.2
	LSD (α = 0.1)	4	9	12	NS
In-Furrow	None	50	156	206	3.1
	Ascend SL	51	162	213	3.2
	Optify/Stretch	49	158	207	3.2
	LSD (α = 0.1)	NS	NS	NS	NS
Management*In-Furrow	Standard*None	48	147	195	3.1
	Standard*Ascend SL	46	146	192	3.2
	Standard*Optify/Stretch	46	145	191	3.2
	Intensive*None	52	166	218	3.2
	Intensive*Ascend SL	55	178	233	3.2
	Intensive*Optify/Stretch	52	171	224	3.3
	LSD (α = 0.1)	NS	NS	NS	NS

Source of Variation	*p-value*			
Management	0.0064	<0.0001	0.0001	0.4138
In-Furrow	0.8172	0.6671	0.7096	0.6981
Management*In-Furrow	0.6821	0.5956	0.5744	0.9380

† Values calculated based on final plant stand measurements.

Table 20. Effect of management and in-furrow plant growth regulator and/or foliar biostimulant treatment effect on V8 plant biomass and test of fixed effects at Champaign, IL in 2018.

Management	In-Furrow	Foliar	Shoot Weight
			kg dry wt / hectare †
Standard	None	None	1240
		Toggle	1407
		Voyagro	1364
	Ascend SL	None	1471
		Toggle	1488
		Voyagro	1449
	Optify/Stretch	None	1249
		Toggle	1431
		Voyagro	1672
Intensive	None	None	1273
		Toggle	1483
		Voyagro	1307
	Ascend SL	None	1436
		Toggle	1524
		Voyagro	1391
	Optify/Stretch	None	1435
		Toggle	1545
		Voyagro	1354
LSD Management*Treatment (α = 0.10)			NS

Source of Variation	*p-value*
Management	0.8923
In-Furrow	0.0288
Management*In-Furrow	0.8911
Foliar	0.0174
Management*Foliar	0.0519
In-Furrow*Foliar	0.4920
Management*In-Furrow*Foliar	0.3943

† Values calculated based on final plant stand measurements.

Table 21. Effect of management and in-furrow plant growth regulator on V8 shoot biomass and tests of fixed effects at Champaign, IL in 2018.

Treatment Factor	Treatment	Shoot Weight
		kg dry wt / hectare †
Management	Standard	1416
	Intensive	1411
	LSD (α = 0.1)	NS
In-Furrow	None	1345
	Ascend SL	1459
	Optify/Stretch	1436
	LSD (α = 0.1)	74
Management*In-Furrow	Standard*None	1337
	Standard*Ascend SL	1469
	Standard*Optify/Stretch	1427
	Intensive*None	1354
	Intensive*Ascend SL	1450
	Intensive*Optify/Stretch	1444
	LSD (α = 0.1)	NS

Source of Variation	—— *p-value* ——
Management	0.8923
In-Furrow	0.0288
Management*In-Furrow	0.8911

† Values calculated based on final plant stand measurements

Table 22. Effect of management and foliar biostimulant on V8 shoot biomass and test of fixed effects at Champaign, IL in 2018.

Treatment Factor	Treatment	Shoot Weight
		kg dry wt / hectare †
Management	Standard	1416
	Intensive	1411
	LSD (α = 0.1)	NS
Foliar	None	1351
	Toggle	1480
	Voyagro	1411
	LSD (α = 0.1)	74
Management*Foliar	Standard*None	1319
	Standard*Toggle	1443
	Standard*Voyagro	1472
	Intensive*None	1381
	Intensive*Toggle	1517
	Intensive*Voyagro	1351
	LSD (α = 0.1)	104

Source of Variation	——— ***p-value*** ———
Management	0.8923
Foliar	0.0174
Management*Foliar	0.0519

† Values calculated based on final plant stand measurements

Table 23. Slice effects of the management by foliar interactions on V8 shoot biomass averaged over three locations in Illinois in 2018.

Management †	***p-value***
Standard	0.0449*
Intensive	0.0216*
Foliar ±	***p-value***
None	0.3445
Toggle	0.2228
Voyagro	0.0565

*Significant at α = 0.05.

† Comparisons of foliar products when managements are held constant.

± Comparisons of managements when foliar products are held constant.

Table 24. Effect of management and in-furrow plant growth regulator and/or foliar biostimulant treatment on corn grain yield, yield components (kernel number and kernel weight), and grain quality (oil, protein, and starch concentrations), and tests of fixed effects averaged over three locations in Illinois in 2018. Grain yield is presented at 15.5% moisture, and kernel weight and grain qualities are presented at 0% moisture.

Management	In-Furrow †	Foliar ‡	Yield	Yield Components		Grain Quality		
				Kernel Number	Kernel Weight	Oil	Protein	Starch
			Ton/ha	number/m^2	mg/seed	———	g/kg	———
Standard	None	None	14.5	4977	246	42.8	70.2	728
		Toggle	14.2	4825	247	42.4	69.8	730
		Voyagro	14.0	4821	240	42.6	69.4	728
	Ascend SL	None	14.1	4807	248	42.2	69.4	730
		Toggle	14.3	4842	243	42.6	69.8	728
		Voyagro	14.0	4883	244	42.5	69.8	729
	Optify/Stretch	None	14.1	4847	245	42.3	70.4	729
		Toggle	13.8	4775	245	41.9	69.9	729
		Voyagro	13.9	4802	245	42.8	69.7	728
Intensive	None	None	15.4	5294	248	42.8	71.0	728
		Toggle	16.0	5325	252	42.7	71.8	727
		Voyagro	16.2	5280	250	42.0	71.6	729
	Ascend SL	None	16.2	5356	252	42.5	71.4	728
		Toggle	16.2	5412	252	42.7	71.0	728
		Voyagro	16.4	5422	255	43.2	71.8	726
	Optify/Stretch	None	16.1	5368	253	43.4	70.9	727
		Toggle	15.7	5284	249	42.1	70.2	728
		Voyagro	16.1	5354	254	43.2	71.2	726
Management*In-Furrow*Foliar LSD (α = 0.10)			NS	NS	NS	NS	NS	NS

Source of Variation	Yield	Kernel Number	Kernel Weight	Oil	Protein	Starch
	p-value					
Management	<0.0001	0.0006	0.0005	0.6431	0.3537	0.0297
In-Furrow	0.1473	0.0767	0.5652	0.9809	0.6515	0.8518
Management*In-Furrow	0.2016	0.2173	0.8583	0.6165	0.5098	0.7139
Foliar	0.9212	0.8992	0.9140	0.5102	0.7794	0.4987
Management*Foliar	0.1585	0.3393	0.2312	0.8904	0.1131	0.9791
In-Furrow*Foliar	0.6897	0.0855	0.4606	0.5222	0.7191	0.3985
Management*In-Furrow*Foliar	0.3468	0.4485	0.6717	0.7342	0.3399	0.3122

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.
‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.

Table 25. Yield differences of corn grown under the intensive management system compared to standard management-grown corn due to nine different plant growth regulator and/or biostimulant treatments at Harrisburg, Champaign, and Yorkville, IL in 2018.

		Location			
In-Furrow †	**Foliar ‡**	**Harrisburg**	**Champaign**	**Yorkville**	**All**
		Tons / hectare			
None	None	+ 1.0	+ 0.6	+ 1.3	+ 0.9
	Toggle	+ 1.9	+ 1.8	+ 1.9	+ 1.9
	Voyagro	+ 1.8	+ 2.4	+ 2.4	+ 2.2
Ascend SL	None	+ 1.7	+ 2.6	+ 2.0	+ 2.1
	Toggle	+ 1.5	+ 2.6	+ 1.8	+ 1.9
	Voyagro	+ 2.0	+ 2.6	+ 2.4	+ 2.4
Optify/Stretch	None	+ 2.1	+ 2.7	+ 1.5	+ 2.0
	Toggle	+ 1.8	+ 1.6	+ 1.6	+ 1.9
	Voyagro	+ 1.6	+ 2.4	+ 2.5	+ 2.2
Management LSD ($\alpha = 0.10$)		0.3	0.4	0.4	0.2

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.

‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.

Table 26. Effects of in-furrow plant growth regulator and/or foliar biostimulant treatments on corn grain yield differences compared to the respective management control at Harrisburg, Champaign, and Yorkville, IL in 2018. Grain yield is presented at 15.5% moisture.

			Location			
Management	**In-Furrow †**	**Foliar ‡**	**Harrisburg**	**Champaign**	**Yorkville**	**All**
			Tons / hectare			
Standard	None	None	13.1	15.5	14.8	14.5
		Toggle	- 0.6	- 0.4	+ 0.0	- 0.3
		Voyagro	- 0.5	- 0.6	- 0.4	- 0.5
	Ascend SL	None	- 0.4	- 0.9	+ 0.4	- 0.4
		Toggle	- 0.1	- 0.9	+ 0.5	- 0.2
		Voyagro	- 0.4	- 0.6	- 0.1	- 0.4
	Optify/Stretch	None	- 0.5	- 1.2	+ 0.4	- 0.4
		Toggle	- 0.3	- 0.9	- 0.1	- 0.6
		Voyagro	- 0.4	- 0.8	- 0.5	- 0.6
Intensive	None	None	14.1	16.0	16.1	15.4
		Toggle	+ 0.4	+ 0.8	+ 0.6	+ 0.6
		Voyagro	+ 0.3	+ 1.2	+ 0.7	+ 0.8
	Ascend SL	None	+ 0.3	+ 1.1	+ 1.1	+ 0.8
		Toggle	+ 0.4	+ 1.2	+ 0.9	+ 0.8
		Voyagro	+ 0.6	+ 1.4	+ 0.9	+ 1.0
	Optify/Stretch	None	+ 0.6	+ 0.9	+ 0.6	+ 0.7
		Toggle	+ 0.5	+ 0.1	+ 0.3	+ 0.3
		Voyagro	+ 0.2	+ 1.1	+ 0.7	+ 0.7
Management*In-Furrow*Foliar LSD (α = 0.10)			NS	NS	NS	NS

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.

‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.

Table 27. Effect of management and in-furrow plant growth regulator treatment on corn grain yield and tests of fixed effects averaged over three locations in Illinois in 2018. Grain yield is presented at 15.5% moisture.

Management System	In-Furrow Treatment †	Grain Yield
		Tons / hectare
Standard	None	14.2
	Ascend SL	14.2
	Optify/Stretch	13.9
Intensive	None	15.8
	Ascend SL	16.3
	Optify/Stretch	16.0
Management*In-Furrow LSD ($\alpha = 0.1$)		NS

Source of Variation	*p-value*
Management	<0.0001
In-Furrow	0.1473
Management*In-Furrow	0.2016

† Both in-furrow treatments applied at planting; Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.

Table 28. Effect of management and foliar biostimulant treatment on corn grain yield and tests of fixed effects averaged over three locations in Illinois in 2018. Grain yield is presented at 15.5% moisture.

Management System	Foliar Treatment †	Grain Yield
		Tons / hectare
Standard	None	14.2
	Toggle	14.1
	Voyagro	14.0
Intensive	None	15.9
	Toggle	16.0
	Voyagro	16.2
Management*Foliar LSD (α = 0.1)		NS

Source of Variation	*p-value*
Management	<0.0001
Foliar	0.9212
Management*Foliar	0.1585

† All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}

Table 29. Slice effects of the in-furrow by foliar interactions on kernel number averaged over three locations in Illinois in 2018.

In-Furrow †	*p-value*
None	0.6751
Ascend SL	0.1457
Optify/Stretch	0.1228
Foliar ±	***p-value***
None	0.6347
Toggle	0.0102*
Voyagro	0.0847

*Significant at α = 0.05.
† Comparisons of foliar products when in-furrow products are held constant.
± Comparisons of in-furrow products when foliar products are held constant.

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APPENDIX A: ANOVA ASSUMPTION TESTS

Table 30. Shapiro-Wilk and Brown-Forsythe tests for normally distributed errors and homogeneity of variance for ANOVA assumptions in tests of corn grain yield, yield components, and kernel quality at Harrisburg, Champaign, and Yorkville, IL, in 2017.

	Shapiro-Wilk †				**Brown-Forsythe ±**			
	All	**Harrisburg**	**Champaign**	**Yorkville**	**All**	**Harrisburg**	**Champaign**	**Yorkville**
	p-value							
Yield, T/ha	0.0916	0.0746	0.3252	0.8064	0.3695	0.3063	0.5221	0.4923
Pop.	0.1108	0.4974	0.8392	0.3892	0.5514	0.9442	0.4063	0.3940
number/ m^2	0.1415	0.4550	0.1738	0.1714	0.2503	0.0452	0.7896	0.8469
g/kernel	0.8165	0.0265	0.1896	0.1280	0.6821	0.4095	0.8442	0.4075
Oil, %	0.0423	0.4405	0.0365	0.9409	0.4709	0.6226	0.2194	0.4318
Protein, %	0.1438	0.4733	0.3407	0.4730	0.1646	0.7830	0.7110	0.7761
Starch, %	0.3801	0.2099	0.0014	0.0494	0.7478	0.6912	0.9781	0.6866

† Shapiro-Wilk significane declared at $\alpha = 0.01$.
± Brown-Forsythe significance declared at $\alpha = 0.05$.

Table 31. Shapiro-Wilk and Brown and Forsythe tests for normally distributed errors and homogeneity of variance for ANOVA assumptions in tests of corn grain yield with control treatment removed, averaged across three locations in Illinois, in 2017.

ANOVA Assumption Tests	Final Grain Yield
	All locations
	——————*p-value* ——————
Shapiro Wilk †	0.1484
Brown-Forsythe ±	0.9557

† Shapiro-Wilk significane declared at α = 0.01.
± Brown-Forsythe significance declared at α = 0.05.

Table 32. Shapiro-Wilk and Brown and Forsythe tests for normally distributed errors and homogeneity of variance for ANOVA assumptions in tests of V4 and V8 growth, corn grain yield, yield components, and kernel quality at Harrisburg, Champaign, and Yorkville, IL in 2018.

	Shapiro-Wilk †				Brown-Forsythe ±			
	Harrisburg	Champaign	Yorkville	All	Harrisburg	Champaign	Yorkville	All
	p-value							
V4 root, kg hectare^{-1}	-	0.2636	-	-	-	0.6870	-	-
V4 shoot, kg hectare^{-1}	-	0.7885	-	-	-	0.2922	-	-
V4 shoot:root ratio	-	0.9610	-	-	-	0.7163	-	-
V4 total, kg hectare^{-1}	-	0.8630	-	-	-	0.4771	-	-
V8 shoot, kg hectare^{-1}	-	0.6778	-	-	-	0.9163	-	-
Yield, T/Ha	<0.0001	0.0655	<0.0001	0.3403	0.5368	0.9697	0.6984	0.9333
Pop.	0.0114	0.1703	0.3115	0.4632	0.8302	0.6648	0.9615	0.8295
number/m^2	0.8478	0.0678	0.6486	0.1883	0.4948	0.9554	0.5333	0.9814
g/kernel	0.0032	0.2218	0.0394	0.0217	0.6864	0.6310	0.4631	0.6195
Oil, %	0.0133	0.0995	0.6082	0.0077	0.2711	0.6648	0.7517	0.9542
Protein, %	0.9717	0.0698	0.9416	0.4799	0.1846	0.9416	0.6220	0.1377
Starch, %	0.0081	0.1668	0.0117	0.4534	0.6269	0.1997	0.5482	0.0936

† Shapiro-Wilk significane declared at α = 0.01.

± Brown-Forsythe significance declared at α = 0.05.

APPENDIX B: INDIVIDUAL LOCATION DATA

Table 33. Effect of management and in-furrow plant growth regulator and foliar plant growth regulator or biostimulant treatment on corn grain yield, yield components (kernel number and kernel weight), and grain quality (oil, protein, and starch concentrations), and tests of fixed effects at Harrisburg, IL, in 2017. Grain yield is presented at 15.5% moisture, and kernel weight and grain qualities are presented at 0% moisture.

Management	In-Furrow †	Foliar ‡	Yield	Yield Components		Grain Quality		
				Kernel Number	Kernel Weight	Oil	Protein	Starch
			T/ha	kernels/m²	mg/kernel		—g/kg —	
Standard	None	None	15.3	5009	262	40.2	64.7	710
	Ascend SL	None	15.3	5000	258	39.8	64.7	712
		Ascend SL	15.6	5020	266	40.1	65.0	713
		Toggle	15.6	5097	262	39.8	64.2	712
		Voyagro	15.5	4995	266	39.1	64.7	715
	Optify/Stretch	None	15.1	4808	264	37.6	63.4	721
		Ascend SL	15.5	4987	266	39.3	64.7	710
		Toggle	15.3	5042	260	39.7	65.5	711
		Voyagro	14.7	4969	259	41.0	65.0	709
Intensive	None	None	16.7	5339	267	40.6	66.5	709
	Ascend SL	None	16.7	5442	263	39.9	66.0	712
		Ascend SL	16.9	5425	267	40.0	65.8	713
		Toggle	16.4	5371	261	40.3	65.9	712
		Voyagro	16.9	5386	268	40.3	66.3	711
	Optify/Stretch	None	16.4	5238	268	41.0	65.7	709
		Ascend SL	16.5	5350	264	39.7	64.1	715
		Toggle	16.8	5506	261	38.7	63.5	715
		Voyagro	16.7	5366	268	40.2	66.2	712
Management*Treatment LSD (α = 0.10)			NS	NS	NS	NS	NS	NS

Source of Variation	*p-value*					
Management	<0.0001	<0.0001	0.1573	0.3039	0.0937	0.6606
Treatment	0.6739	0.2454	0.3669	0.8229	0.9286	0.7179
Management*Treatment	0.7812	0.9796	0.9171	0.4689	0.6600	0.1503

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.
‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Ascend SL at 490 ml ha^{-1}, Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.

Table 34. Effect of management and in-furrow plant growth regulator and foliar plant growth regulator or biostimulant treatment on corn grain yield, yield components (kernel number and kernel weight), and grain quality (oil, protein, and starch concentrations), and test of fixed effects at Champaign, IL, in 2017. Grain yield is presented at 15.5% moisture, and kernel weight and grain qualities are presented at 0% moisture.

Management	In-Furrow †	Foliar ‡	Yield	Yield Components		Grain Quality		
				Kernel Number	Kernel Weight	Oil	Protein	Starch
			T/ha	kernels/m^2	mg/kernel		—g/kg —	
Standard	None	None	13.3	3923	285	38.8	64.7	717
	Ascend SL	None	13.0	3764*	291	40.3	67.6	720
		Ascend SL	13.5	3902	291	40.1	67.2	720
		Toggle	13.3	3865	290	40.0	67.5	719
		Voyagro	13.3	3849	292	41.0	68.2	719
	Optify/Stretch	None						
			13.6	3918	293	39.6	67.2	721
		Ascend SL	13.2	3907	286	39.3	67.2	722
		Toggle	12.7	3700*	289	39.2	68.1	718
		Voyagro	13.4	3835	295	39.5	67.1	719
Intensive	None	None	13.6	4298	276	37.0	66.0	721
	Ascend SL	None	13.7	4234	275	37.6	66.2	724
		Ascend SL	13.1	4206	271	38.2	67.9	724
		Toggle	13.2	4359	267	38.6	67.4	721
		Voyagro	13.6	4184	275	37.5	67.0	722
	Optify/Stretch	None	13.3	4134*	279	38.1	67.7	724
		Ascend SL	13.5	4167	281	38.5	67.2	723
		Toggle	14.0	4269	280	40.1	67.7	720
		Voyagro	13.5	4241	277	38.6	66.9	724
Management*Treatment LSD (α = 0.10)			NS	153	NS	NS	NS	NS

Source of Variation		*p-value*				
Management	<0.0001	<0.0001	<0.0001	0.0010	0.8188	0.0710
Treatment	0.9966	0.4036	0.8754	0.8383	0.1469	0.9521
Management*Treatment	0.1950	0.0913	0.7274	0.5347	0.8252	0.9998

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.

‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Ascend SL at 490 ml ha^{-1}, Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.

Table 35. Effect of management and in-furrow plant growth regulator and foliar plant growth regulator or biostimulant treatment on corn grain yield, yield components (kernel number and kernel weight), and grain quality (oil, protein, and starch concentrations), and tests of fixed effects at Yorkville, IL, in 2017. Grain yield is presented at 15.5% moisture, and kernel weight and grain qualities are presented at 0% moisture.

Management	In-Furrow †	Foliar ‡	Yield	Yield Components		Grain Quality		
				Kernel Number	Kernel Weight	Oil	Protein	Starch
			T/ha	kernels/m^2	mg/kernel		—g/kg —	
Standard	None	None	14.4	4420	278	40.5	66.4	712
	Ascend SL	None	14.0	4386	272	39.2	67.4	718
		Ascend SL	14.5	4416	283	40.7	67.7	709
		Toggle	14.7	4408	283	39.4	68.2	713
		Voyagro	14.7	4352	288	39.6	68.6	710
	Optify/Stretch	None	14.8	4439	285	40.4	66.2	715
		Ascend SL	14.5	4455	278	40.0	66.6	715
		Toggle	14.6	4413	282	40.1	67.6	716
		Voyagro	14.7	4428	282	40.7	68.2	715
Intensive	None	None	15.7	4789	276	39.3	65.7	713
	Ascend SL	None	15.6	4855	271	39.6	66.2	713
		Ascend SL	15.8	4869	274	38.7	65.7	714
		Toggle	15.5	4714	276	40.2	67.9	712
		Voyagro	16.3	4895	274	38.6	66.7	716
	Optify/Stretch	None	15.5	4784	274	38.9	67.4	716
		Ascend SL	16.0	4865	278	39.0	66.6	718
		Toggle	16.2	4844	282	38.9	66.1	715
		Voyagro	16.0	4828	279	41.1	66.7	711
Management*Treatment LSD (α = 0.10)			NS	NS	NS	NS	NS	NS

Source of Variation	Yield	Kernel Number	Kernel Weight	Oil	Protein	Starch
		p-value				
Management	<0.0001	<0.0001	0.2664	0.0828	0.0251	0.7617
Treatment	0.6193	0.9688	0.3848	0.6839	0.3333	0.5792
Management*Treatment	0.8378	0.8803	0.6065	0.7233	0.6056	0.6224

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.
‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Ascend SL at 490 ml ha^{-1}, Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.

Table 36. Effect of management and in-furrow plant growth regulator and/or foliar biostimulant treatment on corn grain yield, yield components (kernel number and kernel weight), and grain quality (oil, protein, and starch concentrations), and tests of fixed effects at Harrisburg, IL, in 2018. Grain yield is presented at 15.5% moisture, and kernel weight and grain qualities are presented at 0% moisture.

Management	In-Furrow †	Foliar ‡	Yield	Yield Components		Grain Quality		
				Kernel Number	Kernel Weight	Oil	Protein	Starch
			T/ha	kernels/m^2	mg/kernel		g/kg	
Standard	None	None	13.1	4496	246	43.3	73.6	721
		Toggle	12.5	4261	245	42.9	72.8	725
		Voyagro	12.6	4307	233	42.3	71.6	725
	Ascend SL	None	12.6	4220	248	43.1	74.1	721
		Toggle	13.0	4499	243	42.9	73.8	722
		Voyagro	12.6	4363	243	43.1	74.3	722
	Optify/Stretch	None	12.6	4183	247	42.4	74.1	724
		Toggle	12.8	4155	245	41.7	73.6	725
		Voyagro	12.7	4358	245	43.1	73.1	721
Intensive	None	None	14.1	4771	251	43.0	75.4	721
		Toggle	14.5	4820	253	42.5	75.7	723
		Voyagro	14.3	4745	252	42.3	74.5	724
	Ascend SL	None	14.3	4757	252	44.0	75.5	721
		Toggle	14.5	4877	250	42.6	74.7	721
		Voyagro	14.7	4743	254	42.2	75.4	724
	Optify/Stretch	None	14.7	4752	253	42.8	74.5	725
		Toggle	14.6	4889	252	42.0	74.5	723
		Voyagro	14.3	4694	252	43.0	75.5	720
Management*In-Furrow*Foliar LSD (α = 0.10)			NS	NS	NS	NS	NS	NS

Source of Variation	p-value					
Management	<0.0001	<0.0001	<0.0001	0.9522	0.2847	0.7803
In-Furrow	0.7999	0.7374	0.2979	0.4839	0.6097	0.4718
Management*In-Furrow	0.6618	0.8122	0.3917	0.8518	0.4035	0.8295
Foliar	0.7066	0.4277	0.1723	0.2336	0.6561	0.7469
Management*Foliar	0.8292	0.6214	0.0936	0.7083	0.8179	0.6664
In-Furrow*Foliar	0.8693	0.4328	0.3411	0.4307	0.8148	0.0967
Management*In-Furrow*Foliar	0.2448	0.5706	0.5238	0.8778	0.8904	0.9451

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.
‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.

Table 37. Effect of management and in-furrow plant growth regulator and/or foliar biostimulant treatment on corn grain yield, yield components (kernel number and kernel weight), and grain quality (oil, protein, and starch concentrations), and tests of fixed effects at Champaign, IL, in 2018. Grain yield is presented at 15.5% moisture, and kernel weight and qualities are presented at 0% moisture.

Management	In-Furrow †	Foliar ‡	Yield	Yield Components		Grain Quality		
				Kernel Number	Kernel Weight	Oil	Protein	Starch
			T/ha	kernels/m^2	mg/kernel		—g/kg —	
Standard	None	None	15.5	5202	261	44.0	68.0	726
		Toggle	15.0	5059	261	42.5	67.2	730
		Voyagro	14.8	5028	259	43.9	67.5	726
	Ascend SL	None	14.5	4962	257	42.1	64.8	731
		Toggle	14.6	5023	255	42.7	66.0	729
		Voyagro	14.9	5112	255	42.9	66.8	727
	Optify/Stretch	None	14.3	5105	257	42.8	67.8	727
		Toggle	14.5	4983	257	43.0	66.7	727
		Voyagro	14.7	5038	256	43.6	67.2	722
Intensive	None	None	16.0	5264	264	42.8	66.8	730
		Toggle	16.9	5325	266	43.0	69.0	726
		Voyagro	17.2	5378	270	41.4	68.2	731
	Ascend SL	None	17.1	5372	269	41.5	68.0	729
		Toggle	17.2	5489	266	42.8	68.5	727
		Voyagro	17.5	5418	272	43.5	69.5	726
	Optify/Stretch	None	17.0	5428	263	42.6	68.3	727
		Toggle	16.2	5226	260	42.4	66.0	728
		Voyagro	17.1	5432	266	43.1	68.0	725
Management*In-Furrow*Foliar LSD ($\alpha = 0.10$)			NS	NS	NS	NS	NS	44

Source of Variation	Yield	Kernel Number	Kernel Weight	Oil	Protein	Starch
	———	———	*p-value*	———	———	
Management	<0.0001	0.0127	0.0006	0.7964	0.1520	0.6665
In-Furrow	0.5554	0.9223	0.4704	0.7723	0.8467	0.5168
Management*In-Furrow	0.2868	0.4758	0.4246	0.5000	0.3794	0.4969
Foliar	0.5709	0.7558	0.7865	0.6112	0.3975	0.6354
Management*Foliar	0.7143	0.8212	0.5746	0.6796	0.8808	0.6250
In-Furrow*Foliar	0.9724	0.6814	0.9904	0.4410	0.6805	0.7946
Management*In-Furrow*Foliar	0.6062	0.7398	0.9969	0.5855	0.8456	0.5508

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.
‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.

Table 38. Effect of management and in-furrow plant growth regulator and/or foliar biostimulant treatment on corn grain yield, yield components (kernel number and kernel weight), and grain quality (oil, protein, and starch concentrations), and test of fixed effects at Yorkville, IL, in 2018. Grain yield is presented at 15.5% moisture, and kernel weight and grain qualities are presented at 0% moisture.

Management	In-Furrow †	Foliar ‡	Yield	Yield Components		Grain Quality		
				Kernel Number	Kernel Weight	Oil	Protein	Starch
			T/ha	kernels/m^2	mg/kernel		—g/kg —	
Standard	None	None	14.8	5372	231	41.9	67.3	735
		Toggle	14.8	5296	234	42.5	67.8	736
		Voyagro	14.4	5266	227	42.5	67.7	734
	Ascend SL	None	15.2	5378	238	42.2	67.8	738
		Toggle	15.3	5145	230	42.9	68.2	733
		Voyagro	14.7	5314	232	42.1	66.8	738
	Optify/Stretch	None	15.2	5433	231	42.5	67.7	737
		Toggle	14.7	5328	232	41.6	67.8	736
		Voyagro	14.3	5151	233	42.4	67.3	739
Intensive	None	None	16.1	5822	237	42.8	71.0	732
		Toggle	16.7	5806	238	42.8	71.0	733
		Voyagro	16.8	5692	229	42.4	72.3	733
	Ascend SL	None	17.2	5915	234	41.9	71.0	736
		Toggle	17.0	5855	237	42.7	70.2	736
		Voyagro	17.0	6080	238	44.0	71.3	729
	Optify/Stretch	None	16.7	5900	240	44.7	70.0	730
		Toggle	16.4	5711	233	42.1	70.3	734
		Voyagro	16.8	5910	241	43.3	67.8	733
Management*In-Furrow*Foliar LSD (α = 0.10)			NS	NS	NS	NS	NS	NS

Source of Variation	*p-value*					
Management	<0.0001	<0.0001	0.2653	0.0815	<0.0001	0.0002
In-Furrow	0.0488	0.0520	0.1387	0.8088	0.6380	0.5945
Management*In-Furrow	0.9145	0.3866	0.5607	0.6516	0.6380	0.2641
Foliar	0.5418	0.4779	0.8240	0.7343	0.9670	0.8403
Management*Foliar	0.1013	0.0993	0.9488	0.6764	0.4965	0.0736
In-Furrow*Foliar	0.5195	0.3937	0.5205	0.2297	0.9523	0.2245
Management*In-Furrow*Foliar	0.8941	0.3929	0.7154	0.5687	0.9807	0.0729

† Ascend SL was applied at 387 ml ha^{-1} and Optify/Stretch at 730 ml ha^{-1}.
‡ All foliar treatments applied at V5 growth stage with MasterLock surfactant at 468 ml ha^{-1}; Toggle at 2.9 L ha^{-1}, and Voyagro at 585 ml ha^{-1}.