Illinois Soybean Association
White Paper: Soybean Podding Research
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IMPROVING SOYBEAN YIELD:

RESEARCH INTO INCREASING SOYBEAN POD NUMBER

Executive Summary

Demand for soybeans from a growing world population and increasing standard of living is pressuring producers to increase production. However, soybean yields have only increased about 0.35 bushels per acre since the 1920s, with improvements virtually stalling in recent years. Much of the industry's body of research into the physiology of soybean yield production is also decades old. There is hope – Missouri grower Kip Cullers' 160.6-bushel-per-acre world record yield in 2010 demonstrated that there is significant upside potential to soybeans. But average yields in the U.S. are about one-fourth to one-third of Cullers', and there appears to be little direction on how growers can shoot for truly impressive advances in production.

Examining the components of yield – from plant population to pod number to seed size – the number of pods a plant can set, retain and grow to maturity appears to be the most promising factor to influence with good management practices. This paper explains the importance of pod count, explores the existing knowledge base of the variables that appear to influence it, and sets direction for future avenues of research.

The Illinois Soybean Association is in the exciting position of being able to direct research into the physiology of pod set and retention, growth regulator and nutrient management for improved production, the use of crop protection products such as Cobra and Headline to enhance yields, and the development of soybean varieties whose growth habits could enhance yield potential. In the meantime, growers can improve their pod counts, and presumably their yields, by planting earlier and minimizing stress during crucial periods of crop growth.

Discussion

With global population on the rise, demand for soybeans and soybean meal in China exploding, and worldwide competition an ever-present threat, improving yields of U.S. soybeans is imperative.

But progress in improving soybean yield has been slow relative to corn, especially since the mid-20th century. Yield improvement in both soybeans and corn were neck-and-neck through the 1940s – increasing 23 to 35% -- but from 1950 to 2005, corn yields increased about twice as fast as soybean yields (Egli, 2008). In all, corn yields rose from 27 bushels per acre in 1907 to 148 bushels per acre in 2008, a 5.5-fold increase, while soybean yields improved from 11 bushels per acre in 1924 to 43 bushels per acre in 2005, marking less than four-fold improvement over 80 years of breeding (Egli, 2008).

Beginning as early as 2004, crop physiologist Emerson Nafziger wondered aloud if soybeans had achieved a yield plateau. Though improvements have slowed, many of his colleagues, including D.B. Egli and Palle Pedersen, found the idea too pessimistic.

In “Managing Soybean for High Yield,” an Iowa State University Bulletin, Pedersen wrote, “The ‘yield plateau’ reported by many producers does not exist, and is a perception largely brought on by misuse of an overly simplified management system.”

Soybeans are extremely responsive to management decisions and equally susceptible to environmental stresses. Because soybeans fix much of their own nitrogen from atmospheric sources and adapt relatively well to changes in populations, planting dates and other management practices, generations of farmers have counted on the crop to get along fine in a variety of situations. As a result, many growers only really start thinking about soybeans after they've taken care of their corn planting. Soybeans have traditionally been treated as a stepchild crop.

To break the stagnation in yield, breeders must continue developing new germplasm, but producers also need to manage soybeans more closely and effectively. To accomplish that, we must better understand their physiology and how the crop responds to our management practices. We need to understand the triggers that regulate pod production and survival and create management solutions that enable to exploit those triggers to increase pod count and yield. However we do not need research that just focuses on answering scientific questions, no matter how curious, but research that focuses on creating answers that lead to immediate and practical solutions.

This paper cites a diverse body of soybean research stretching from North America, to Asia and Europe. However, much of the research is decades old. That highlights a significant problem facing today's soybean producers – much of the understanding of the crop is built on backdated varieties and old management practices, as well as a physiology knowledge base that is decades out of date.

We need to know what happens inside of today's elite germplasm, in the conditions we're facing now – which climatologists say may reflect new weather regimes and even changing balances of atmospheric gases – using the tillage and management strategies we deploy in the 21st century. We also need to explore new ways of expanding yield instead of just relying on the usual tactics of breeding and conventional crop management practices. If we continue to deploy the same approaches, we will continue to achieve the same disappointing results.

"When soybeans were five or six dollars a bushel, a lot of their (growers) attention was focused on how to maintain yield and reduce costs," noted Cullers (pers. comm., 2011). With commodity prices at record levels and demand expected to remain high, our focus must shift to increasing production, not reducing the cost of production.

The Soybean Plant

Building a strategy for improving yields requires at least a basic appreciation of the changes that occur in a developing soybean plant. Most of the following description is drawn from Casteel (2010).

When a soybean seed is exposed to moisture and appropriate soil temperatures, it begins to imbibe water and trigger germination. Cell division begins within 48 hours of imbibition. The seed delivers the first boost of energy for the plant, and the cotyledons can sustain growth for the 7 to 10 days following emergence. The embryo within the seed already contains three nodes – the cotyledon, the unifoliate and the first trifoliate – and the plant begins its race to establish its photosynthetic platform to fuel further growth.

Nitrogen-fixing *Bradyrhizobia japonicum* bacteria penetrate young root tissues around the V2 stage of growth – when the plant has two fully developed trifoliates exposed to the light – and begin forming the nodules and the apparatus that gather atmospheric nitrogen from the soil and convert it to amino-nitrogen that the plant can use. Nitrogen is vital for soybeans, whose seeds are high in nitrogen-rich protein. In fact, a 60-bushel soybean crop removes 40% more nitrogen from the soil than a 180-bushel corn crop. The general rule of thumb is that a soybean plant can fix and supply enough nitrogen for 50 bushels of yield. Additional nitrogen resources must come from the soil.

Every five to seven days through the V5 stage of growth, the plant produces another trifoliate, along with nodes where stalk-like racemes can form and someday set branches and/or produce flowers and pods. As the plant matures and begins to shift its energy from vegetative to reproductive development, the pace of node-building increases and a new node is established every three to five days. By the time the fifth trifoliate is fully unrolled, the average soybean plant has the cellular structures to produce about 18 to 20 nodes on its main stem. The plant's success in actually setting those nodes and then setting flowers and pods on them will depend largely on how much stress it encounters during the sensitive reproductive stages of growth (R1 to R5). Signals of environmental stress lead plants to abort flowers and pods as it balances what pods and seeds it can support and fill.

The unrolling leaves can be measured using a leaf area index, or LAI. The LAI increases throughout the vegetative growth stages, and in many varieties, stalls when rapidly growing pods begin demanding a greater proportion of the photosynthates the leaves are producing. This stage, around R4, is another critical juncture in the crop's development – the physiology surrounding the shift in partitioning sugars is only vaguely understood by scientists.

From the R4 through R6 stages of growth, the soybean plant is shunting most of its nutrients into its growing seeds. After about the R5 stage, pod abortion is minimal – environmental stress at that stage yields smaller seeds instead of fewer pods. As the seeds mature, the plant begins to senesce, tapping out its photosynthate reserves and preparing to dry down its maturing seeds.

Throughout the process, growers must protect the yield potential of their crop. Missouri grower Kip Cullers, who holds the world record for soybean yields, attributes much of his success – and much of his extraordinary pod count – to minimizing crop stress. "I'm removing stress," he said (pers. comm., 2011). "Your stress can come in several forms – lack of nutrients, water, and disease or weed pressure. You want to remove any of those you can."

Dr. Dan Davidson (pers. comm., 2011), who visited Culler's soybean fields in 2006 and 2007 when he won with 139 and 156 bushels, respectively, reports that he routinely count between 120 and 200 pods per soybean plant in his contest fields. He compared that to the average pod count of 30 to 40 he recorded participating in the Pro Farmer annual crop tour for a number of years. He stated, anecdotally that Cullers had four times more pods and four times greater yield.

The Limits of Models

Crop production models indicate that soybeans grown in ideal conditions have a maximum yield potential of 110 to 120 bushels per acre (Sinclair, 2004; Specht et al., 1999 and Specht, pers. comm. 2011). But Kip Cullers' record-setting yields – including his 2010 world record harvest of 160.6 bushels per acre – have left models in the dust and researchers shaking their heads in disbelief and denial.

In fact, University of Arkansas crop physiologist Larry Purcell applied in-field measurements in Cullers' contest field to Sinclair's crop production model in 2006 and

2007 and predicted yields in the 80-to-90-bushel range. The fields actually yielded 139 bushels in 2006 and 154 in 2007. Clearly, models contain limits that don't always describe the real world.

It's analogous to the old saying that scientists "proved" that bumblebees can't fly. When French entomologist Antoine Magnan (1934) wrote, "initially driven by what was in aviation, I applied to insects the laws of air resistance, and I arrived…a conclusion that their flight was impossible," he and his engineer colleague recognized that they were applying the rules of fixed-wing aircraft to creatures that could flap, dip and rotate their wings in complex patterns. Similarly, today's soybean yield prediction models may overlook factors such as nutrient limitations, hormone balances and more efficient use of solar radiation in their calculations. It is precisely those sorts of factors that American soybean producers and their advisors need to better understand.

Researchers in other crops – notably wheat, which has also experienced slow improvement in yields over the past several decades – have begun addressing the same challenge. The First International Workshop of the World Wheat Yield Consortium (Reynolds et al., 2011), coordinated by the global wheat and corn breeding institution CIMMYT, sets a high bar for the soybean industry to strive for. The consortium has begun systematically addressing yield challenges ranging from analyzing what isn't yet known about photosynthetic capacity of wheat leaves to understanding how to improve grain fill. Wheat has to ability to produce an almost unlimited number of tillers as soybeans have an ability to produce an unlimited number of pods. However while soybeans tend to abort a lot of flowers and pods wheat tiller initiates never develop into full head-bearing tiller.

It's time for the soybean industry to do the same. Soybeans can no longer be the stepchild to corn and cotton – they must be treated as a front-runner and managed to achieve their true potential.

Components of Yield

Soybean yield is a factor of several key components, including:

- The number of plants per acre
- Nodes per plant
- Average number of pods per plant
- Seed number per pod
- Seed size.

Each of those plays an important role in yield, but some are more responsive to management – or more feasible to study – than others.

Plant population – adjusted by seed spacing as well as row width and actual population planted – has been well-studied. Although growers base their decisions on a wide array of factors largely driven by their equipment set-ups, recommendations exist on optimum row spacing based on variety, planting date and other factors. Today's planting rates were unheard of a decade ago – rates as low as 140,000 seeds per acre have become the norm, and some growers rely on the inherent adaptability and compensatory ability of soybeans to plant 100,000 to 120,000 seeds per acre, which is roughly half of the recommendations of just a few years ago (Davidson, pers. comm., 2011).

Seed size is a surprisingly large factor in soybean yield, said plant physiologist Jim Specht at the University of Nebraska, Lincoln. A change in seed size of 500 seeds per pound – just 0.0003 ounces per seed – can represent a yield gain of 10 to 11 bushels per acre (pers. comm., 2011). However, although soybean plants can compensate for an increase or decrease in seed number during the season by slightly altering the size of their seed, size is largely genetically determined, he noted. As a result, Specht considers using management to attempt to increase yield by exploiting seed size is not a promising opportunity.

Seed number is another element in the race to improve yields, especially when growers have a chance to count four-seed pods in their crop or encounter one of the rare five-seed pods that have been found in recent years. Specht pointed out that adding just four seeds per square foot of crop can increase yield by 1 bushel per acre (pers. comm., 2011). Though management can affect seed number to some extent, seed number – like seed size – appears to be largely genetically determined, hovering at an average of 2.4 seeds per pod across the range of commercial varieties (Specht, pers. comm., 2011).

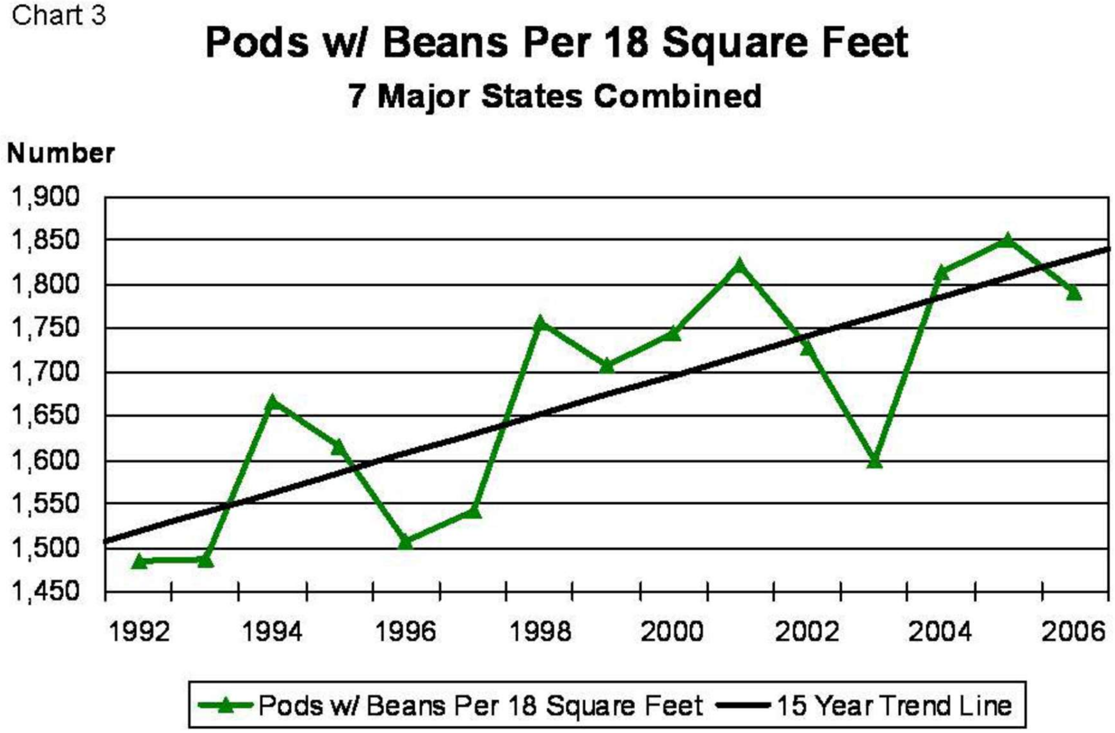
That leaves the number of nodes – potential podding sites – and pod number. Citing Herbert and Litchfield (1982) and Board et al. (1992), Liu et al. (2010) wrote, “Pod number per plant as the yield component was most influenced by change in cultural and environmental conditions.”

Influencing Pod Number

Pod number increased significantly between 1992 and 2006, according to USDA’s National Agricultural Statistics Service (NASS, 2007) – data from 15 years of the service’s national objective yield survey in seven states charted a 21% increase, from 1,484 pods per 18 square feet in 1992 to 1,791 pods in the same square footage in 2006.

Though the trend line is steady, it is interesting to note the significant peaks and valleys in the data over the course of the study period: clearly, pod number is a highly variable attribute.

Chart 3



That's really not a surprise. Setting, maintaining and ultimately filling soybean pods are a complex affair, susceptible to disruption at nearly any moment. Soybeans are inherently compensatory in that lone plants with no competition and plenty of resources can produce 100 or even 200 pods. However as plants are crowded together and/or stress sets in, pod count goes down to 20, 30, or 40 pods per plant with some outlier plants occasionally producing 60 or 80 pods. It is well accepted that soybean plants produce far more flowers and pods than they will ever fill.

A widely cited paper by Schaik and Probst (1958) recorded flower and pod abortion of 43 to 81% in four soybean varieties and one-third to one-half of the aborted organs were pods. Auburn University's Curt Peterson (1986) saw an average of 79% abscission (loss) in a determinate variety; Wiebold et al. (1981) charted 67 to 82% abortion among 11 varieties of soybean.

Seth Naeve, extension soybean agronomist at the University of Minnesota, pointed out, "I don't know of anyone in the past 30 years who has seriously looked at this. Soybeans are flowering over a longer period of time than they were before. I'll bet the current abortion rate is actually greater than it was then" (pers. comm., 2011). Retaining and maturing 10 to 20 percent of the pods that currently abort could result in a significant increase in yield.

Creating and filling soybean seeds are very costly to the plant. Soybeans are rich in oil and proteins – long, complex molecules that command more resources that filling the seed pulls the bulk of the photosynthate out of the plant's green tissue and triggers the crop into senescence. All the while, the crop is subject to biotic stresses – challenges from living organisms such as insects, weeds, nematodes, fungi and viruses – and abiotic stresses such as drought, heat, hail, wind, limiting soil factors and other challenges.

The plant's reaction to stress – or, as we'll soon see, to hormonal shifts that could hint that stressful conditions are afoot – is to jettison pods to lower demands on its threatened resources. The soybean plant is constantly reacting to its environment by adjusting its pod count, and thus the number of seeds it must fill by the end of the season.

As a result, factors that influence pod number can serve as both triggers and controls. They include:

- Number of nodes
- Flower production
- Flower fertilization
- Pod production from pollinated flowers
- Pod survival
- Seed number
- Seed size

Understanding the physiology underlying each of those factors and learning how to optimize them through management holds some of the greatest promise for increasing yields in the coming decades.

Fighting Flower Abortion

Increasing pod count doesn't appear to be a factor in increasing the number of potential pods formed as each node. Instead, it seems more important to increase the number of pods that are actually set and maintained by the plant along the raceme, or main flower stalk. Liu et al. (2010) pointed out that "in indeterminate soybean, there is only a slight variation in the number of flowers formed at each node, and high rate of flower abscission was the major factor determining the pod number per node."

The mechanisms governing flower and pod set (or abortion) are poorly understood. Makie Kokubun (2011) of Tohuko University in Japan reviewed decades of studies exploring competition for – or decreases in – photosynthates, including shade and a variety of stresses. He concluded that flower abortion could be the result of reduced dry matter production, or perhaps changes in partitioning – the allocation of photosynthates to reproductive tissue. The question that remains is how reduced dry matter production actually triggers a flower structure to abort and what the regulatory mechanism.

Brun and Betts (1984) pointed out that most flower abscission occurs when the plant is still young and photosynthate availability to fuel pod set should be high and ample. However, they also observed a marked drop in sink intensity – the plant's ability to actually accumulate photosynthates – in the three days following anthesis.

The role of foliage (and LAI) in minimizing pod abortion is perhaps a bigger mystery than people realize. Conventional wisdom, backed up by studies such as Hammond, (1989) and Hicks and Naeve (2009), indicate that soybean plants in the early vegetative stages of growth can recover from significant losses of foliage. Banks and Hammond (1987) removed the tips (apical growing points) of growing soybean plants at various stages of crop development and determined that tip loss of 20% of the stand at the beginning of flowering reduced yield by at least 10%, while tip loss of 50% of the plant population was needed to lower yields the same amount when the damage was caused prior to flowering.

In fact, counting the number of damaged leaves following hail, insect feeding or other damage may not be the best indicator of a potential yield problem. Board et al. (2010) noted that light interception is a better predictor of yield impact of foliage loss during the R5 to R6.2 stages of growth, when defoliation must be great enough to reduce light interception by at least 20% in order to cause significant yield loss. The general rule of thumb is that soybeans produce more foliage than it can efficiently use for photosynthesis and 25% defoliation will not impact yield.

The bottom line: there are shifts, changes and decisions happening inside the plant that aren't understood. But because physiologists are not publishing new studies on flower production and survival within the soybean plant, these questions remain unanswered. And unfortunately very little soybean physiology research is being conducted today so some of these questions will remain unanswered.

Improving Genetics

Breeding is a fundamental tool in the race to improve yields. The gains that geneticists are making in understanding the soybean genome and the individual genes that comprise it are opening doors to significant improvements in germplasm. Identifying crucial genes and teasing apart the complex, multi-gene traits that enable plants to better endure stress could produce varieties that set and maintain more pods in the face of adversity. However these same scientists need to have included increasing final pod set as one of their initiatives, not just yield in general.

Kokubun (2011) noted that overexpression of the DREB1 gene in rice improved drought tolerance in the crop; today, breeders are exploring ways to achieve a similar effect in soybeans.

The rate at which soybean seeds fill – tightly linked to genetics – may be another key target for breeders. University of Arkansas' Purcell noted that "it may seem counterintuitive, but we want to have a very, very slow seed fill rate. With a rapid seed filling rate, the crop takes all the proteins and sugars it stores in vegetative tissue and throws it at the seed. With slow seed growth, we prevent that self-destruction mechanism, or slow it down. The plant can continue to photosynthesize longer, continue to fix nitrogen." (Purcell, pers. comm., 2011)

Could slowing the drain of photosynthates from the leaves reduce the plant's tendency to abort flowers and pods? Is there a feedback mechanism or metabolic loop that causes the plant to shut down its photosynthate production – and can we influence it? These are certainly important questions to explore.

The architecture of soybean plants is another variable that falls squarely into the realm of the breeder. Crop growth models are limited by the amount of light the canopy can capture (Specht, pers. comm., 2011). In an innovative study of the effects of light and shade on soybean yields, Liu et al. (2010) noted, "a decrease in radiation use efficiency was responsible for the yield ceiling usually observed in population density experiments." Further, wrote the team, "Three soybean cultivars differ in yield sensitivity to light enrichment, which might be due to their differences in physiological character and canopy structure."

Liu and his colleagues used mesh fencing to push aside foliage from neighboring soybeans in their field trials, and compared the enhanced-light plots with shaded rows and untreated checks that experienced normal levels of competition for light in the canopy. They noted that "light enrichment and shading initiated from the early flowering influenced the final pod number through changing flower and pod abscission at all nodes." In fact, the Liu et al. study recorded an increase in seed yield of 71.7%, which they attributed mainly to an increase in pod number. That increase was lower than another experiment they cited (Matthew et al., 2000), which achieved seed yield increases of 144 to 252% through light enhancement. The Liu et al. paper explained a key difference: "First, soybean cultivars in their experiment were more profusely branching ones, while cultivars used in our studies were main axis ones without branches."

The remarkable improvements in pod number and seed yield in the light enhancement studies hints at two exciting angles – first, that pod number can be influenced by the crop's exposure and efficient capture of sunlight, and second, that the architecture of the plant can create greater opportunities to turn solar energy and carbon dioxide into more pods and higher yields.

We need a clearer understanding about how many nodes soybean plants can create under specific genetic and environmental conditions, as well as statistics on the average number of pods produced per node. We can then begin to target specific growth habits in soybean cultivars, whether they are profusely branched to produce more nodes, as Kip Cullers' are (Houghton, 2011) or have their leaves arrayed for more efficient interception of sunlight. But we can't change what we don't know, and we can't measure our progress if we don't have a clear sense of where we are right now.

Planting Date: A Critical Factor

Making the most of sunlight is at the heart of the push toward optimum planting dates for soybeans. Early planting delivers two key benefits to the crop – the opportunity to put more nodes on the plant and the chance to capture more light during the growing season. It also creates a longer window between emergence and summer solstice, when nights start to become shorter and plants become reproductive and node set stops. Concerns about germination and stand in the cool, disease-prone early spring are offset by crop protection tools and the promise of significant improvements in yield potential, according to many researchers.

The node issue is simple mathematics. Bastidas et al. (2008) logged that a new soybean main stem node is formed every 3.74 days. The sooner that process starts and the longer it lasts, the more potential podding sites will exist on the plant. And more nodes mean more racemes, flowers and pods.

Photosynthesis then fuels the set and development of those potential pods. At the University of Nebraska, Specht has long pushed growers toward a May 1 target planting date and a crop that is "green to the eye by the Fourth of July," a field completely covered by foliage with no valuable sunlight wasted on warming a patch of soil (Specht, pers. comm., 2011).

In Arkansas, Purcell explained the role planting date appears to play a role in Kip Cullers' record-breaking yields.

"When you have that soybean planted in mid-April or so, you get a plant that begins to bloom around the first week of June," Purcell said. "It continues to bloom for six or eight weeks. The summer solstice is June 22, so it's blooming during the entire period of the highest-intensity solar radiation. He's setting up a really long flowering period, and setting up a good situation for maturation." (Purcell, pers. comm., 2011) Davidson (pers. comm., 2011) added that he counted more than 20 established pods per plant in Cullers' fields on the summer solstice in 2008.

In Illinois, David and Nafziger (2001) calculated that in high-yielding environments, growers stand to lose 0.10 bushels per acre per day planting between May 1 and May 10, 0.23 bushels per acre per day planting between May 11 and May 20, and

0.54 bushels per acre per day if they hold off until June 1 to 10. Despite the compelling data, the researchers pointed out in a 2009 paper, just half the soybean crop in Illinois was planted by mid-May in 2004-2008, and an average of 20% of the soybeans weren't planted by June 1. That is a significant amount of yield potential to leave on the table.

Is More Nitrogen Needed?

However, it appears that intensive management of plant nutrients can play a role in improving yields and making up for later planting dates. Dan Davidson, director of strategic research for the Illinois Soybean Association, noted that he always plants some soybeans on his Nebraska farm during the latter half of May, but is able to make up for the late planting date through a foliar feeding program (pers. comm., 2011).

Conventional wisdom – and accepted production budgets – has long held that soybeans can hold their own on residual nitrogen from applications of fertilizer to previous crops and the atmospheric nitrogen that the bacteria in their root nodules fix in the soil. However, aggressive fertility programs, including Kip Cullers' use of chicken litter on his prize-winning fields and foliar feeding, indicate that soybeans are actually quite responsive to applied nitrogen. Significant questions about the optimum form of nitrogen, timing of availability and the pattern of plant use of the nutrient abound.

Few of those questions can be answered by scientific literature available today. Though a wide variety of nutrient management programs are available through fertilizer companies, the study of fertility in soybeans – in terms of what to apply and how it is used by the plant – is an under-funded area. And most literature on nitrogen applications on soybeans focus on spring applied when supplemental nitrogen reduces N-fixation. A more relevant approach is to study applications during pod fill when N-fixation is slowing, soil N supplies is diminishing and when N demanding growing.

"There's a lot of work that looks at changes in nutrient levels during seed fill stages," said Purcell of the understanding of source/sink relationships within the plant and the uptake of soil nutrients. "But a lot of that work is older literature. I don't know how applicable it is to a lot of the varieties being grown today." (Purcell, pers. comm., 2011)

Indeed, an online literature search on nitrogen needs of soybeans turns up decades-old data: a *Crop Science* paper from 1974, a 1975 article in *Science*, a paper from *Planta* in 1975. A lot has changed since then, in the varieties we grow and the way we grow them.

Meanwhile, producers and crop consultants in search of higher soybean yields have taken to relatively high applications of nitrogen for their bean crops. "Beans are nitrogen hogs," said Jeff Littrell of fertilizer company FHR Farms in Rochester, Minn. Littrell advises growers in his consulting program to apply as much as six pounds of N per bushel of anticipated yield, accompanied by P, K and a suite of humectants, bacteria and micronutrients (Littrell, pers. comm., 2011).

When Purcell analyzed Cullers' 2006 and 2007 soybean crops through a crop production model, the model displayed its built-in assumption that meeting the needs of the reproductive tissues of the crop would drain enough nitrogen from the foliage to initiate early senescence, cutting off additional seed production. Purcell changed the model to assume that the crop's nitrogen demand could be completely satisfied by fixed or applied nitrogen, and the calculated prediction jumped to a more accurate 134-to-160 bushels per acre (Purcell, 2008).

Tweaking the numbers in a crop production model may improve the predictive ability of the program, but understanding the physiology in play is more important if we are to understand the triggers regulating pod production and survival.

“If the extraordinary yields from Mr. Cullers’ are due to increased nitrogen availability, the question becomes “How is enough nitrogen applied or fixed by soybean to prevent leaves from exporting their nitrogen to seeds?” wrote Purcell (2008). Understanding that phenomenon and managing for it could contribute significantly to yields by supplying a truly adequate nutrient load and allowing the crop to effectively produce photosynthate for as long as it takes to set and fill more seed.

Another pressing question is which form of nitrogen is best utilized by the soybean plant. Crop consultant Dave Mowers of Toulon, Ill., said of Cullers’ success with chicken manure, “I think it is marking one thing for us – that there is a response. I think it’s the type of nitrogen contained in that product. I think we are going to have to supplement nitrogen to soybeans. It’s got to be slow-release so it’s available later in the season. Later in the growing season, there will be some type of nitrogen formulation we come up with that will enhance soybean yields.” (Mowers, pers. comm., 2011)

Specht explored slow-release nitrogen applications in the root zone of soybeans and found that they did not depress nitrogen fixation, but also that they did little to improve yields (pers. comm., 2011). Mowers’ is studying the action of amino acids and a variety of root exudates as they release soil nitrogen.

Other Nutrients

In addition to investigating various forms of nitrogen to supply soybean plants, researchers are working to optimize programs for phosphorus, potassium and micronutrients. Understanding where pH can be limiting to soybean yields, and where lime applications can be productive, is also important.

A soil pH of less than 6.0 can decrease soybean yields (Kassel and Tidman, 1999). A five-year study by Kassel and Tidman (1999) in acidic soils in northwest Iowa showed a linear relationship between lime rate and yield response in soybeans, though the authors noted that one to two tons of ag lime per acre generated a yield response of two to four bushels per acre across the various tillage systems in the study. In North Carolina, M. Ray Tucker of the state's Department of Agriculture cited a yield response of 15 bushels of soybeans per acre following the application of one ton of lime per acre to acid soils (Tucker, 1997).

He also pointed out that soybeans remove a great deal of potassium – 100 pounds of K per acre by a 50-bushel crop – and require most of their potash during the first 100 days of growth (Tucker, 1997). Potassium is involved in dozens of enzymatic pathways in plants, from water regulation to building cell walls. Potassium, with manganese, also helps up-regulate invertase, which in turn strengthens male reproductive tissues in flowers and in turn improves pollination and seed set (Stoller, pers. comm., 2011).

A promising area of study is the efficacy of phosphites, which some formulators say are more readily absorbed by foliage and translocated to root tissues, where they cause a flush of exudates that enhance the solubilization of soil nutrients and promote uptake by root hairs (Agro-K, 2010).

Micronutrients can play a wide variety of important roles in the soybean plant, including serving as co-factors in most enzymatic reactions in plant cells. As a result, strategies to supplement such nutrients as zinc, manganese, iron and others have proliferated. Theories and tactics abound among proponents of micronutrient application – sorting among them could be an important direction for research in the future.

In addition to N, P, K and micronutrients, many fertilizer companies and consultants believe strongly in the role of humates and other biological yield enhancers in improving soybean yields.

In Minnesota, Littrell applies blends of both liquid and dry fertilizers, humectants and a product that contains more than 200 species of live bacteria to soybeans on his farm as well as the farms of growers whom he advises (Littrell, pers. comm., 2011). Littrell believes an aggressive at-plant fertilizer program, followed by frequent sidedress and topdress applications of P, K, humectants and bacteria, stimulate rapid growth and extra node production.

“We’re trying to force very rapid growth,” he explained in mid-July. “We’re in the sixth trifoliate and we’ve probably got seven nodes right now that we’ve forced on that.” Littrell says his program has yielded an average of 24 to 29 podded nodes per plant over the past three years and has pushed many clients’ yields into the 80-to-100-bushel range (pers. comm., 2011). Following a program of growth promoters, antioxidants, fertilizers and diphenylether herbicide, Cullers reported that his soybean plants typically have 28 internodes (Houghton, 2011).

Clearly, the role of nutrients and biological agents in the formation of nodes and the stimulation of both vegetative and reproductive growth is an avenue worth exploring.

Hormones: Mystery Chemicals

Everything in a plant's life cycle is governed by an ever-shifting balance of hormones, the chemical regulators and signals that initiate and govern changes at the molecular level. As hormone levels – and the ratios among them – rise and fall, they exert a delicate tug-of-war within the plant, spurring cells to form, split and differentiate into specific types of tissue. Shifts in hormones spark the crop's change from vegetative to reproductive phases of growth, much as children undergo adolescence driven by surges in hormonal production. Flowers form and are set or aborted. Another adjustment in hormone balance causes seeds to fill and pods to ripen, then ultimately to push the plant into senescence and cell death.

The complexity of individual hormonal pathways and the even greater complexity of the interactions among hormones, demands far greater study than current funding levels permit.

"Hormonal effect is the key to making this whole machine work, and nobody understands how it works," said plant physiologist Jerry Stoller of Stoller USA in Houston, Texas (pers. comm., 2011). "Once the embryo is fertilized, the hormones trigger cell division. The ability to set pods is going to depend on the amount of cell division, the rate the cells divide, and proper differentiation so the cells know what kind of pod tissue or seed tissue to form."

Liu's thesis (2004) on pod set and drought reviewed in detail the often-conflicting research on the roles of abscisic acid and cytokinins on pod set and seed development. Dozens of studies detail the effects of introducing or blocking specific hormones and looking for effects on flowering, pod set and seed formation. Reese et al. (1995) studied the transcription and translation of a soybean vegetative protein (VSP-β) and linked it directly to flower set. Kokubun (2011) cites a 1977 study by Abernethy speculating that reduced levels of a cell mediation factor may result in the abscission of flowers in the post-embryo stage.

Cytokinins appear to be a critical hormone in setting flowers and pods.

Heindle et al. (1982) demonstrated that there is a nine-day peak in cytokinin concentration from the beginning of anthesis (the opening of the flower bud), which closely corresponds to the stage in which initiation or abortion typically takes place. Kokubun and Honda (2000) tracked peaks in cytokinin concentration in the raceme – the central stalk that supports soybean flowers and pods – for the first one to two weeks after the bloom of the first flower on that stalk. They also noted a significantly higher concentration of cytokinin near the main stem compared to the portion of the raceme farthest from the stalk, where flowers and pods are more likely to abort.

Peterson et al. (1990) saw a significant increase in seed set in two soybean varieties following the application of BAP (a cytokinin) – more than 600% in one variety and nearly 400% in the other – as a result of more pod set and less flower abscission. Kokubun (2011) believed cytokinins may help improve pod set where the availability of photosynthates is high, but are highly subject to environmental factors. He pointed out that selecting varieties for their production and regulation of cytokinins could hold great promise, writing, "genetic improvement of synthesis and transport of endogenous cytokinins from the root system, via conventional breeding or molecular approaches, may strengthen pod-set capacity of agriculturally significant genotype."

The key to success with appears to be balance – the ratio of auxins from the growing point in the tip of the shoot to cytokinins traveling up from the roots. That ratio differs at different points in the plant, during different stages of maturity, and in response to biotic and abiotic stress, Stoller noted. “If the ratio of auxin to cytokinin is too great, it will stop cell division,” he warned. “If it’s too small, it will stop cell division.” (Stoller, pers. comm., 2011)

Some literature exists on the search to understand hormonal balance.

Nooden and Nooden (1985) demonstrated a 40% increase in pod number with little pod abortion following an application of MCF, a chemical that inhibits auxin transport. Other auxin transport inhibitors with significantly different chemical properties also increase pod number, the authors noted. “These results imply, but do not prove, that auxin (possibly auxin from the leaves) may play a role in regulating pod number (apparently acting at an early stage)” (Nooden and Nooden, 1985).

Nonokawa et al. (2006) tracked the shifting relationship between auxin and cytokinin during the development of racemes, as well as at different points along the flowering axis. Applying an auxin at the anthesis of the first-position bloom on the raceme increased flower abortion. Applying a cytokinin before anthesis increased abortion, but the same hormone applied around seven days after anthesis significantly increased pod percentage. Clearly, timing plays a key – and little-understood – role in the effect of hormones to influence pod set and development.

Stoller’s research revolves around hormonal balance and the removal of excessive ethylene, which regulates the movement of hormones within the plant. Strong interactions have been documented between ethylene and auxins in plants (Muday Lab web site). Excessive ethylene, manufactured by plants in response to stress, can cause premature abscission, ripening or cell death (Stoller, pers. comm., 2011). His line of products is designed to address hormone balance and ethylene production. Growers would be well-served by conducting more applied research on how those products work, and how they may be best utilized to improve plant health and crop yields.

More research needs to be done on the details of proper ratios among the hormones – and the timing of those ideal levels – as well as the best ways to deliver products that influence hormone levels. A future challenge will be exploring how hormone levels interact with levels of photosynthate produced by the foliage during the critical stages of flower and pod formation.

Will Protecting Roots Protect Pods?

Healthy roots are obviously important to yield – they are the site of water and nutrient uptake, the exchange of key compounds (some of which are very poorly understood), and in soybeans, nitrogen-fixing nodules. But root tips are also the source of cytokinins and other hormones, which can significantly impact flower and pod set and the development of seeds.

Root health and activity in the rhizosphere, or root zone, is another ripe area for research that could help improve yields. As Kokubun (2011) noted, “clarification of the physical and chemical properties of the rhizosphere optimizing synthesis of endogenous cytokinins in roots should improve pod set.”

However studying root structure and physiology is a tedious and difficult process that requires persistence and patience.

Fungicides and Herbicides: More Than Protection?

Competing claims and debate within the scientific community have swirled around the possible "plant health effects" of strobilurin fungicides such as Headline or Quadris. Manufacturers claim the products can lengthen the period in which leaf tissue remains green and productive, boosting yields, and some field research supports the claims (Specht, pers. comm., 2011).

Little is known about what the strobilurin molecule is doing within the plant to create these effects, or what conditions exacerbate or minimize the impact of the fungicide on plant growth. Researchers are also working to zero in on the most effective timing to achieve a yield boost in the absence of economic levels of disease – current recommendations suggest an application around the R3 stage of growth. Clearly, this is an area worth exploring.

The use of Cobra (lactofen) or Blazer (acifluorfen), diphenylether herbicides – also shows some promise in stimulating greater pod number or in some other way promoting higher yields.

The localized burndown effect of Cobra on exposed soybean leaf tissue is widely recognized, and researchers including Wichert and Talbert (1993) have documented that despite the startling visual symptoms, well-timed applications of the herbicide cause little to no yield loss.

But there is a growing exploration of the possibility that lactofen may somehow encourage higher yields. Kip Cullers reported using Cobra to burn down his soybeans at the two-to-three-trifoliate stage, forcing them to create more branches as they recover from the herbicide injury – possibly a way to create more nodes (Houghton, 2011). Dave Mowers has seen yield increases from Cobra applied during the vegetative stages of soybean growth (Mowers, pers. comm., 2011). Perhaps Cobra injury damages the young soybean plant's growing point, interfering with the main stem's apical dominance and causing the plant to respond by producing multiple branches. Such an effect resulted from the application of TIBA, an auxin inhibitor, in Nooden and Nooden's study (1985). They noted that "the promotion of axillary outgrowth producing more flowers may also be a factor leading to increased pod number."

Is the Cobra effect replicable? Is it a structural effect – more branches, more sites for nodes – or a physiological one like the plant health effects claimed by the strobilurin? What is the optimum timing for application? There are many questions to answer – but the prospect of using an existing tool to boost yields in a new way is very appealing.

New Directions for Research

There is no question that the soybean industry needs new insight into increasing productivity, nor any doubt that growing demand makes higher yields absolutely imperative. Pushing soybean yields to new heights – breaking the steady, slow pattern of 0.35-bushel-per-year incremental improvements tracked by USDA since the 1920s – will require new directions for research, both basic and applied. It will require scientists, consultants, entrepreneurs and producers to seek answers to new questions and find novel new solutions.

Improving pod count appears to be an extremely promising strategy for boosting yields in soybeans – pod number is responsive to management, quantifiable to breeders and directly connected to improving seed number. However, Davidson at the Illinois Soybean Association (pers. comm., 2011) said soybean breeders do not focus on pod count when breeding for higher yields, because unlike the number of seeds per pod and the average size of the seed, pod count does not appear to be a strongly heritable trait – and because soybeans, ever adaptable, can retain or abort pods readily to respond to growing conditions. Still, reports from geneticists such as Zhang et al. (2010), who have identified several portions of the soybean genome that appear to govern flower and pod numbers, opening up avenues for genetic selections based at least in part on the potential for higher pod numbers.

Understanding the issues and turning that understanding into beans in the hopper will require both basic and applied research. The direction of future research can – and must – take several paths in order to build an up-to-date knowledge base of understanding and recommendations. Some key approaches should include:

- Develop a protocol for taking pod counts in the field into reliable estimates;
- Beginning widespread pod counts and data collection to provide a baseline so we know what current average pod numbers are and can chart our progress in the years to come;
- Zeroing in on fertility programs that accurately reflect the nutrient needs of top-yielding soybean crops – including the development of a realistic view of how much nitrogen a high-yielding soybean plant can utilize;

- Protecting the plant and its foliage, adopting the proper strategies to protect against disease and insects that stress a plant and alleviate stress in general.
- Continuing to fine-tune plant population recommendations based on varietal characteristics, soils, tillage systems and other management considerations;
- Understanding hormonal activity in the plant that governs flowering, pod set, abortion and fill;
- Comparing an array of fertilizer and growth regulator products, applications and timings to turn "spray and pray" programs into finely tuned management strategies;
- Digging into the mechanisms by which crop protection products such as Headline and Cobra or Blazer may help improve plant performance;
- Breeding for plants whose architecture and high rates of pod set and retention help maximize yield potential; and
- Sharpening recommendations for lime application on acid soils.

In addition to setting the course for new avenues of research, we must gather researchers together to explore such basic challenges as study design. Many of the topics we have discussed in this paper are complex interactions among plants and several factors in their environments. Isolating the key variables is vitally important, and may require insight from specialists in plant hormone physiology, crop science, molecular biology, microbiology, analytical chemistry and other disciplines simply to develop appropriate protocols for study and replication.

In the meantime, growers can adopt practices that may help increase pod number, too, including:

- Planting in early May or even, when conditions permit, in April;
- Protecting their soybean crops from stresses such as insect feeding, disease, nutrient deficiency, and where irrigation is available, drought stress;
- Experimenting with more aggressive fertility programs, helping their soybeans not only "get by," but thrive on enough N, P, K and micronutrients to be all they can be.

Asked about his record-breaking yields, Kip Cullers said, "The biggest thing for me is continually trying new things" (pers. comm., 2011).

Over nearly a century, public research has turned soybeans from an exotic Asian vegetable into a mainstay of crop production on millions of acres of American farmland. But our knowledge base is slipping farther and farther out of date, and the soybean research agenda in many university and federal labs appears to be stalled. To break free of our slow rate of yield increase and jolt productivity, we need to spark innovation in research. Perhaps the spark will inspire university programs. Perhaps it will find fuel among innovative crop consultants and private industry researchers who will match the quest for science with entrepreneurial enthusiasm.

The Illinois Soybean Association is at an exciting and vital crossroads. We have a mission: to ensure Illinois soy is the highest quality, most dependable, sustainable and competitive in the global marketplace. We have a membership and a customer base that is relying on us to find ways to increase yields. We have the resources to direct research beyond the well-trodden paths of past and present efforts – we can fund efforts to answer the many questions surrounding improved pod number.

As crop consultant Dave Mowers pointed out, “Some of this stuff is foo-foo dust and some of it has real merit. We have to sort through what is junk and what is really working.”

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