Grain yield is the product of the season-long development of the four individual components of yield.

- Plants per acre
- Ears per plant
- Kernels per ear
- Weight per kernel

Optimizing yield requires optimizing each component.
The story begins with germination, emergence, & stand establishment...

Season-long development of yield components

The success or failure of stand establishment largely determines the final harvest population... unless you replant.

Health & uniformity of the stand by V6 has large impact on future potential growth rates & tolerance to stress.

Next, ear size determination...

Season-long development of yield components

Minimal stress from ~V6 to ~V14 enables good potential ear size; i.e., # of ovules
Then, pollination & kernel set…

Silk+Pollen “nick” is crucial, especially for silks from upper ovules on ears. Post-silk stress leads to kernel abortion.

Source of graphic: Nielsen’s imagination
Image © RL Nielsen, Purdue Univ

Grain filling completes the story…

Minimal late-season stress enables maximum deposition of dry matter (starch) in the developing kernels, but earlier growth rates may determine max. potential kernel weight.

Source of graphic: Nielsen’s imagination
Image © RL Nielsen, Purdue Univ
Kernel black layer closes the book

Season-long development of yield components

- Productive # of plants
- Potential # of rows & kernels per row
- Actual # of kernels per ear
- Dry weight per kernel
- Physiol. maturity
- Germ. and emergence
- Stand establishment
- Ear size determination
- Success of pollination
- Kernel survival
- Grain filling
- Kernel black layer

Season-long risk of plant mortality and, thus, loss of harvestable plant population

Because yield is the product of the season-long development of the individual components of yield...

...achieving high yield requires minimizing stress all season long.
Effects of Stress on Corn

GERMINATION, EMERGENCE, AND STAND ESTABLISHMENT
Germination & Emergence (G&E)

- Seeds **imbibe** water within the first 24 to 36 hrs after planting into moist soil, which renews the cellular activity of the embryo (germination).
- Emergence of the embryo through the seed coat occurs in a distinct visual sequence.

~ 35 GDD after planting

Radicle root ruptures through the seed coat near the tip end of kernel, effectively creating an open entry for pathogens. Important consideration when G & E occurs slowly.

How many days to acquire 35 GDDs?
GDD Calculation for Corn

- “Modified 86/50 Cutoff Method”
  - Daily average temperature minus 50
  - Calculation of “average” includes limits:
    - Daily high temperature no greater than 86F
    - Daily low temperature no less than 50F
  - Example based on 60F high and 45F low
    - \[ \frac{(60 + 50)}{2} - 50 = 5 \text{ GDD for the day} \]
  - About 82 GDDs per leaf collar from VE to V10
  - After that, about 50 GDDs per leaf collar

Remainder of embryo also enlarging

- Mesocotyl & coleoptile
- Coleoptile encases the PLUMULE (4 or 5 embryonic leaves + apical meristem)
- Radicle root
~ 60 GDD after planting

Mesocotyl & coleoptile clearly visible

~ 70 GDD after planting

Mesocotyl & coleoptile

Lateral seminal roots are now visible
The mesocotyl...

- ... is the tubular, white, stem-like tissue that connects kernel and base of coleoptile or "crown".
  - Technically, is the first internode of the seedling.
- Elongation of the mesocotyl elevates the coleoptile toward the soil surface.

~ 100 GDD after planting

- Radicle root
- Coleoptile/plumule
- Mesocotyl
- Lateral seminal roots
- Not quite at VE
~ 115 GDD after planting

Growth stage VE: Emergence

- 1st true leaf emerging from coleoptile
- Mesocotyl
- Radicle root
- Lateral seminal roots
- Coleoptile

Image © RL Nielsen, Purdue Univ
Rapid germination & emergence…

- …shortens the calendar “window of vulnerability” to stresses prior to stand establishment.
- Rapidly developing seedlings are more “resilient” to stress than slower “stragglers”.

Soil temperature is the driver

- Seedling emergence occurs ~ 115 growing degree days (GDDs) after planting.
  - The number of GDDs to emergence is fairly consistent, especially when based on soil temperature, unless other stresses exist.
- For corn to emerge 7 days after planting requires AVERAGE daily soil temperatures during that time period no less than 66F.
Variable seedbed temperatures result in variable Germination & Emergence

- Variable seedbed temperatures can result from variable…
  - Soil color and texture.
  - Seedbed moisture.
  - Seeding depths.
  - Distribution of surface trash in no-till systems.

Especially important when soil temperatures are only hovering around 50F (10C).
Variable G & E can lower yields

- Young plants 2 or more leaves behind in development cannot compete with older, more established plants once the latter begin their rapid growth phase ~ V6 stage.
- If the “effective” population is reduced below the agronomic optimum, yield loss will occur relative to the “stand loss”.

Manage the risks of cool soils

- Avoid planting early in fields with poor drainage and/or high residue (slower to warm).
- Avoid using less than optimum seed quality.
- Hedge bets by avoiding extremely small seed lots (80,000 kernel bags weighing less than about 40 lbs).
- Consider “extra” seed treatments, though limited data to say with certainty.
Chilling injury

- In addition to simply slowing the physiological processes, soil temperatures lower than 50F can cause outright injury.
  - Imbibitional chilling injury to the embryonic tissue that arrests germination.
  - Chilling injury to the exterior surfaces of the mesocotyl that interferes with normal elongation during emergence.

Imbibitional chilling injury

- Seeds swell in response to imbibition.
- Under cool temperatures, cell walls become less elastic...
- Can rupture or tear with swelling...
- Causing irreversible physiological damage.

Photo courtesy of J Nagel, CERES Solutions
Imbibitional chilling injury

One consequence is simply arrested development. (image taken 3 wks after mid-April planting)

Cold temperatures during emergence can cause Corkscrews & Curly Q’s

Caused by chilling injury to surface layers of the mesocotyl, but occurring unevenly around the circumference.
Example of full corkscrew symptom

Seedbed moisture for G & E

- Kernels need to imbibe enough soil moisture to bring seed moisture content to about 30% on fresh weight basis.
- Optimum soil moisture for germination generally considered to be field capacity.
  - Excessively dry soils → Inert seed
  - Excessively wet soils → Inert seed and, eventually, death of embryo
Uneven G & E due to variable soil wetness

26 May, 16-20 days after planting

Causes of uneven seedbed moisture...

- Soil variability for texture and natural or artificial drainage.
- Soil drying patterns due to soil compaction.
- Uneven distribution of surface trash in no-till systems.
- Uneven seeding depth.
Good seed-2-soil contact facilitates the initial imbibition of moisture by the kernels

- Poor substitutes...
  - Seed-to-residue
  - Seed-to-rock
  - Seed-to-clod

Variable seed-to-soil contact...

- Rough, cloddy seedbeds.
- Uneven distrib. of surface trash in no-till.
- “Hairpinning” of surface trash into furrow.
- Coulters set deeper than seed placement.
- Incorrect furrow opener adjustment.
- Incorrect furrow closer adjustment.
- Excessively fast planting speed.
Delayed or failed emergence

Can occur when surface crusts or clods physically impede emergence of the coleoptile (spike)

Symptom looks similar to chilling injury to the mesocotyl, but was due to something else...

...Compacted, smeared, seed furrow caused by planting in soils that were “a bit on the wet side”
Recognize that successful emergence is not the same thing as successful stand establishment.

The success of stand establishment is determined by the success of the initial establishment of the nodal root system AND the transition of the young plants from reliance on kernel reserves to reliance on the nodal root system.

Until nodal roots are well established…

- Seedlings depend primarily on the energy reserves of the kernel, translocated through the connecting mesocotyl “pipeline” to the young stalk and leaves.
  - Therefore, a healthy kernel, seed roots, and mesocotyl are absolutely vital until the nodal roots are well established by about V6.
Damage to kernel or mesocotyl...

- Up to about V3, will kill seedlings.
- From about V3 to about V6, will stunt seedlings but usually not kill them.
- After about V6, will have little to no effect.

Understanding this helps you determine the approximate time period when stress occurred in a field, which then may help you identify the cause of a stand problem you are investigating.

Seminal (seed) roots originate from a node located within the embryo

- Consist of radicle root + lateral seminal roots
- Anchor the seedling
- Minimal uptake of water & nutrients
- Cease new growth shortly after seedling emergence
The “other” root system...

- **Nodal roots** originate from axillary meristems at each of the stalk nodes.
  - The individual “whorls” of nodal roots develop sequentially & acropetally over time.
  - One set or “whorl” of roots develops from every below-ground stalk node plus 1 or more above ground stalk nodes (brace roots).

---

Nodal Roots at VE (emergence)

Nodal roots begin elongating from 1st node shortly after seedling emergence.
Nodal Roots at V2

Three to four roots from Node #1 are visible by the V2 or 2-leaf collar stage.

Roots & their environment

- Roots develop downward naturally… Why?
- Roots will develop wherever growing conditions are conducive.
  - Favorable temperature
  - Favorable moisture
  - Adequate soil nutrients / pH
  - Absence of physical limitations

Image source: www.sciencefun.org
Effects of Stress on Corn

Roots exposed at the soil surface.
Why?

Drier surface soil = More oxygen

Growing point of a root is located near the end of the root, just behind the root cap

Axillary meristems eventually develop along the length of the root that facilitate root branching.

Image © RL Nielsen, Purdue Univ

© Purdue Univ
Desiccated & dead nodal roots

Excessively dry and/or hot soils during initial elongation of nodal roots.

Nodal Root Morphology

Nodal Roots in Corn
Relative positions of nodal roots and their respective nodes...

Roots can develop from higher nodes...

In this example, a result of hormonal changes in response to root lodged stalk angle.
Seedlings “wean” themselves…

...from reliance on kernel reserves for sustenance to increasing reliance on nodal roots beginning at about V3.

A true transition period

- Success or failure largely determines whether stand establishment will end with a healthy, vigorous, uniform stand of corn or a crappy™ stand of corn.
- Subsequently influences how well the crop will tolerate stresses later in the growing season and, thus, can have major bearing on yield potential.
Traditional 2x2 starter fertilizer...

- ...is a form of “crop insurance” and can aid young corn plants when they struggle to “wean” themselves from the kernel reserves to the nodal roots.
  - Yield response admittedly does not always occur.
  - When no yield benefit, crop still uses the nutrients and cost per bushel remains the same.
  - Grain is often drier at harvest and so fewer $$ are spent on post-harvest grain drying.

Nodal root development

In the absence of severe stress, nodal roots will be well-established by the 6-leaf collar stage and the plant will have completely “weaned” itself from support from the kernel reserves.
Successful stand establishment relies on...

- Excellent seed quality
  - Germination ratings
- Excellent genetic seedling vigor
  - Company ratings
- Seed protection from insects or diseases
  - Seed treatments
- Seedbed and soil free of crust or compaction
- Adequate soil nutrients
  - Starter fertilizer (esp N)
- Error-free seeding
  - Planter maintenance
  - Planter adjustments
  - Planting speed
- Adequate & uniform
  - Soil temperatures
  - Soil moisture
  - Seed-soil contact

"The sins of planting will haunt you all season."

Ozzie Luetkemeier, former superintendent of the Purdue Agronomy Farm
Effects of Stress on Corn

Yield components develop all season long

Ear size determination

Stand establishment
Pollination & kernel set
Grain fill period

Potential # of rows & kernels per row

Productive # of plants

Germ. and emergence
Stand establishment
Ear size determination

Sources of graphic: Nielsen's imagination
Image source: Somewhere on the Internet

© Purdue Univ
Coincides with rapid growth phase

Shortly after V5, a healthy corn field “turns the corner” and seemingly overnight its growth begins to accelerate as it enters the rapid growth phase (RGP).

- Above ground
- Below ground
- Repproductively

Miller et al., M.S. thesis, Purdue Univ. 2010, NW Indiana
The start of the RGP “race”…

… coincides with the differentiation of the tassel initial from the apical meristem of the stalk AND the differentiation of the uppermost (harvestable) ear initial from its axillary meristem at about V5.

… and is driven by hormonal changes in the plant that encourage rapid growth.
Meristems = “Growing points”

- Physiologically active regions where cell division & cell differentiation occur.
- The shoot apical meristem (SAM) in corn initiates...
  - Primordia for all the leaves except the 4 – 5 preformed leaves in the embryo.
  - Following initiation of the final leaf primordium, the apical meristem initiates the tassel primordium.

Initially, GP is located below ground

Very late V1 to very early V2 seedling

Crown of plant about 3/4 inch below surface

Growing point region
While the GP is below ground…

- ...it is relatively impervious to above-ground damage to the plant.
  - Hail, insect feeding, frost, UAN burn, etc.

While the GP is below ground…

...is vulnerable to below-ground damage from soggy soils, disease, insects, lethal cold temperatures, pounding hail stones, etc.
Stalk elongation begins ~ V4

- Prior to about V4, very little elongation of the stalk tissue occurs.
  - During this time, the above-ground “stem” consists of visible leaves and rolled-up leaves.

Split stalk of V6 plant

- Is the “growing point” label on this image technically correct?
- By V6, elongation of stalk internodes has elevated stalk sections and tassel above the soil surface.
As internode elongation continues, the stalk nodes or “joints” become increasingly visible.

- As do the elongating internode sections.

The top of the stalk tissue is about 9 inches above the soil surface in this V9 image >>>

- About 7.5 inches of stalk elongation during two leaf stages of development.
Axillary meristems...

- ...are initiated acropetally, one per stalk node, in an alternating fashion, beginning at the lowermost stalk node and finishing at about the 7th stalk node below the tassel.
  - Beginning shortly after emergence and ending around the V5 stage of development.

Axillary meristems differentiate into either tillers or ears, depending on hybrid genetics and/or hormone activity

- Tiller differentiation tends to occur at the lowermost axillary meristems.
- Ear differentiation tends to occur at the uppermost axillary meristems.
- Tiller vs. ear is indistinguishable to the naked eye at early stages of development.
Tillers / ears are located…

- behind the base of their respective leaf sheaths and can be found even at the lowermost nodes below ground.
  - Remember, the first 4 nodes comprise the triangle of pithy stalk tissue.
  - The #5 node is also usually below ground.

Remember; tillers vs ear shoots essentially indistinguishable to naked eye at early stages.
Ear shoot “seniority”

- Ear primordia are formed at multiple stalk nodes, but the upper one or two ear shoots eventually take priority because...
  - Of their closer proximity to the uppermost active photosynthetic leaves of the plant.
  - Hormonal apical dominance expressed by the uppermost ears on the lower ones.
  - Damage to an uppermost ear can “allow” lower ear shoots to develop more aggressively.

Tassel & upper ear are linked...

- The uppermost, harvestable, ear is initiated around V5 at the same time that the tassel is initiated at the apical meristem (Lejeune & Bernier, 1996).
  - No further ears are initiated at upper nodes after the tassel initiates (apical dominance).
  - For typical central Corn Belt hybrid maturities, the node # of the uppermost ear ranges from #11 through #14 on the stalk.
An elegant article on ear development.
- “An organism matures through a series of sequential steps ordered by the genetic complement.”
- “The succession of stages in development can be diverted by hormones, surgery, control of nutrition, and by light and temperature.”

Interpretation: Severe stress can screw up the process.
Meristems initiate leaves

The vegetative meristem (vm) of the main stalk or the ear shank differentiates into leaf primordia (lp) that develop into leaves on the main stalk or husk leaves on the ear shank.


Tassel forms at apical meristem
Ears form at axillary meristems

Following initiation of the final husk leaf, the vegetative meristem transitions to become the ear meristem (em) with longitudinal rows of branch primordia (bp) that differentiate acropetally.
Branch vs. spikelet primordia

- Each branch primordium differentiates into paired spikelet primordia (sp).
- Each individual spikelet primordium has its own spikelet meristem (sm) that initiates two glume primordia (g) and then ultimately initiates an ovule.

Interesting trivia

The fact that each branch primordium eventually differentiates into two spikelet primordia explains why kernel row number on an ear of corn is always an even number.
Potential ear size is determined during the rapid growth phase

- Maximum row number is “set” no later than V8 (Strachan, 2004).
  - Row number is influenced more by the hybrid’s genetics than by growing conditions.
- Maximum ovule number per row is determined by at least V15, perhaps as early as V12 (Strachan, 2004).
  - Ovule number per row is influenced less by genetics and so is influenced more easily by growing conditions.
Not much to look at…

- By V9 (about thigh-high), the uppermost ear shoots and the tassel can be easily dissected.
  - Fraction of an inch long.
  - Visible tassel branches.
  - Ears are mostly husk leaves at this point, yet cob length is about half-way complete.

Severe stress during RGP…

- ...can directly reduce yield potential by limiting the potential number of kernels (ovules) on the developing ears (no. of rows or no. of ovules per row).
  - Although, our research suggests that ovule formation appears to be amazingly resilient to stress from factors like severe N deficiency and excessively high plant populations.
Perhaps more importantly...

- Severe stress during RGP can indirectly reduce yield potential by stunting the potential size of the photosynthetic “factory” prior to pollination and thus limiting the potential photosynthate output during pollination and grain filling.
  - Incomplete pollination success
  - Abortion of young kernels
  - Low kernel weights

So, certainly makes sense...

...to minimize the risk of severe stress during the rapid growth phase that would significantly decrease photosynthesis.

- Excessively wet or dry soils
- Significant competition with weeds
- Root-limiting soil compaction
- Significant nutrient deficiency
- Significant herbicide injury
Corn leaves change during RGP

Prior to the RGP, corn plants are light green and have dull leaf surfaces.

Once Rapid Growth Period begins

Leaves become darker green and shiny.
Impact of dull to shiny conversion

- From VE to ~ V4:
  - Cuticular leaf wax (leaf surface) is crystalline in nature... low spray retention... low leaf wettability... herbicide tends to run off leaves.

- Shortly after RGP begins...
  - Cuticular leaf wax changes to a smoother nature... greater spray retention... greater leaf wettability... greater risk of herbicide absorption into corn leaves.


The RGP is a sensitive time period

- Young, developing ear shoots are physiologically & hormonally very active.
- Herbicides often naturally “move” towards physiologically active meristematic areas.
- Herbicides and/or additives may penetrate upper husk leaf tissue & physically contact the ear shoots (e.g., arrested ears & NiS).
Pinched ear example

Steadfast ATZ (nicosulfuron, rimsulfuron, atrazine) applied to abt V10 – V11 corn (label restriction at the time was V6 or 20 inches tall)

Arrested ear examples

Status, Durango, AMS, Array (drift control), Fraction (acidifier), and NIS applied w/ 18-inch drops to shoulder-high corn. From 30-40% affected plants.
Many RoundupReady™ hybrids are heterozygous dominant (Rr) for the trait. 

25% of the embryos of the fertilized ovules expected to be susceptible to glyphosate.
Jumbled kernel symptom

AKA “bubble” kernel symptom caused by death of embryo, while endosperm & maternal seed coat remain alive.

Glyphosate + AMS applied with drop nozzles to head-high RoundupReady™ corn. EVERY SINGLE EAR in this field was affected. Yield loss was 25% at the minimum.

To summarize…

- The uppermost ear forms ~ V5 at the same time that the tassel is initiated.
- Max. row # is determined no later than V8.
- Max. ovule # per row determined by at least V15, perhaps as early as V12.
- Many herbicide labels restrict app’s after certain leaf stages because of the risk of physiological damage to developing ears.
Next, pollination & kernel set…

Yield components develop all season long

Productive # of plants
Germ. and emergence
Stand establishment
Ear size determination
Potential # of rows & kernels per row
Success of pollination
Actual # of kernels per ear
Kernel survival

V6
V14
R3
R5

Source of graphic: Nielsen's imagination
A review of corny sex...

Gravity, wind or human effort transports the pollen to the silks to eventually fertilize the ovules.

Pollen produced in the tassel anthers contains the male genetic material.

Ovules produced on the ears contain the female genetic material.

R1 – Silking stage

- Silks typically emerge in close synchrony with pollen shed from tassels.
- First silks to emerge are typically those from basal third of the cob.
- Silks are most receptive to pollen during the first four days of exposure.
Female flowers of corn…

- Every ovule (potential kernel) on the cob develops a single silk (functional style of the female flower).
  - Approx. 800 to 1000 ovules per ear.
  - Usually 400 to 600 develop into harvestable kernels.

Silk emergence timing

- Basal (butt-end) silks typically develop & emerge first and apical (tip-end) silks develop and emerge later.
  - Tip silks usually pollinated last; younger tip kernels are more susceptible to abortion under stress.
Pollen capture by silks...

- Pollen grains are “captured” by the small “hairs” or trichomes located along the entire length of the exposed silks.
  - Survival of the “fastest” determines which one fertilizes the ovary.

Pollen & silks...

- A pollen grain germinates within 30 minutes after landing on receptive silk,
- A pollen tube (containing male sperm cells) develops and penetrates the silk,
- The pollen tube elongates the length of the silk within 24 hours and fertilizes the egg & endosperm of the ovary.
Pregnancy Test for Corn

- The base of a silk collapses a few days after successful fertilization of the ovary and detaches from the developing kernel.
- Pollination success can be estimated by % of silks detached.

Silks elongate until...

- ...they are pollinated or until they deteriorate with age.
- Emerged silks initially lengthen from 1 to 2 inches per day, but then slow over the next few days due to natural aging or the inhibition caused by "captured" pollen grains as they germinate and initiate pollen tubes that penetrate the silk and elongate toward the ovule.
If not pollinated early on…

- Silks may become quite long.
- Earliest emerging silks may deteriorate and become non-receptive to pollen; resulting in “blanks” on the cob.
- Later emerging silks may “shade” earlier emerging silks from pollen; resulting in “blanks” on the cob.

Symptoms of long silks…

Typical Silk Length

Unusually Long Silks
Symptoms of long silks…

Unusually long silks. Why?

- Drought stress commonly delays silk emergence & hastens pollen shed.
- Cool temperatures & ample soil moisture favor prolonged rapid silk elongation.
- With some hybrids, silk emergence seems to occur 1 to 4 days prior to pollen shed.
  - An unintended consequence of genetic selection for drought resistance (aggressive silking).
Male flowers of corn…

A single tassel produces about 6,000 pollen-bearing anthers.

Male flowers of corn…

About 1000 spikelets form, in pairs, along the length of the tassel.
Male flowers of corn…

Two florets form per spikelet.

Male flowers of corn…

Three anthers form per floret, total of six anthers per spikelet.
Corn pollen is nearly microscopic, spherical, yellowish or whitish translucent.

Anthers & pollen shed...

- Anthers first appear & shed pollen from the middle of the central tassel spike.
- Then, slowly over the remainder of the tassel & its branches over about a 7 day period.
- Whole field takes 10 to 14 days to shed all of its pollen due to plant-to-plant variability for development.
Pollen dispersal...

Anthers exsert from the florets of the tassel in the early morning hours.

- As the humidity drops & temperature rises, small pores develop at the tips of the anthers and pollen disperses into the air.
  - aka “Poricidal dehiscence”
  - Pollen dispersal occurs mostly by gravity & wind, but also by virtue of...
    - Insect movement
    - Plant breeders, agronomists
    - Crop scouts, Field inspectors

The rate of pollen shed...

- Usually peaks by mid-morning, then tapers off in the afternoon as temperatures rise.
- Once dispersed, pollen grains may remain viable for 1 to 2 hrs before they desiccate and collapse.

Estimates of total pollen production from single tassel range from 2 to 25 million pollen grains.
Silks deteriorate over time…

Kernel set w/ 1-day abstinence
Kernel set w/ 2-day abstinence

No Pollen First 2 Days of Silks
(Full Pollen Availability Thereafter)

Kernel set w/ 3-day abstinence

No Pollen First 3 Days of Silks
(Full Pollen Availability Thereafter)
Kernel set w/ 4-day abstinence

No Pollen First 4 Days of Silks
(Full Pollen Availability Thereafter)

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Kernel set w/ 5-day abstinence

No Pollen First 5 Days of Silks
(Full Pollen Availability Thereafter)

© 2006, IL Nielsen, Purdue Univ.
Kernel set w/ 7-day abstinence

No Pollen First 7 Days of Silks
(Full Pollen Availability Thereafter)

Pollen & silks “mate” quickly...

Silk Bag Placed Over Ear Shoot to Protect Silks from Pollen Capture
Kernel set w/ 1 day of pollen

Kernel set w/ 2 days of pollen
Kernel set w/ 3 days of pollen

Kernel set w/ 4 days of pollen
So, flowering is THE critical period for determining grain yield

- More yield potential can be lost per day of severe stress during pollination than any other developmental period.
- Drought + heat are especially deadly during pollination.
Pollination can fail due to…

- Persistent silk clipping by insects.
- Silk emergence delay due to drought stress.
- Desiccation of exposed silks due to heat & low humidity.
- Photosynthetic stress in general.
- Herbicide injury to the developing ovules or tassel.
- Unavailability of pollen.
- Silk “balling”.
- Old age.
Minimal stress during pollination

- Ensures successful ovule fertilization and maximum kernel set
- Minimizes risk of kernel abortion

Favorable conditions for pollination

- Minimal stress from moisture deficits.
  - Stored soil moisture
  - Rainfall or irrigation
  - Moisture conservation by zero tillage
- Moderate day/night temperatures (86/64F).
- Plenty of solar radiation.
- Minimal interference of pollination by silk clipping insects.
- Rooting profile free of soil compaction or other rooting restrictions.
- Healthy crop canopy capable of intercepting 95% or more solar radiation.
Grain filling completes the story…

Yield components develop all season long

- Productive # of plants
- Potential # of rows & kernels per row
- Actual # of kernels per ear
- Dry weight per kernel
- Germ. and emergence
- Stand establishment
- Ear size determination
- Success of pollination
- Kernel survival
- Grain filling
Grain Filling Period

- Technically begins with silk emergence and ends at physiological maturity.
  - Silking (R1)
  - Blister kernel (R2)
  - Milk kernel (R3)
  - Dough kernel (R4)
  - Dent kernel (R5)
  - Physiological maturity (R6)

For much of Indiana, R6 (maturity) occurs approximately 60 days after silking.

The grain filling sequence…

- Begins with embryo development.
  - Including oil, protein
- Finishes with endosperm development.
  - Starch (dry matter)
Optimal grain fill requires…

- a photosynthetic plant “factory” capable of “harvesting” no less than 95% of available sunlight during grain fill.
  - Possible ½ to ¾ percent yield increase for each percentage point increase in sunlight capture up to about 95% capture.
    - (Andrade et al., 2002)

Maintaining canopy health…

- throughout grain filling is important to maintain the necessary photosynthetic output to maximize both kernel survival and kernel dry weight.
  - Plant nutrition, diseases, insects, temperature, soil moisture.
Temperature during grain fill...

- Affects the length of entire grain fill period.
  - Warm = shorter (fewer days) grain fill period.
  - Cool = longer grain fill period. **Desirable**

- Affects daily rate of photosynthetic output.
  - Warm = More carb’s per day. **Desirable**
  - Cool = Fewer carb’s per day.

The overall balance favors cool grain fill periods for optimizing grain yields.
Windshield surveys…

- May help spot problems in the field early in the season, but cannot easily assess kernel set success early in the grain fill period.
- Kernel set failure occurs from a combination of:
  - Pollination problems
  - Kernel abortion during grain fill

R2 – Blister kernel stage

- About 10 to 12 days after silking begins, the fertilized ovules develop into “blisters” filled with clear sugary fluid.
- By the end of R2, the embryonic radicle root, coleoptile, and 1st leaf have formed.
- Kernel moisture content at beginning of R2 is about 85%.
- Severe stress can easily abort R2 kernels.
The so-called “brown silk” stage referenced by fungicide application recommendations.

Clear sugary fluids from cut kernel. Growth stage early R2 (blister).
R3 – Milk kernel stage

- About 18 to 20 days after silking, the developing kernels are mostly yellow and contain milky white sugary fluid.
- Kernel moisture content at the beginning of R3 is about 80%.
- Severe stress can still cause kernel abortion.
Kernel abortion

- Kernels can abort in response to severe stress during blister and early milk stages of kernel development.
- Symptoms are shrunken, white or yellow kernels, often with a visible yellow embryo.
Causes of kernel abortion?

- Primarily severe photosynthesis problems
  - Severe heat or drought
  - Severe nutrient deficiency
  - Severe leaf disease
  - Leaf loss due to hail
  - Severe ECB stalk tunneling
  - Excessively warm nights during or shortly after pollination
  - Consecutive cloudy days during or shortly after pollination

Most commonly occurs at tip…

Youngest kernels are most susceptible to abortion.
R4 – Dough kernel stage

- About 24 to 26 days after silking, continued starch accumulation in the endosperm creates a doughy consistency to the kernels.
- Embryo development is nearly complete.
- Kernels are ~ 50% of mature dry weight.
- Kernel moisture content at beginning of R4 is about 70%.
R4 – Dough kernel stage

Risk of kernel abortion decreases once kernels have reached early dough stage.

Subsequent severe photosynthetic stress late in the season decreases yield by decreasing kernel dry weight (primarily starch).

- Drought & heat
- Corn borer damage
- Hail defoliation
- Disease defoliation
- Stalk rots
- Early killing frost
R5 – Dent kernel stage

- About 31 to 33 days after silking, nearly all kernels are denting near their crowns.
- Embryo development is complete.
- Dry matter content ~ 45% of mature at beginning of R5 and 88% of mature by late dent (half-milkline).
- Kernel moisture content ~ 60% at early dent stage and ~ 40% by half-milkline.
By about mid-R5, the kernel “milkline” becomes visible near the dent end as sugary fluids convert to solid starch and progresses “down” over time.

The “half-milkline” stage of kernel development occurs approximately 250 GDD or about 10 to 14 days prior to physiological maturity.

- Grain moisture content ~ 40%
Kernel milkline

Mid R5 (Dent) Stage
(38 days after silking)

Kernel milkline 1/4 to 1/3 of way “down” from dent end of kernel

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Kernel milkline

Mid R5 (Dent) Stage
(38 days after silking)

Placentals cells beginning to discolor

Endoosperm

Embryo

© Purdue Univ, R.L. Nielsen
Kernel milkline

Late R5 (Dent) Stage
(56 days after silking)

Kernel milkline is beginning to "disappear" into glumes

© 2007 Purdue Univ, RL Meinem

Kernel milkline

Late R5 (Dent) Stage
(56 days after silking)

Placental cell layers discolored and noticeably thinner

Endosperm
Embryo

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Premature plant death

- Severity of yield loss depends on timing and extent of death.
  - If only leaf death (e.g., light frost)...
    - Plant may be capable of remobilizing stored carbohydrates from stalk tissue to the immature ear.
  - If whole plant death (e.g., killing frost).
    - Remobilization not possible.
    - Kernel black layer soon forms.

Yield loss & timing of death

![Graph showing yield loss percentages for different stages of development and types of death.

Source: http://www.agcom.purdue.edu/AgCom/Pubs/NCH/NCH-57.html

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Grain fill stress & stalk rots

- Stress during grain fill impairs the ability of the photosynthetic “factory” to produce adequate amounts of carbohydrates to satisfy the plants’ carbohydrate needs.
  - Cell maintenance & repair throughout the plant, including the root system.
  - Kernel development.

Carbohydrate availability

- Physiologically, kernel development takes priority over all the maintenance needs of the plants (i.e., kernel development is a strong physiological “sink”).
- Under severe photosynthetic stress, plants will remobilize stored carbohydrates from lower stalk and leaf tissue and send them to the developing ear.
Opens the door for rots…

- The combination of inadequate cell maintenance of root and lower stalk tissue; plus the additional reduction in carbohydrate levels due to remobilization not only compromises the integrity of the roots and stalk tissue, but lowers the natural resistance against the root and stalk rot fungi.

Remobilization, but little rot…
Remobilization and rot...

Photosynthetic stress & rots

Defoliated at R1 on 13 July
Defoliated at R3 on 27 July

Photos taken on 19 August
Grain fill stress & Kernel BL

Premature BL resulting from severe defoliation at R3.

Half-milkline stage on plants not stressed during grain fill.

Photos taken same day.

Kernel black layer = Physiological maturity

- The kernel BL effectively “closes the door” for any further movement of photosynthate into the kernel.
- Moisture at R6 averages 30% and ranges from 25 to 40%.
Kernel black layer always forms

- Kernel BL forms “on time” when grain fill occurs with minimal stress.
- Kernel BL forms prematurely when severe stress during grain fill causes early death of the plant (e.g., drought, leaf disease).
- Kernel BL eventually forms following lethal frost or freeze injury to immature corn plants.

Grain moisture loss occurs slowly throughout the entire grain filling period

<table>
<thead>
<tr>
<th>Stage</th>
<th>Grain moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R3</td>
<td>80%</td>
</tr>
<tr>
<td>R4</td>
<td>70%</td>
</tr>
<tr>
<td>R5</td>
<td>55%</td>
</tr>
<tr>
<td>Half-milkline</td>
<td>40%</td>
</tr>
</tbody>
</table>
Important drydown factors…

- Temperature, humidity, sunshine, wind.
- Consequently, calendar date of physiological maturity greatly influences rate of subsequent grain drydown.
- Hybrid characteristics…

Hybrid characteristics & drying

- Kernel pericarp characteristics
- Husk leaf number
- Husk leaf thickness
- Husk leaf senescence
- Husk coverage
- Husk tightness
- Ear declination

Grain moisture loss occurs primarily through the kernel pericarp; not through the pedicel and cob.
Examples of drydown rates

- **Yield**
- **Stand establishment**
- **Pollination & kernel set**
- **Grain fill period**
- **Ear size determination**
Herbicide label language…

- “Up to 20-inch corn”
- “Up to 6 collars”
- “30-inch or 8-leaf corn”
- “4 to 20-inch corn”
- “Up to V8 corn”
- “V1 to V6 stage”
- “Apply through layby stage”
- “Avoid spraying into the whorl or leaf axils”
Plant height restrictions

1. Large corn canopies intercept more of a broadcast-applied herbicide…

…targeted weeds intercept less…

…and so weed control will be less effective.

2. Greater interception of broadcast herbicide by a large corn canopy also increases the risk of herbicide injury to the corn crop.
Label Language Fuzziness

- Often, label language is not clear…
  - How plant height should be measured or
  - What is meant by a particular leaf stage.

Corn Plant Height

- Most agronomists agree that corn plant height = that of free-standing plants.
  - Height from the soil surface to the arch of the uppermost leaf that is at least 50% emerged from the whorl.

Herbicide Labels?
Usually not clear whether plant height refers to free-standing plants.
Leaf staging in corn

- Corn leaf staging is technically quite simple and straightforward.
- All it requires is the ability to correctly identify the parts of a leaf and the ability to count.

Leaf staging method...

[Image source: www.abacus.ca]

[Logo: https://www.iastate.edu/]

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Three distinct morphological leaf parts…

Leaf collar staging method…

...begins with the lowermost leaf that is shorter than the others and has a rounded tip.

Some uncertainty whether herbicide label growth stage definitions include 1st true leaf.
Leaf collar staging method…

…ends with the uppermost leaf with a visible leaf collar.

Staging older plants can be difficult once lower leaves have “disappeared”

Yet, even the missing lower leaves must be included.
Once stalk elongation begins to occur, individual stalk nodes become visible.

The first recognizable individual node on a split stalk is usually Node #5.
Once Node #5 is identified…

Identify the leaf sheath that connects to that node, then count upward to uppermost leaf with visible leaf collar to determine leaf stage.

The leaf stage for an entire field is equal to that of the majority of the individually staged plants.

E.g., if 51 of 100 sampled plants are V10, then the field is defined as V10.
Phenology can be Phrustrating

- From the perspective of herbicide label restrictions, how should one deal with variable leaf stages across a field?
  - Let’s say label restriction = “Apply up to V8”
  - If 15% of the sampled plants are V7 and 55% are V8 and 30% are V9, should you spray?

To spray or not to spray?

- Unofficial OISC response...
  - “No one has asked that question before, but the majority Vstage probably prevails.”

- Some industry colleagues’ responses…
  - Variable Vstages are more important than variable heights relative to label.
  - When was the field staged and when will the applicator arrive to spray?
  - Depends on corn sensitivity to chemical.
  - What is the cost of “being wrong”?
Monitor leaf stages by…

- Visiting fields regularly prior to herbicide applications to document leaf stages.
- Predicting leaf stages at your computer using dates of planting (or better yet, emergence) and accumulated numbers of Growing Degree Days (aka heat units).
- Generally about 82 GDDs per leaf collar appearance up to about V10.
- DISCLAIMER: Actual rate can vary among hybrids and growing conditions.

Online options to track leaf stage

- U2U Corn GDD$_{DST}$ tool
  - [http://mrcc.isws.illinois.edu/U2U/gdd/](http://mrcc.isws.illinois.edu/U2U/gdd/)
- Agrible’s Morning Farm Report®
  - [https://www.morningfarmreport.com](https://www.morningfarmreport.com)
- Others I’ve not personally used…
  - DuPont Pioneer Encirca… Yes
  - Becks FarmServer… GDDs, but no leaf stage
  - AgriReliant Genetics® Advantage Acre®?
  - Climate Fieldview™?