North Central Region Extension Publication 303

Plant Growth Regulators:
Their Use in Crop Production

Charles L. Harms
Department of Agronomy
Purdue University

Edward S. Oplinger
Department of Agronomy
University of Wisconsin-Madison

Plant growth regulators (PGRs) are organic compounds, other than nutrients, that modify plant physiological processes. PRGs, called biostimulants or bioinhibitors, act inside plant cells to stimulate or inhibit specific enzymes or enzyme systems and help regulate plant metabolism. They normally are active at very low concentrations in plants.

The importance of PGRs was first recognized in the 1930s. Since that time, natural and synthetic compounds that alter function, shape, and size of crop plants have been discovered. Today, specific PGRs are used to modify crop growth rate and growth pattern during the various stages of development, from germination through harvest and post-harvest preservation.

Growth regulating chemicals that have positive influences on major agronomic crops can be of value. The final test, however, is that harvested yields must be increased or crop quality enhanced in order for PGRs to be profitable.

Of the many current uses of PGRs, effects on yield are often indirect (Morgan, 1979). Some of these uses include: (1) preventing lodging in cereals, (2) preventing preharvest fruit drop, (3) synchronizing maturity to facilitate mechanical harvest, (4) hastening maturity to decrease turnover time, and (5) reducing labor requirements. Studies conducted on major grain crops, such as corn, soybean, wheat, and rice, have identified materials capable of altering individual agronomic characteristics like lodging, plant height, seed number, and maturity. Even so, these changes have not always resulted in increased yields.

Field crops produce relatively low dollar returns compared to horticultural crops. Therefore, use of PGRs on field crops has not been as vigorously pursued by chemical companies and public research scientists. In fact, PGRs represent the smallest market share of the principal categories of chemicals applied to field crops in the United States. They are primarily used to control suckers in tobacco, as lodging control agents for cotton and cereals, as harvest aids for cotton, and as ripeners for sugarcane.

Classes of Growth Regulators

PGRs may be naturally occurring, plant produced chemicals called hormones, or they may be synthetically produced compounds. Most PGRs, natural and synthetic, fall into one of the following classes:

- *Auxins* primarily control growth through cell enlargement, although there are instances of auxin-induced cell division. They may act as both stimulators and inhibitors of growth, and cause different plant parts (shoots, buds, and roots) to respond differently. For example, at low concentrations, the auxin-like herbicide 2,4-D stimulates cell enlargement, whereas at higher concentrations, it inhibits enlargement or is even toxic to cells. Auxins also stimulate differentiation of cells, the formation of roots on plant cuttings, and the formation of xylem and phloem tissues.
- *Gibberellins* control cell elongation and division in plant shoots. They have been shown to stimulate ribonucleic acid and protein synthesis in plant cells.
- *Cytokinins* act in cell division, cell enlargement, senescence, and transport of amino acids in plants.

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For the specific regulation of many plant processes and the differentiation of cells into specific plant parts, a variety of ratios and concentrations of these three plant hormone classes are required rather than a single hormone acting alone.

Other naturally occurring regulators of plant growth and plant metabolic activity can be classed as inhibitors and ethylene. *Inhibitors* represent a wide assortment of internally produced chemical compounds, each of which inhibits the catalytic action of a specific enzyme. Since a plant cell may contain as many as 10,000 different enzymes, there are a wide variety of inhibitors acting inside the cell. *Ethylene* is internally produced by plants and has a multitude of effects on cell processes. It interacts with auxins to regulate many metabolic processes. Several chemical compounds that release ethylene after being sprayed on plants are currently commercial PGR products.

A wide assortment of plant growth-promoting products are being marketed with claims made for beneficial effects on crop growth and yields. Typically, these products are supposed to: (1) promote germination and/or emergence, (2) stimulate root growth, (3) promote mobilization and translocation of nutrients within plants, (4) increase stress tolerance and improve water relations in plants, (5) promote early maturity, (6) increase disease resistance, (7) retard senescence, or (8) improve crop yields and/or quality.

Usually, the claims are made for plant hormone products or products that affect the concentrations and ratios of plant hormones internally. Most often, the ingredients in these products are found to be:

- Extracts from bacteria, yeast, fungi, marine algae, and sea kelp. Usually, low concentrations of auxin, gibberellin, and cytokinin and adenine, or adenosine monophosphate (AMP) are claimed.
- Adenine, AMP, and cyclic AMP.
- Indole butyric acid and/or indole acetic acid. Both of these are auxins.
- Gibberellins—a family of approximately 70 chemical compounds.
- Cytokinins—6 furfuryl-amino purine, 6-benzyl-amino purine, zeatin, dihydrozeatin, and 20 other related chemical compounds.
- Polyethylene glycol.
- Dinoseb—2-sec butyl-4,6-dinitrophenol.
- Proteins and/or amino acids.
- Carboxylic, phenolic, and/or humic acids.

These products may provide some of the eight benefits listed above when applied to field crops grown in growth chambers or greenhouses. However, results obtained under carefully controlled conditions are not easy to reproduce in the field (Rappaport, 1980). Effects of environment, crop management, and variety on crop responses and yields are usually much more pronounced than the effects of PGRs. This makes it difficult to demonstrate a yield or quality response to the application of a PGR.

Effects of PGRs on Crop Growth

Germination and Emergence

Several plant hormones have been shown to affect germination of seeds of some plant species (Nickell, 1982). The primary event of breaking seed dormancy is stimulated by gibberellins. Field crops, such as corn, soybean, and small grains, have a very brief dormancy period after seed maturity. Thus, dormancy is not a factor in stand establishment. Volunteer plants of field crops, which begin growing after harvest, attest to the fact that PGRs that break dormancy are not required to aid germination.

Germination of field crops is sometimes decreased by cold soil temperatures (Cole and Wheeler, 1974). Cole and Wheeler's research showed that cotton seeds soaked for 6 to 24 hours in gibberellic acid or cyclic AMP increased germination percentages over a range of temperatures. To be effective, the seeds must absorb the PGR into the embryo cells. For absorption of PGRs to occur, seeds must be placed in a solution containing the PGR for 8 or more hours. More practical methods of seed treatment caused little seed response because the PGR did not penetrate the seed coat (Kellerhals, 1986).

While germination of several crop species has been increased by gibberellic acid, indole acetic acid, succinic acid, and fusiococcin, all treatments required seed soaking to incorporate the chemical into the seed. Soaking initiates water imbibition, germination, and softening of the seed, which makes planting with current planters difficult.

For most field crops, poor seedling emergence through soil crusts, dry soils, and cold soils is more of a problem than is poor germination. Large-seeded broadleaf crops emerge by an elongating hypocotyl dragging large cotyledons through the soil. Some short-statured wheat varieties have short coleoptiles and cannot be planted at soil depths greater than 2 inches. This prevents their use in dry soils, where seeds must be planted deeper than 2 inches to come in contact with moisture.

Data on the effects of PGRs on emergence are very limited, although gibberellic acid has been shown to increase seedling height of beans, wheat, and soybean. It is not known if gibberellic acid increases the force exerted by seedlings against the soil to aid emergence. Seedlings emerging under stress of a soil crust produce ethylene, which results in thickened hypocotyls and greater emergence force.

Currently, seed treatments of commercial value are used as protectants from diseases, insects, and herbicides. Commercially important seed treatments include fungicides, insecticides, and seed safeners. Safeners are chemicals that protect seedlings so a herbicide can be used on a susceptible crop.

Root Growth

Several PGRs in the auxin family of chemicals will stimulate root initiation on plant cuttings. These PGRs are commonly used for horticultural crops (Nickell, 1982). Indole butyric acid is the most frequently used PGR because it is not rapidly degraded by the plant and is not translocated from the site of application.

In field crops, root growth is strongly related to environment and soil nutrient supply, not to any hormonal deficiency in plants. Corn root proliferation into the soil is strongly correlated with increasing soil temperatures during the first two weeks after planting (Barber, 1986). Another strong correlation exists between root growth rate and soil moisture. Growth rate increases with increasing soil moisture up to the field capacity for the soil (Mackay and Barber, 1985). Seasonal root density for corn varies from 4 to 15 inches of root length per cubic inch of soil caused by interactions of soil temperature, soil moisture, and mineral nutrient supply.

Some claims for increased root growth from use of PGRs are made as a result of studies where plants are pulled from the soil. The roots that remained attached are visually examined and compared with treated and nontreated plants. These roots are often broken off within 6 inches of the base of the stalk. Since any individual plant may have up to 1.25 miles of roots in the upper 5 feet of soil, root density within 6 or so inches of the stalk may not be representative of the total amount of roots for that plant.

Mobilization and Translocation of Nutrients

Plant hormones influence mobilization of inorganic plant nutrients and sugars. Most experimental evidence that indicates plant hormones influence nutrient mobilization or translocation within plants comes from short-term laboratory studies.

Gibberellic acid stimulates phosphate uptake into corn root cells, potassium uptake in wheat, and sulfate translocation from root to shoot in pea seedlings. Indole acetic acid both depresses and increases potassium uptake in corn seedlings, depending upon concentration. These studies conducted under controlled environment conditions cannot be duplicated in field studies where foliar- or soil-applied plant hormones must exert control over long periods of time.

Several of the "growth stimulant" products have been evaluated in field studies in Wisconsin, Nebraska, Iowa, and Kansas on several field crops. Nutrient concentrations in plant parts were slightly increased, slightly decreased, or not affected by growth stimulants in the various trials. Nutrient concentrations in crops were increased to a greater extent by fertilizer additions in these trials than by the application of growth stimulants (NCR-103 Committee, 1976).

Nutrient uptake in field crops from the soil is affected by eleven factors relating to both plant and soil parameters (Barber, 1984). These include: (1) root length, (2) rate of root growth, (3) root radius, (4) maximum rate that roots can take up a nutrient, (5) rate when nutrient uptake is half-maximal, (6) minimum concentrate of a nutrient in the soil solution where uptake begins to occur, (7) nutrient concentration in the soil solution, (8) the soil's ability to replenish the soil solution with the nutrient, (9) diffusion rate of the nutrient in soil solution, (10) rate of water uptake by roots, and (11) distance between competing roots, including their root hairs. Nutrient uptake is a complex process with many interacting factors and is difficult to influence by foliar or soil applications of low concentrations of PGRs.

Stress Tolerance and Moisture Relations of Crops

Tolerance to soil moisture stress in crops is related to a crop's ability to control transpirational water loss from leaf surfaces. The opening and closing of stomata, relative numbers of stomata per unit leaf area, and thickness of the cuticle layer influence transpiration rates. Various attempts to decrease water losses from plants include: (1) PGRs that regulate the closure of stomata during moisture stress, (2) chemicals that form water-barrier films over the upper and lower surfaces of plant leaves, and (3) PGRs that decrease plant topgrowth and increase the root/shoot ratio to decrease water usage by the plant (Gale and Hagan, 1966).

Several chemicals have short-term effects, lasting from several hours to several days, on stomatal closure. Among these chemicals are phenyl mercuric acetate, atrazine, alachlor, chlormequat, daminozide, indole acetic acid, and abscisic acid. Chemicals that close stomata have sometimes increased crop yields when crops were grown under moisture stress. However, they decreased yields when crops were grown without stress. Closure of stomata limits entry of carbon dioxide into leaves; photosynthesis is decreased as well. Thus, there are trade-offs when attempting to use growth regulators to decrease transpiration.

Chemicals that form barriers to water loss have also resulted in inconsistent yield responses. Oil-wax mixtures, vinyl acetate-acrylate copolymers, hydrocarbon films, latex, and silicon polymers coat the leaf surfaces to prevent evaporation of water. Some coatings tend to plug stomata and decrease entry of carbon dioxide, which decreases photosynthesis and plant growth. In most cases, both upper and lower leaf surfaces must be coated with water-barrier films in order to effectively increase yields under moisture-stressed growing conditions (Fuehring and Finkler, 1984).

Growth retardant PGRs decrease top growth/root mass ratios and decrease transpiration. Chlormequat and other PGRs that inhibit gibberellin synthesis in plants may increase crop yields when crops are grown under moisture stress, but decrease yields when crops are grown with adequate soil moisture. These PGRs decrease water consumption at the expense of absolute production. Most chemicals that have shown efficacy for decreasing water use are not found in the list of typical ingredients for growth stimulants. Only indole acetic acid as an agent that closes stomata is on this list.

Maturity

Since crop maturity is related more to genetic control than to environmental control, an early-maturing hybrid or a variety with a shorter growing season requirement can be grown, if desired. Seed companies have developed corn and sorghum hybrids with different heat unit (growing-degree-day) requirements from emergence to maturity. Soybean varieties are categorized according to maturity group, which is based on adaptation to north-south latitudes. Heading dates for wheat and other small grain varieties are normally compared to the standard variety in each area. Growth stimulants have less effect than variety or hybrid on maturity date.

Over 50 chemicals have been tested as sugarcane ripeners, and several are in commercial use. In sugarcane, PGRs are used for uniform ripening, which improves sugar accumulation. Several PGRs and herbicides have been tested on cotton to promote uniform boll opening, which aids in mechanical picking and improves quality of the lint. These PGRs, however, are not found on the list of typical ingredients for growth stimulant products.

Disease Resistance

Changing the metabolism of plants with PGRs to control disease has provided mixed results. Some of the auxin materials have given positive results, while gibberellins have both increased and decreased disease severity (Nickell, 1982).

Disease resistance in crop plants is a heritable characteristic of considerable economic importance. Plant breeders are continually working to incorporate new sources of disease resistance into crop varieties. Genetic expression of disease resistance is often a localized response to invasion by the causal organism. The plants produce a toxic substance to kill the microorganisms that cause the disease. Disease resistance is not due to changes in plant hormone concentrations or ratios in infected cells. Claims for plant growth stimulants improving disease resistance in crop plants are largely unsubstantiated.

Senescence

Senescence is the natural termination of plant processes during the development of the seed, and is regulated by several metabolic and environmental signals. In laboratory studies with leaves, senescence was retarded by auxins, gibberellins, and cytokinins and accelerated by abscisic acid and ethylene. In plants growing in controlled environments, as many as 14 control signals or influences have been identified that affect vegetative senescence during reproductive development (Goldthwaite, 1987).

Soybean senescence is sensitive to night length, day and night temperature regime, and seed fill. Maximum seed yields require complete leaf senescence because stored carbohydrates and other nutrients are translocated from leaves to developing seeds.

Senescence delay in corn can be genetically manipulated. Several hybrids currently possess a stay-green characteristic for the leaves. When compared to hybrids of similar genetics without the stay-green characteristics, they often have slightly lower grain yields. This is because the hybrids without the stay-green leaves will mobilize and translocate carbohy-

drates and nutrients from the leaves and stalk to the grain to a greater degree than the hybrid with stay-green leaves. Thus, retarding senescence is not necessarily related to crop yield increases. Applications of plant hormones either in the soil or as a foliar spray on the crops has less influence on senescence than environment and plant genetics.

Crop Yield and Quality

Commercial applications of plant hormones have been limited to the use of gibberellic acid in fruit production. Both indole acetic acid and cytokinins are broken down very rapidly by microorganisms to inactive products when applied in the soil or on the foliage of plants. Restricted penetration of the cuticle and entry into plant cells has been another problem with indole acetic and cytokinins.

Gibberellic acid is foliar applied on seedless grapes to loosen the cluster, decrease diseases, and increase berry size. It is also used on the "Delicious" apple to control fruit shape, on lemons to delay ripening, on sugarcane to increase both internode elongation and sugar yields, on malting barley to improve the malting process, on artichokes to accelerate flower bud production, and on celery to increase petiole elongation during cool weather conditions. At present, there are no recognized commercial applications of gibberellins on field crops such as corn, soybean, wheat, grain sorghum, cotton, and rice.

The PGRs that have been studied for increased yield or quality of field crops are dinoseb, 2,3,5-triiodobenzoic acid (TIBA), ethephon, chlormequat, and mepiquat. Dinoseb applications on corn at low concentrations as a biostimulant have produced erratic grain yield responses. Yields have been increased by 5 to 15% in some studies, whereas no yield responses have been observed in other trials (Oplinger, 1983). Hybrid sensitivity and precise timing of applications to each hybrid have affected results with this chemical compound.

TIBA on soybeans has also produced inconsistent results across many environments (Stutte and Davis, 1983). Ethephon on small grains provides protection from lodging and increases yields if lodging is prevented during the early part of grain-fill. In addition, it aids in mechanical harvest of small grains. Chlormequat is another anti-lodging agent for small grains; it is used in Europe as a crop protectant (Jung and Rademacher, 1983). Mepiquat is applied on cotton as a growth retardant to prevent excessive vegetative growth and increased boll set. However, PGRs have not come into wider usage on field crops because of inconsistencies in yield or quality improvements when they are used.

Summary

Advertising claims for benefits of applying plant hormones and PGRs often are derived from plant physiology text books. The effects of plant growth stimulants on plants in research are often observed on excised plant parts and in controlled environment growth chambers for very brief time periods.

In order for a PGR to increase yields or quality of a field crop, it must (1) act over a relatively long period of time, (2) over-ride the effects of environment, (3) influence many varieties or hybrids of a particular crop, (4) be readily absorbed into the plant and able to cross cell membranes to enter cell protoplasm, and (5) be stable on the plant surfaces or in the soil for a long enough time so absorption can occur. These problems have not been resolved; therefore, PGR use in field crop production is, at this time, strictly limited.

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This publication was prepared by North Central Regional Committee NCR-103, Specialized Soil Amendments, Products, and Growth Stimulants. It summarizes existing information on plant growth regulators and does not include original research results obtained by the NCR-103 committee. Members of the committee include:

State Agricultural Experiment Stations

Illinois	Robert G. Hoeft	Missouri	Daryl D. Buchholz
Indiana	Charles L. Harms	Nebraska	Richard A. Wiese
Iowa	Regis D. Voss	North Dakota	William C. Dahnke
Kansas	David A. Whitney	Ohio	Paul Sutton
Michigan	Maurice L. Vitosh	South Dakota	James R. Gerwing
Minnesota	George W. Rehm	Wisconsin	Keith A. Kelling

U. S. Department of Agriculture Cooperative State Research Service

Charles M. Smith

Administrative Advisor

Dale H. Vanderholm (Nebraska)

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Issued in furtherance of Cooperative Extension work, Acts of Congress of May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture and Cooperative Extension Services of Illinois, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin. H. A. Wadsworth, Director, Purdue University Cooperative Extension Service, West Lafayette, IN 47907.

NEW 12/88 (20M)