Wheat growth guide

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Contents

At-a-glance information on key terms (glossary), benchmarks and growth stages can be found on page 34.

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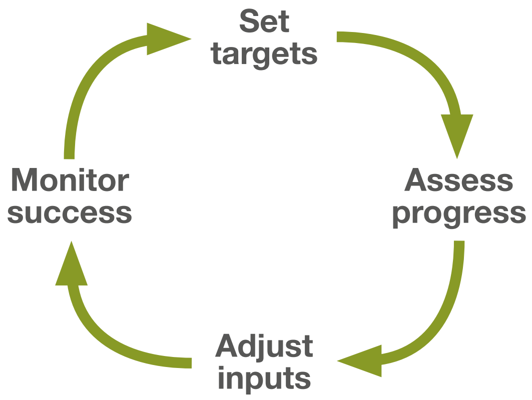
AHDB would like to thank ADAS for their contribution to this guide.

Introduction

This guide aims to support understanding and enhancement of wheat production through improved management.

The steps in any cycle of management are to:



Measurements are vital to good management and for learning. As well as assessing weeds, pests and diseases, crop managers must assess the crop itself. Crop progress, structure and final performance can then be compared with benchmarks or new targets.

A crop's growth best relates to the natural resources it captures. By knowing available resources, managers can tell whether better or worse than expected growth is due to weather or husbandry.

Crop assessments should be objective and, where possible, measured. This guide presents metrics by which production targets can be set and crop progress monitored. It also explains how the metrics interrelate and can be influenced.

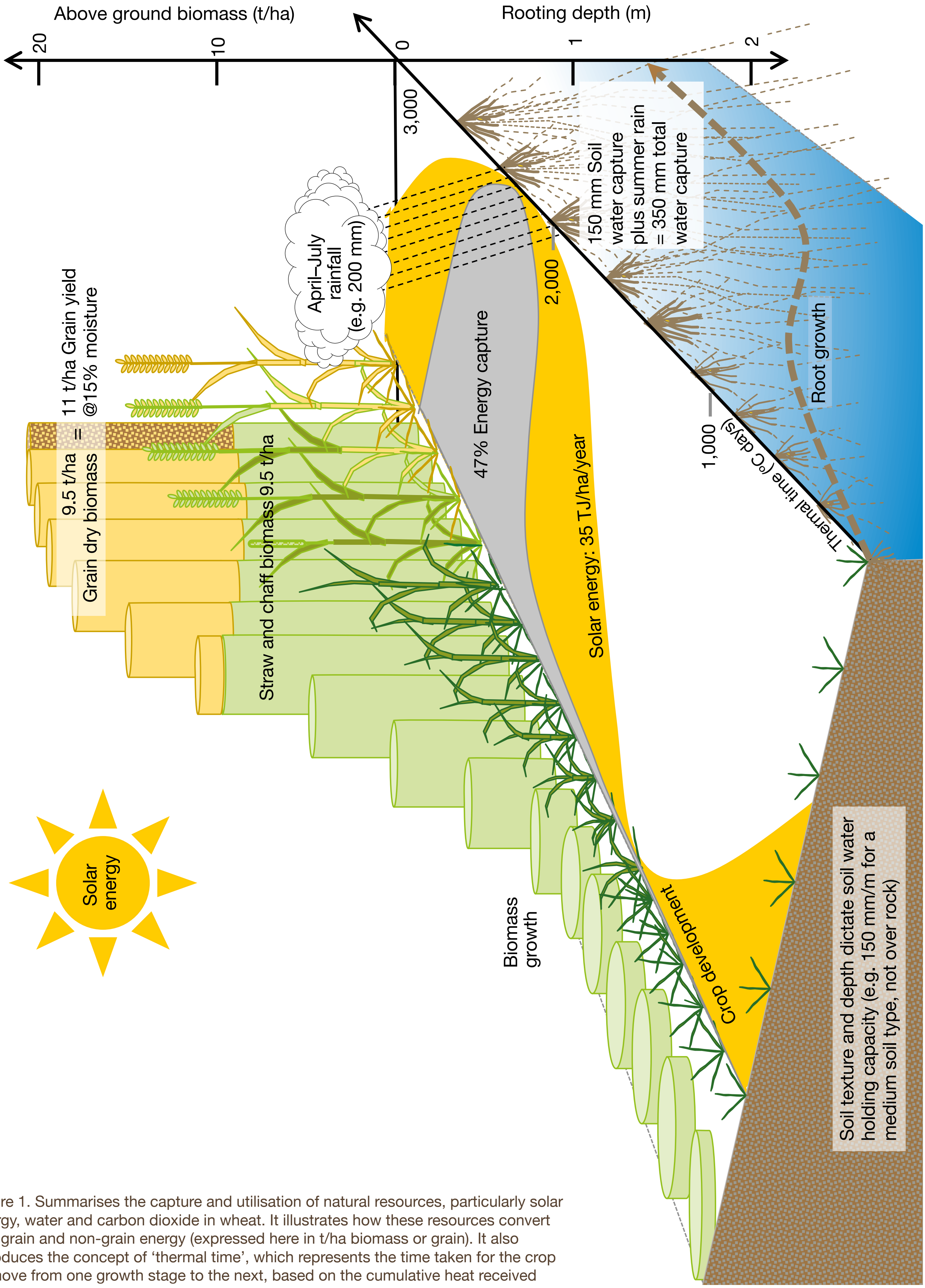


Figure 1. Summarises the capture and utilisation of natural resources, particularly solar energy, water and carbon dioxide in wheat. It illustrates how these resources convert into grain and non-grain energy (expressed here in t/ha biomass or grain). It also introduces the concept of 'thermal time', which represents the time taken for the crop to move from one growth stage to the next, based on the cumulative heat received

Source: ADAS

Managing wheat yields

Yield determination

Crops harvest energy – they convert natural resources (solar energy, carbon dioxide and water) into edible and other forms of energy. Water is required in proportion to the energy captured.

Cereal yields depend on the following:

- Available natural resources
- Their capture
- Their conversion to harvestable grain

If light is limiting

- Yield (t/ha) = Light energy (TJ/ha) x Capture (%) x Conversion (t/TJ) x Harvest Index

If water is limiting

- Yield (t/ha) = Available water* (mm) x Capture (%) x Conversion (t/ha/100 mm) x Harvest Index

*The sum of summer rainfall and soil-held water.

In the UK, light limitation of wheat yields is more common than water limitation. Water limitation becomes more common as yields increase.

Available natural resources cannot generally be controlled, so yields must be managed primarily through influencing their capture.

Light capture depends mainly on green canopy longevity. Each five extra days of full light capture by a green canopy should be associated with 1 t/ha of extra crop growth.

Water capture depends mainly on rooting depth. On a soil holding 15% available water, an increase in rooting depth of 14 cm should provide an extra 20 mm of water, which should support one extra t/ha of biomass growth.

The Harvest Index is the proportion of total crop biomass growth that is harvested as grain. The benchmark is 51% at harvest (Figure 2).

Grain biomass arises from all growth after flowering plus some biomass (proteins and sugars) transferred from the straw.

The Harvest Index is thought to be influenced more by variety choice than by husbandry.

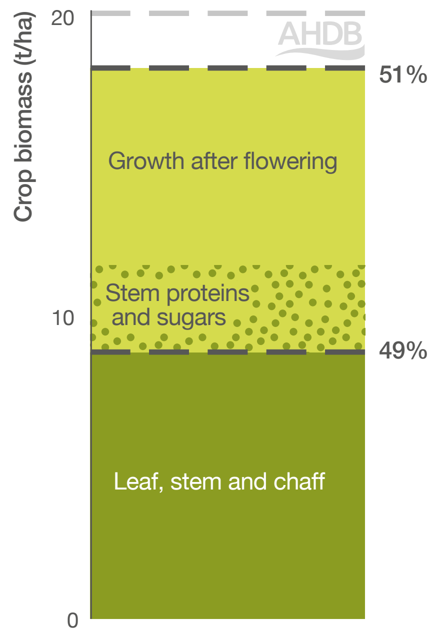


Figure 2. Crop biomass distribution in wheat (%)
Source: ADAS

Resource capture and conversion

Rates of energy absorption, carbon dioxide fixation and water transpiration by leaf canopies (Figure 3) are inherently linked, so light use, water use and biomass formation are roughly proportional.

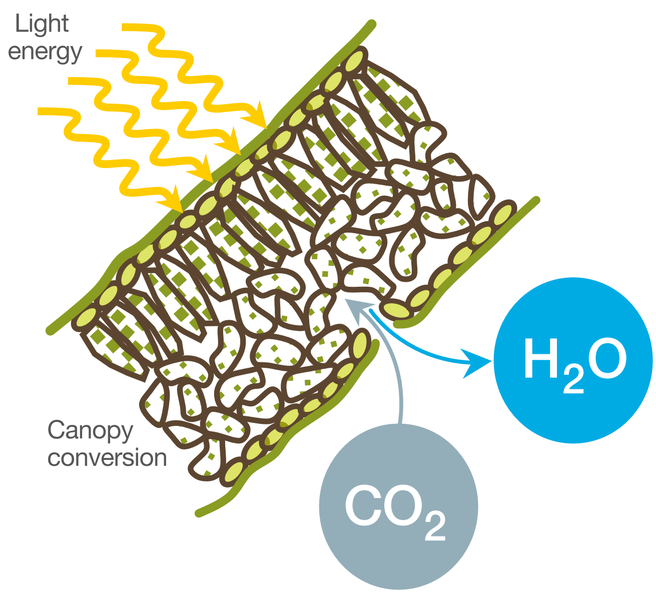


Figure 3. Canopy capture and conversion of natural resources
Source: ADAS

Benchmark rates of conversion by wheat canopies are 1.2 t biomass per terajoule (TJ) of energy intercepted and 5 t/ha biomass per 100 mm of water captured and transpired.

Resource conversion can be reduced if storage capacity for assimilate is insufficient (sink limitation) but this is not often the case in wheat, because grain is usually responsive to assimilate availability (source limitation).

Biomass production can be monitored to indicate the success of resource capture, based on these rates of conversion.

Resource conversion is thought to be influenced more by variety choice than by crop management.

Yield potential

Although the benchmark yield for UK wheat is 11 t/ha, potential grain yields could be as high as 20 t/ha. This higher figure is based on average resources available, season-long energy capture increased from 47 to 60% (Figure 4), its conversion increased to 1.4 t/TJ and Harvest Index increased from 51 to 60%.

New varieties and new agronomy practices must be developed and combined to achieve such yield potentials. The UK record grain yield achieved in 2015 of 16.5 t/ha shows the potential to push yields.

Energy capture can be increased mainly by delaying canopy senescence from seven to 10 days beyond the benchmark. Such canopies will often need an extra 100 mm soil water capture. So, depending on soil water-holding capacity, roots will need to reach 0.5–1.5 m deeper into the subsoil. Figure 5 shows typical soil water capture at different rooting depths.

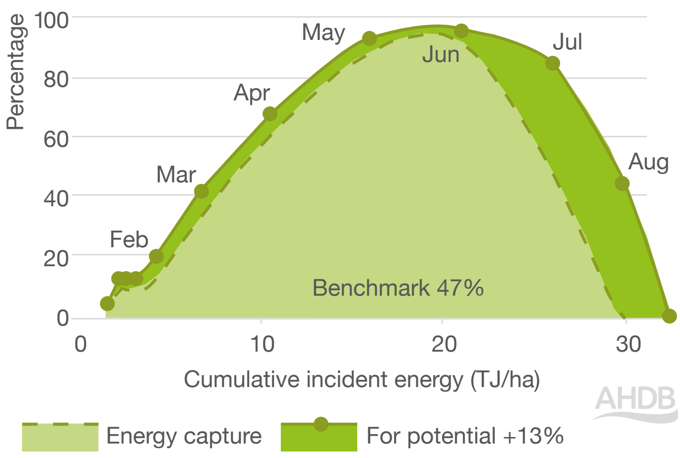


Figure 4. Typical solar energy capture by wheat crop grown in the UK. Potential to increase season-long energy capture to 60% (+13%) also shown

Source: ADAS

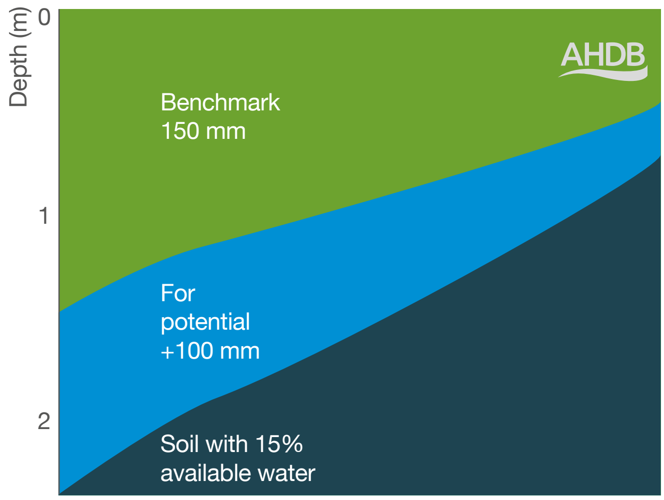


Figure 5. Typical soil water capture at different rooting depths

Source: ADAS

Mapping yield potentials

As southern regions receive the most solar radiation (Figure 6a) and western regions receive the most summer rainfall (Figure 6b), the greatest yield potentials are in the south-west and the smallest in the north and east (Figure 6c). Coastal areas have least cloud, so get more radiation than inland. Local soil variation also affects yield potentials.

Yield potential can be achieved, assuming 60% energy capture, 1.4 t/TJ energy conversion or 5.5 t/ha/100 mm water conversion and 60% Harvest Index, and assuming roots can capture >250 mm water from the soil profile.

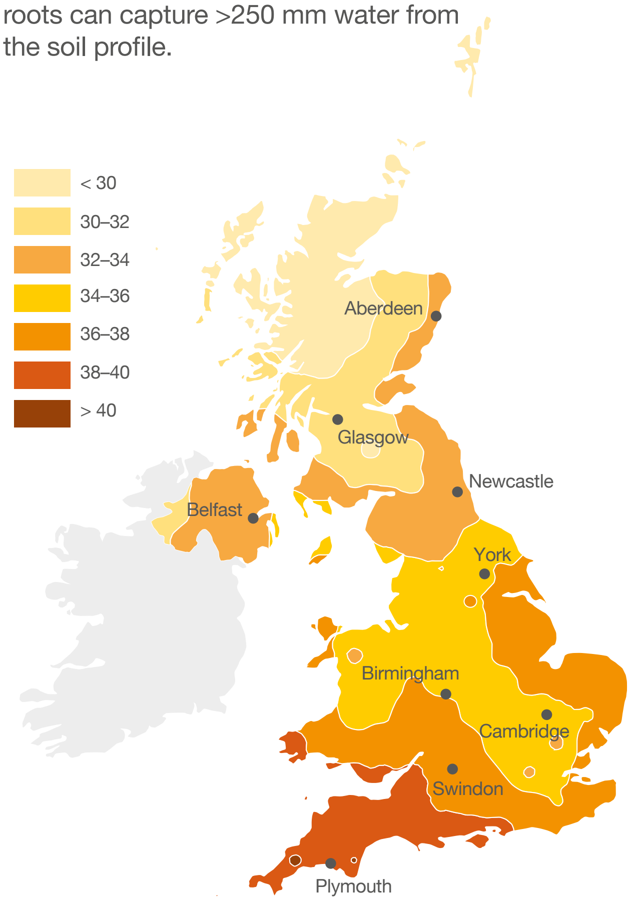


Figure 6a. Average annual solar radiation 1981–2010 (TJ/ha)

Source: ADAS

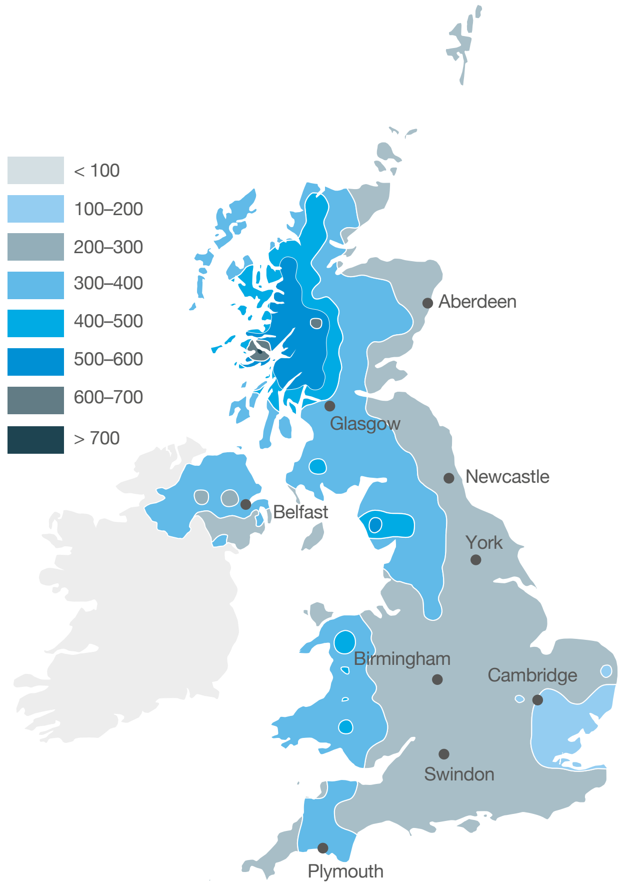


Figure 6b. Average summer rainfall April–July, 1981–2010 (mm)
Source: ADAS

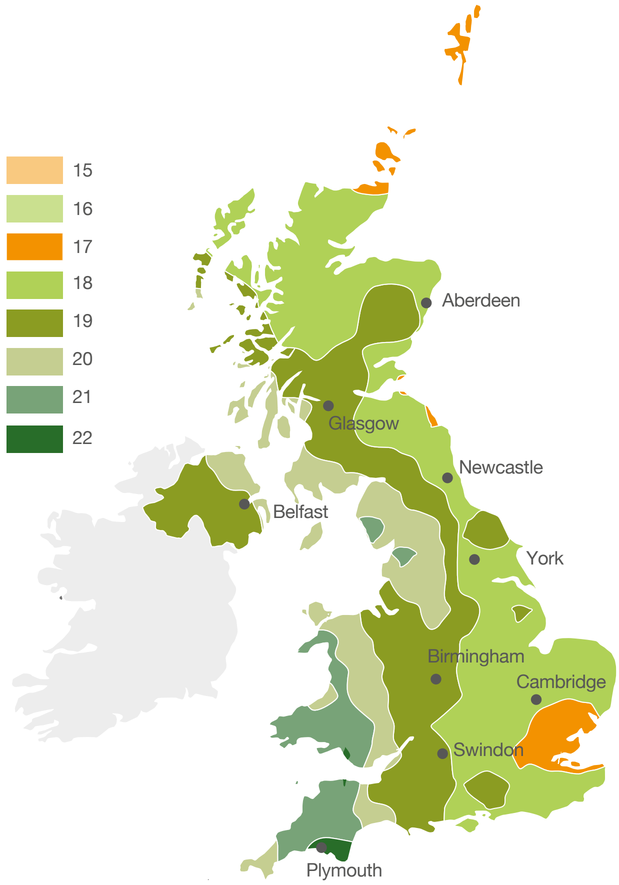


Figure 6c. Potential grain yields (t/ha)
Source: ADAS

What are benchmarks?

B

This symbol identifies a benchmark – a quantitative reference point against which a crop's performance can be compared. By assessing crops against benchmark values, growers can determine how best to manipulate husbandry. Some targets and husbandry responses are suggested, but this guide is not an agronomy manual.

At-a-glance benchmark values are provided at the back of this guide.

Each benchmark is based on observations of a high-yielding feed wheat with a slow rate of development at UK sites through several seasons. Unless otherwise stated, crops were sown in early October at 375 seeds/m² and grown with ample nutrition, complete crop protection and without lodging.

Some graphs to illustrate growth processes are based on example crops and may give data that differs from benchmarks. Some benchmark data for modern varieties can be found within the AHDB Recommended Lists datasets: **ahdb.org.uk/rl**

Varietal influence

Benchmarks vary in the extent to which they are affected by genetics (heritability). Benchmarks with high heritability are strongly influenced by choice of variety, whereas benchmarks with low heritability are principally controlled by husbandry choices.

The heritability of each benchmark is indicated as High, Medium or Low and the other management choices with a significant effect are listed.

Crop life cycle

Throughout the growing season, a crop changes in form (development) and accumulates dry matter (growth).

Key facts

Development

Governed by temperature and day length.
It can't be managed easily during the season
Varietal influence: High
Other influences: Sowing date

Growth

Can be managed using interventions through the season
Varietal influence: Medium
Other influences: Nutrition, crop protection products, growth regulators

The key development phases

Cereal growth stages are published near the back of this guide. The key growth stages – crop emergence (GS10), the start of stem extension (GS31), flowering (GS61) and the end of grain filling (GS87) – separate the key development phases: 'foundation', 'construction' and 'production', as explained in Figure 7.

The duration of each phase is governed by:

Temperature: More growth occurs in any phase during cool temperatures, as phase duration is prolonged.

Vernalisation: A period of cool temperatures (0–12°C) advances floral development and reduces the duration of the foundation phase. The majority of winter wheat varieties respond strongly to vernalisation, and spring wheats may have a slight response.

Day length: Long days advance floral development in most varieties. Day length affects the duration of both foundation and construction phases. Almost all commercial UK wheat varieties respond to day length.

Stress-sensitive stages

The apex is frost-tolerant until reproductive development starts. Susceptibility to frost damage is highest when the ear is developing. Frost risk falls significantly from April. Overall risk of damage is lowest in late May and early June. From July onwards, drought risk increases.

Implications for management

Varieties vary in their response to vernalisation and day length. The relative speed of development of varieties to reach GS31 from early, medium and late sowings is published in the AHDB Recommended Lists. Conservative times for the latest safe sowing date to allow sufficient vernalisation to trigger flowering are also published.

Prolonging any development phase increases dry matter formation during that phase.

- Prolong development by sowing slow-developing varieties early
- Management after sowing influences growth, not development
- For highest yields, feed and protect leaves that emerge during stem extension in preference to earlier, lower leaves
- T1 sprays should be timed to protect final leaf 3. Spraying early will be ineffective, as the leaf will be within the leaf sheath

Key management action timings

Key periods and specific timings for key nutrition and crop protection products are shown in Figure 7.

These timings are indicative of what may be applied to a typical wheat crop and are not intended as recommendations.

Advisers who are BASIS-qualified (for crop protection products) or FACTS-qualified (for fertiliser) should be consulted for specific rate and timing recommendations.

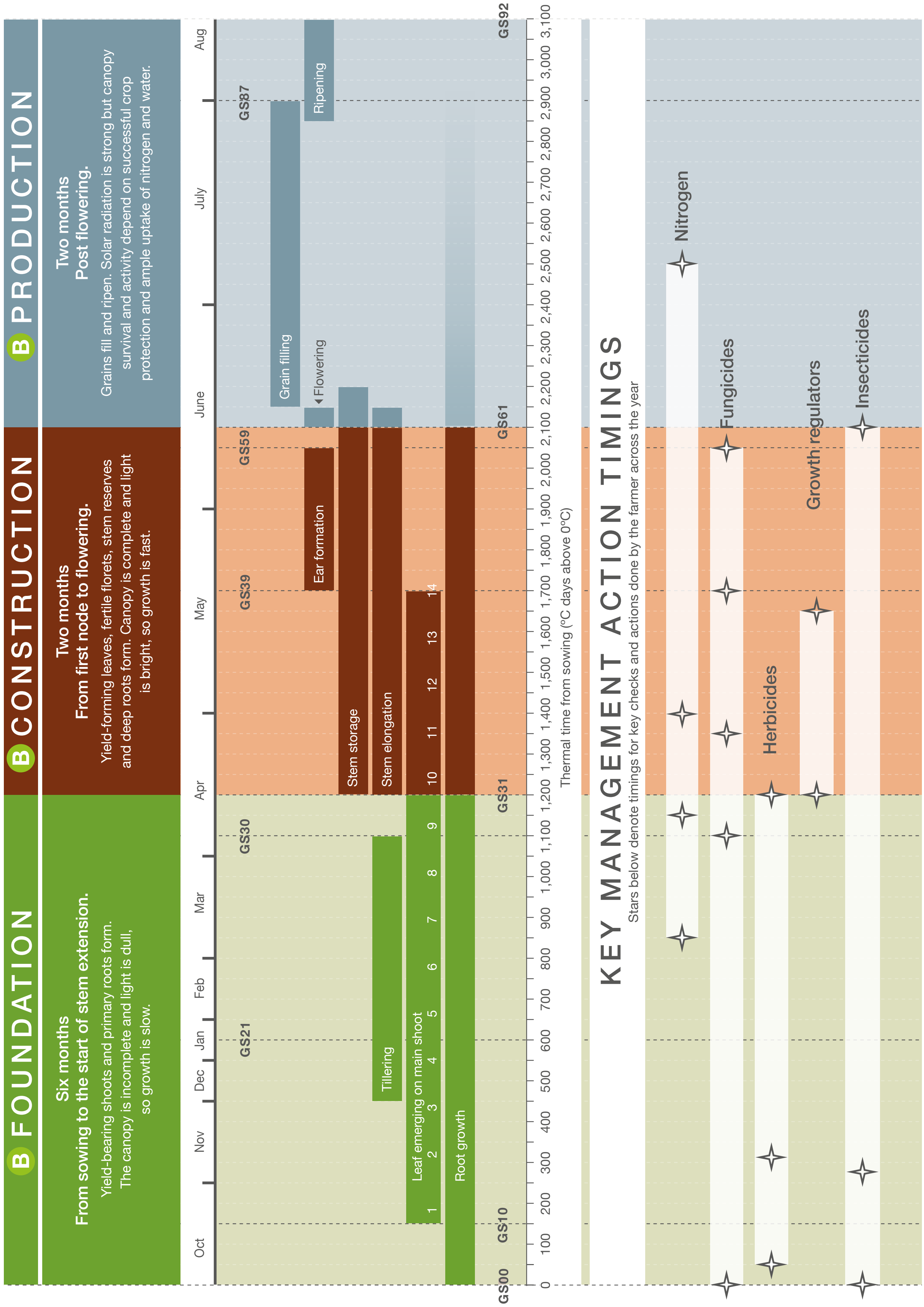


Figure 7. Wheat development phases and key management action timings

Establishment

Part of the foundation phase, establishment includes germination, emergence and overwinter survival.

Key facts

- Plant density markedly affects crop structure but, above a low threshold, has little effect on grain yield
- Poor establishment or low plant population density only reduces yield if:
  - Significant areas of the field have very few or no plants
  - Conditions are unsuitable for compensatory tillering and root growth
  - Weed pressure is high
- Soil type and cultivations can have strong effects on establishment – average establishment for sandy soils is 90%, compared with 65% for loams and clays
- High seed rates, coupled with good establishment, increase lodging risk

Sowing to emergence

B 150 °C days

- 11 days in September
- 15 days in October
- 26 days in November

Varietal influence: Low

Other influences: Sowing depth, soil conditions

Germination and emergence require moisture and warmth. Initially, seeds imbibe water, roots start to grow, coleoptiles emerge and extend to the soil surface, then first leaves emerge.

A proportion of viable seeds fail to emerge due to pests, diseases and poor soil conditions. The proportion of seeds sown that emerge also appears to decrease as the number of seeds sown/m^2 increases, although the reasons for this are unclear. Establishment declines if sowing is delayed after mid-October and will be around 50% of seeds sown in mid-November.

While sowing to emergence takes longer in cold than in warm weather, the thermal time in each case is very similar (150 °C days). Sowing too deep or too shallow can delay or decrease establishment. Optimum sowing depth is around 4 cm but depends on pest threats (e.g slugs and rooks).

Establishment

B 70% of seeds sown established

B 260 plants/m^2

Varietal influence: Low

Other influences: Weather, soil type, cultivations, seed treatments, seed rate, sowing depth, diseases, pests

By the end of February, the benchmark for establishment is 70%. Plant damage or loss over winter may occur due to:

- Frost damage, especially after early drilling of fast-developing varieties
- Frost heave
- Pest or disease damage
- Poor or impeded drainage leading to poor rooting and waterlogging

Tillering tends to compensate for uneven establishment. It is important to ensure poorly established crops have adequate fertiliser nitrogen. It may even be possible to counteract poor establishment by using fertiliser nitrogen to encourage tillering and tiller survival. Very few plants die after winter.

Effects of plant population

Plant density depends on seeds sown and establishment. Eventual crop structure is markedly affected by surviving plants/m^2 (Figure 8).

Higher plant densities cause:

- Fewer crown roots on each plant
- Fewer tillers on each plant
- More fertile shoots to survive, hence more ears/m^2
- Smaller culm leaves but greater canopy size (GAI)
- Fewer grains on each ear
- Little change in grain yield, above a low threshold

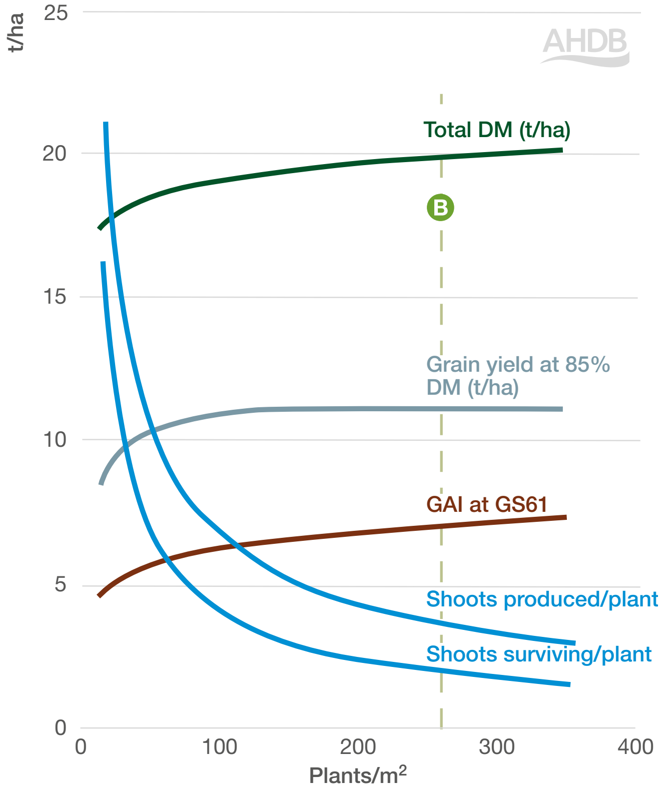


Figure 8. Plant population affects many aspects of crop development and production

Weeds

Delaying autumn sowing is an important strategy for control of weeds, particularly black-grass. Where sowing is delayed, seed rate should be increased.

Increasing seed rate to increase crop density can also reduce black-grass numbers, as shown in Figure 9, by about 25% and diminish seed return by the black-grass that does establish.

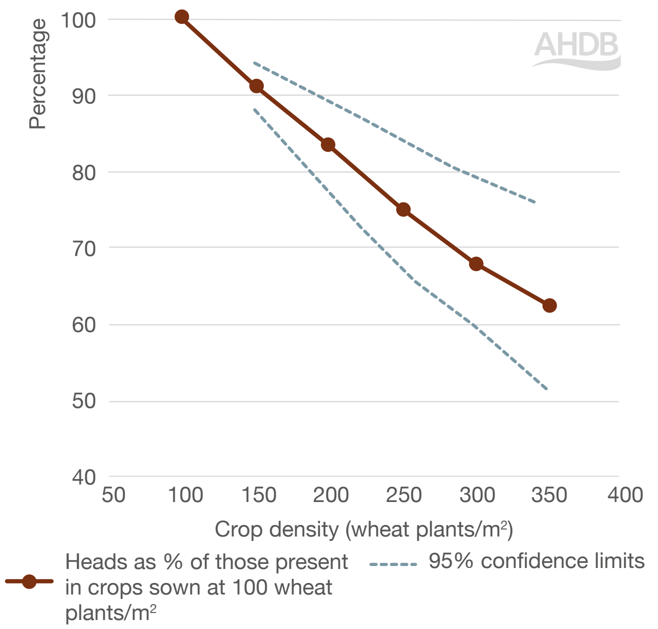


Figure 9. High wheat plant number reduces black-grass heads/m^2 at harvest*

*LUTMAN PJW, MOSS S, COOK SK & WELHAM SJ (2013) A review of the effects of crop agronomy on the management of *Alopecurus myosuroides*. Weed Research 53, 299–313

Lodging

High plant population density weakens plant anchorage. It also increases shoot height and decreases stem diameter and stem wall width. This weakens stem strength. The benefit of small plant populations is greatest for varieties with poor lodging resistance. Shallow drilling can also increase lodging risk.

How to measure plant populations

Seed rate calculations should be carried out to achieve a target plant population in spring, adjusting for expected establishment after overwinter losses.

Seed rate (kg/ha) = Target plant population/m^2 x Thousand Grain Weight (g) ÷ Expected establishment (%)

Plant populations can be counted when the crop is fully established. Place a 0.5 m x 0.5 m (0.25 m^2) quadrat (or four 0.5 m long rods placed as a square) diagonally so that one row goes vertically from one corner to the opposite corner in 10 representative areas of a field and count the number of plants within the quadrat. Take the average of all counts and then multiply by four to get the number of plants/m^2.

For overwinter survival, count the plant population (as per the method above) after winter but before significant warming and growth occurs. At this stage, it can be hard to differentiate between plants and tillers, hence plants may need to be dug up to determine actual numbers.

Target plant populations

The most appropriate target plant population depends on weed pressure and sowing date – the target should be about 150 plants/m^2 in the thinnest areas of the field and more if it is necessary to compete against weeds.

Seed rate: Delayed sowing, which may be necessary for weed control or due to soil conditions, reduces the tillering period. For each month drilling is delayed, an extra 50 plants/m^2 are typically needed to compensate for reduced tillering.

Soil type and cultivations affect establishment. For example, average establishment on sandy soils is 90%, compared with 65% on loams and clays. Cultivations affect seedbed quality and establishment, depending on soil stability and type.

- Avoid overly cloddy seedbeds but maintain some soil aggregate structure; seedbeds should not be overworked
- Consider deep cultivation on unstable silt soils
- Consider reduced tillage on stable, well-structured clay soils

Other factors that may affect emergence and establishment are:

- Germination capacity (seed quality and vigour, which are affected by variety or seed crop ripening)
- Some seed treatments, especially of deep-sown seeds (delay or reduction in emergence)
- High seed rates (reductions in percentage establishment)
- Seeds sown too deep or too shallow
- Disease or pest damage

Leaf emergence and tillering

Leaf emergence indicates plant development and sets tillering potential.

Key facts

- Rate of leaf emergence is controlled mainly by temperature
- Each main shoot produces nine to 14 leaves, of which five to seven are on the extended stem
- At least 400 fertile shoots/m² (400 ears/m²) are required for maximum yield
- All varieties can produce many tillers
- Early sowing and fertile soils increase tillering
- Tillering is prolonged at low plant populations
- Many tillers die between GS31 and flowering
- High nitrogen supplies encourage tiller survival

Leaf emergence

B 122 °C days/leaf (14 main shoot leaves)

Varietal influence: Low

Other influences: Sowing date

Leaf emergence slows or stops in winter and progressively speeds up as temperatures rise in spring. Other environmental factors have little effect on leaf emergence.

The time period measured in thermal time (ºC days above a base temperature of 0ºC) between the emergence of two successive leaves is called the phyllochron. It varies with variety and sowing date. Late sowing decreases both phyllochron and total leaves emerged – e.g. early September drilling may give 15 leaves, while November drilling may give nine leaves.

How to measure the phyllochron

The phyllochron can be measured by tagging the youngest, fully emerged leaf when plants have three fully emerged leaves, and again when they have seven fully emerged leaves. The proportion emerged of the next partially emerged leaf is noted at the same time, as well as the date of tagging. The tagged plants are monitored and at GS39 the number of leaves that have emerged since the last tag was attached are counted. Daily temperature data is then used to calculate the thermal time taken for each leaf to emerge.

Tiller production

B Maximum 35 shoots/plant for October-drilled crop

Varietal influence: Low

Other influences: Sowing date, plant number, nitrogen supply

Tillering is the emergence of side shoots at leaf stem. It can continue until after the start of stem extension.

The first tiller emerges in the junction of the first leaf (or coleoptile) as the second, third or fourth leaves emerge. The next tiller develops in the second leaf junction one phyllochron later, and so on. Secondary tillers develop in leaf junctions of primary tillers. Well-spaced plants can produce fertile tillers until stem extension starts; tillers produced later are rarely fertile.

Crops sown from late September to early October produce about eight to nine leaves by stem extension, so can produce a maximum of 35 shoots on each plant as shown in Figure 10. November-sown crops may have only five leaves by stem extension with a potential for 11 or fewer shoots. However, plants only produce this many tillers when widely spaced and in good growing conditions, so should not be expected to produce such numbers in the field. It is usually necessary to establish at least 150 plants/m² to ensure 400 ears/m² from an October-sown crop.

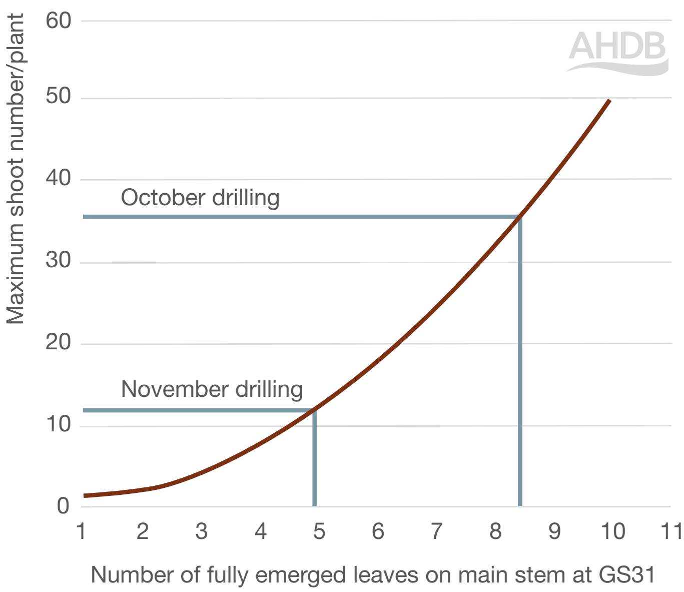


Figure 10. Potential fertile tillers depend on leaves present at stem extension (GS31)

Tillering patterns

B 1,020 shoots/m^2 (8 April, GS30–31)

Varietal influence: Low

Other influences: Sowing date, plant population, nitrogen supply

The timing of tillering depends on sowing date, plant numbers established and temperature.

- Early sowing (early September): Most tillering occurs in autumn. If more than 250 plants/m^2 are established, then tillering usually ends before winter. If fewer than 100 plants/m^2 are established, tillering can continue into spring
- Late sowing (November): Tillering is usually delayed until spring unless unusually warm temperatures follow drilling

Tillering normally ends when Green Area Index (GAI) reaches about 1. In dense crops, this usually occurs just before GS31. Limited resources, especially nitrogen, may limit tiller production.

The benchmark maximum for a late September to early October-sown crop with 260 plants/m^2 is 1,020 shoots/m^2. The benchmark date of maximum shoot number is in early April. Early sown crops or crops with many plants/m^2 tend to have greater maximum shoot numbers. Varieties with large leaves or that reach stem extension early tend to have lower maximum shoot numbers (Figure 11).

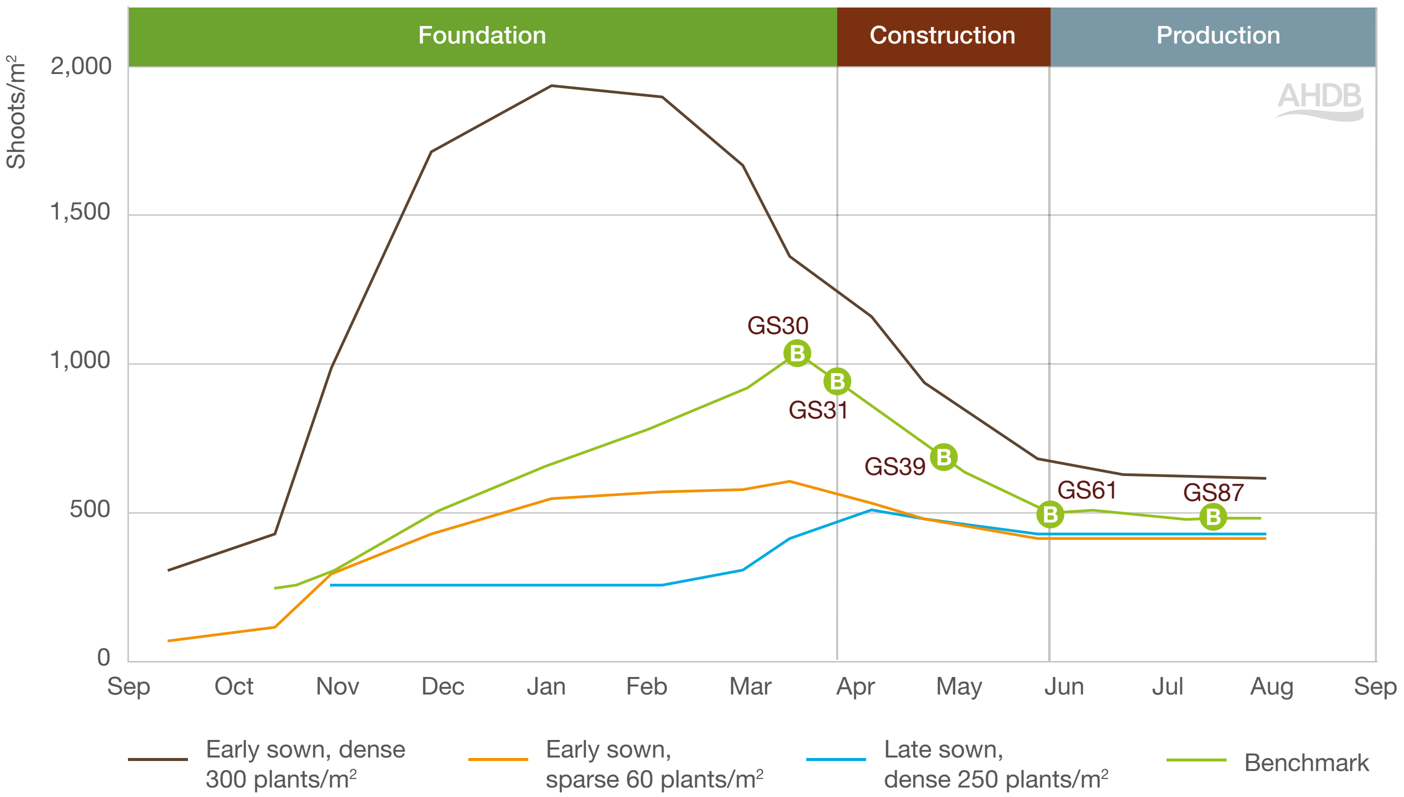


Figure 11. Sowing date affects tiller production in wheat

Source: AHDB-funded research

Final shoot number

B 45% (460/m²)

Varietal influence: Medium

Other influences: Shoot number, nitrogen supply

Some tillers die between the start of stem extension and flowering, with the last-formed dying first. Few die after flowering. Tiller losses are higher in crops with many shoots (Figure 11).

Shoot survival is as important as shoot production in determining final shoot number. Shoot survival fluctuates significantly between varieties – from under 40% to over 70%. However, all varieties can produce sufficient tillers.

Increasing nitrogen reduces tiller loss. Dry matter losses of up to 3 t/ha can occur as shoots die.

Implications for management

Leaf emergence, together with disease risk, determine spray timings.

- Target T1 fungicides at the third from last leaf, which normally coincides with GS32 (depending on sowing date and variety)

Tillering is the most important process governing canopy formation.

- Manage the crop to achieve at least 400 ears/m² for maximum potential yield

How to measure tiller numbers

Tiller numbers/m² are counted using quadrats as per the plant population counts described in the Establishment section (page 11).

Root growth and distribution

Soil structure, management and drainage have major effects on root growth and distribution.

Key facts

- A mature root system has 20 or more main roots per plant, with many branches
- Root growth is slow in the foundation phase, more rapid in the construction phase, then slow during the production phase when dry matter is redistributed and roots senesce
- Good rooting, especially deep rooting, will enhance crop growth when water or nitrogen is limiting

Foundation phase

B 15 km roots/m² at GS31 (0.5 t/ha)

Varietal influence: Low

Other influences: Sowing date, soil structure, take-all

Roots begin to grow at germination, with three to six seminal roots emerging before the second leaf appears. These can grow deep and persist throughout the crop's life.

The number of crown roots, which develop from the stem base, relates to leaf and tiller numbers. Once the main shoot has three to four leaves, crown roots appear with thickened upper regions to anchor the plant. The mature root system has 20 or more roots on each plant, plus numerous branches.

In well-drained and well-structured soil, the rate of root extension depends on temperature. In autumn, if soils are warm, seminal roots can grow quickly (12 mm/day). Extension and branching slow down during winter, then increase in spring. By GS31, maximum rooting depth can exceed 1 m and root dry weight is about 27% of shoot dry weight (Figure 12).

Figure 12. Root weight and length grow proportionally during active growth period in wheat

Construction phase

B 31 km roots/m² at GS61 (1.0 t/ha)

Varietal influence: Low

Other influences: Soil structure, take-all, PGRs

During stem extension, roots grow rapidly. Root extension and branching increase as soil temperatures rise e.g. main root extension of 18 mm/day could be observed during spring, Table 1.

This is the main period of crown root production. However, dry matter may be lost as some roots die, and as assimilate is exuded or respired. At GS61, root dry weight is 1.0 t/ha but twice as much assimilate may have been used in root growth.

With typical root distribution, total root length reaches 31 km/m² by anthesis and maximum rooting depth reaches 1.5–2 m.

Table 1. Typical main root daily extension rates in deep, well-structured soil under optimum soil water supply

Season	Extension rate (mm/day)
Autumn	12
Winter	6
Spring	18

Production phase

After anthesis, root growth slows down – only 10% of total assimilate produced during grain filling is used by the root system. Root growth and death occur at approximately the same rate during the production phase, so total root system size is unchanged.
As roots in the topsoil begin to die, those in the subsoil may continue growing. Protecting leaves with fungicides can prolong root growth and nitrogen uptake after GS61.

Water and nutrient uptake

The relative distribution of roots down the soil profile changes little between GS31 and anthesis. Over 70% of root length is found in the top 30 cm.

High rates of uptake of less mobile nutrients, such as phosphorus (P), only occur when root length densities (RLDs) exceed 5 cm/cm³ of soil. Lower root length densities are adequate for potassium (K) uptake and about 1 cm/cm³ is needed for the take-up of most of the available water and water-soluble nutrients, such as nitrogen. Lower RLDs will take up less of the available water and nutrients, this is shown in Figure 13.

Maximising root growth in the subsoil significantly improves soil water supply to the crop.

How to measure rooting

The established method for measuring root length involves taking soil cores, washing the soil from the roots and using a scanner to measure the roots. This method is time-consuming and requires specialist equipment.

An early visual assessment of rooting can be made by digging up representative plants with a spade within a couple of months of planting, measuring rooting depth with a ruler and weighing the washed roots to obtain root biomass. If a soil core is available, soil can be extracted to 90 cm in the spring and before harvest to assess changes in soil moisture as a proxy for rooting depth. Sampling from representative areas of the field is important, either based on soil type or crop growth.

Alternatively, soil structure can be assessed as a proxy for rooting, as good soil structure will allow the roots to penetrate to depth more easily and capture available water. The Visual Evaluation of Soil Structure (VESS – details available at **www.sruc.ac.uk**) involves soil removal (to 30 cm depth), assessment and scoring, and can be carried out at any time of year (but preferably when the soil is moist).

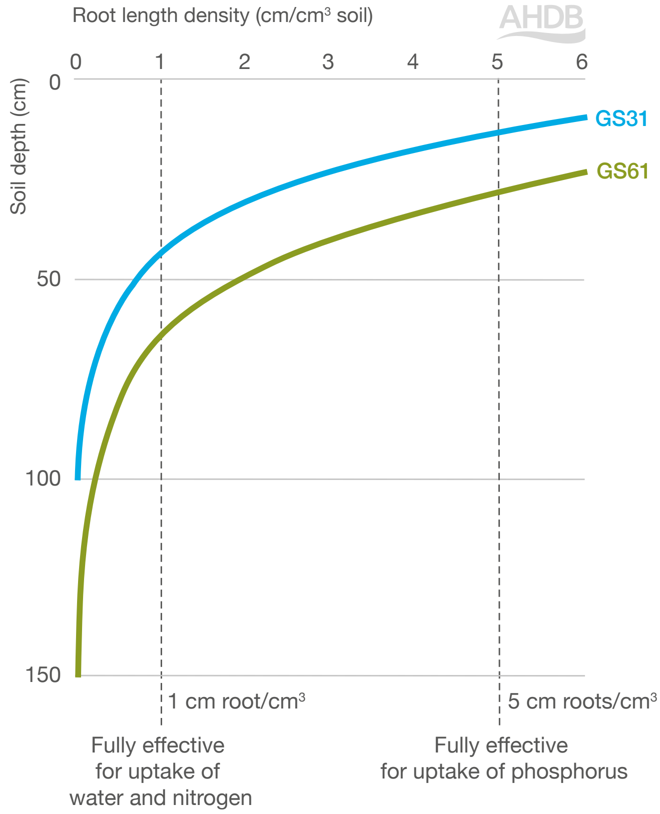


Figure 13. Roots fully utilise water and nitrogen to about 40 cm depth at GS31 and to 70 cm depth by GS61

Source: ADAS

Implications for management

Some PGRs may help to increase rooting but the main ways root systems can be managed is indirectly, through improved soil structure and drainage. Encouraging deep rooting will improve water and nutrient supplies for crop growth. Varietal differences in crown root spread and low plant number can help to maximise root anchorage strength. These differences contribute to the lodging resistance score on the AHDB Recommended Lists (specific data on root and stem lodging may be available from breeders).

- Sow early to increase overall root system size at flowering

Soil structure has a major impact on root growth and distribution. In some clay-rich soils, moisture extraction by roots promotes cracking, which improves soil structure and root access in following seasons. Hence, deep rooting can be self-sustaining, unless wheelings or cultivations destroy soil structure. With minimal tillage, enhanced earthworm activity creates long continuous pores in the subsoil to aid root penetration.

- Consider field drainage and soil management to ensure adequate pore spaces for aeration and root penetration into the subsoil. For further details, see the AHDB Field Drainage Guide
- Take-all reduces rooting at all depths

Nitrogen uptake

Most nitrogen is taken up around May during the construction phase.

Key facts

- Nitrogen uptake can occur throughout the crop's life, although most is taken up around May
- Soils in arable rotations supply sufficient nitrogen for wheat to produce roughly half its unlimited yield
- The other half of unlimited yield can be realised with applied nitrogen:
  - 40% from the first half of nitrogen applied
  - 10% from the second half of nitrogen applied
- Fertiliser nitrogen controls canopy size, primarily through shoot number
- Nitrogen uptake is closely linked to canopy expansion
- During grain filling, a large proportion of nitrogen in leaves and stems is redistributed to grain

Sources of nitrogen

B 75 kg/ha available soil nitrogen

Influences: Cropping history, previous fertiliser applications (including manure), soil type, crop residues, cultivations, soil organic matter

Soil nitrogen release and crop recovery are both very variable.

Seed contributes about 5 kg nitrogen/ha, while 20–40 kg/ha comes from the atmosphere, in rain and nitrogen-containing gases. However, most is acquired from soil. The benchmark is 75 kg/ha available nitrogen (nitrate and ammonium) at soil nitrogen supply (SNS) Index 1. In the UK, more than 50% of soils are Index 1 or above as shown in Figure 14.

Soil nitrogen availability is increased by unrecovered fertiliser from previous crops or organic residues, e.g. legume roots or animal manures.

Soil nitrogen release is stimulated in warm, moist soils and after cultivations that thoroughly disturb the soil. Nitrogen from a previous crop is released in autumn, before sowing to a greater (e.g. OSR, peas) or lesser (e.g. beans) extent depending on the crop.

Crop residues with low nitrogen such as straw can cause temporary unavailability through 'locking up' nitrogen, but some nitrogen is still released after a previous cereal crop through re-mineralisation of previously immobilised fertiliser nitrogen.

Uptake of soil nitrogen continues throughout growth. Early sowing and unimpeded rooting improve soil nitrogen uptake.

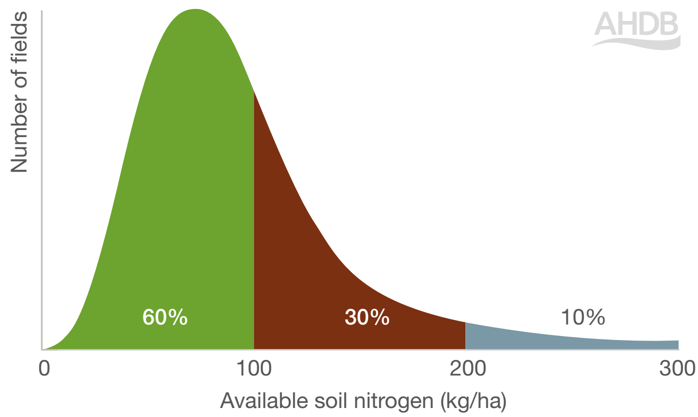


Figure 14. Variation in soil nitrogen supply in UK arable fields
Source: ADAS

Canopy nitrogen requirement

B 36 kg/ha per unit GAI nitrogen

Varietal influence: Low

Other influences: Limited – little variation in value

Nitrogen uptake has a major influence on a crop's green canopy. The way nitrogen controls canopy expansion depends on the stage of crop development, see Table 2 for further information.

Soil nitrogen is particularly prone to leaching when uptake is low due to slow canopy expansion over winter. As temperatures rise, canopy expansion accelerates and demand for nitrogen increases.

Throughout development, the area of green tissues relates to the amount of nitrogen they contain; there is about 36 kg nitrogen/ha of green tissue. Thus, it is possible to control canopy size by controlling nitrogen availability.

Table 2. Effect of nitrogen uptake on plant growth and development

Stage of development	Nitrogen uptake affects canopy size by promoting:
Before stem extension	Tillering
During stem extension	Shoot survival, with some increase in final leaf size
After stem extension	Prolonged survival of yield-forming leaves

> ***How to measure soil nitrogen***
>
> **Soil nitrogen supply can be estimated by a field assessment method (FAM) described in the AHDB Nutrient Management Guide (RB209) or, if the soil nitrogen level is potentially high (>120 kg nitrogen/ha) or is uncertain, by a soil mineral nitrogen (SMN) measurement. SMN is often measured to a depth of 90 cm in the spring (before any nitrogen is applied).**

Pattern of nitrogen uptake

B 81 kg/ha from sowing to first node (GS31)

B 167 kg/ha from first node to flowering

Varietal influence: Low

Other influences: Nitrogen supply

By harvest, a typical crop takes up 279 kg/ha (Figure 15):

- 30% before first node emergence
- 40% between first node and flag leaf (only five weeks). Most is used to produce 'yield-forming leaves' (the top four leaves within a crop's canopy)
- 20% between flag leaf and flowering
- 10% slowly after flowering

Nitrogen redistribution to grain

B 158 kg/ha transferred to grain

B 90 kg/ha left in chaff, straw and stubble

Varietal influence: Low

Other influences: Crop nitrogen content

During grain filling, there is a large redistribution of nitrogen within the crop as proteins in the leaves are degraded and nitrogen is transferred to form grain protein. This, not root uptake during grain filling, is the main source of grain nitrogen. At harvest, chaff, straw and stubble contain 90 kg nitrogen/ha, that is 158 kg/ha less than at flowering.

Occasionally, crop nitrogen decreases slightly before harvest, probably due to loss of leaves (Figure 15).

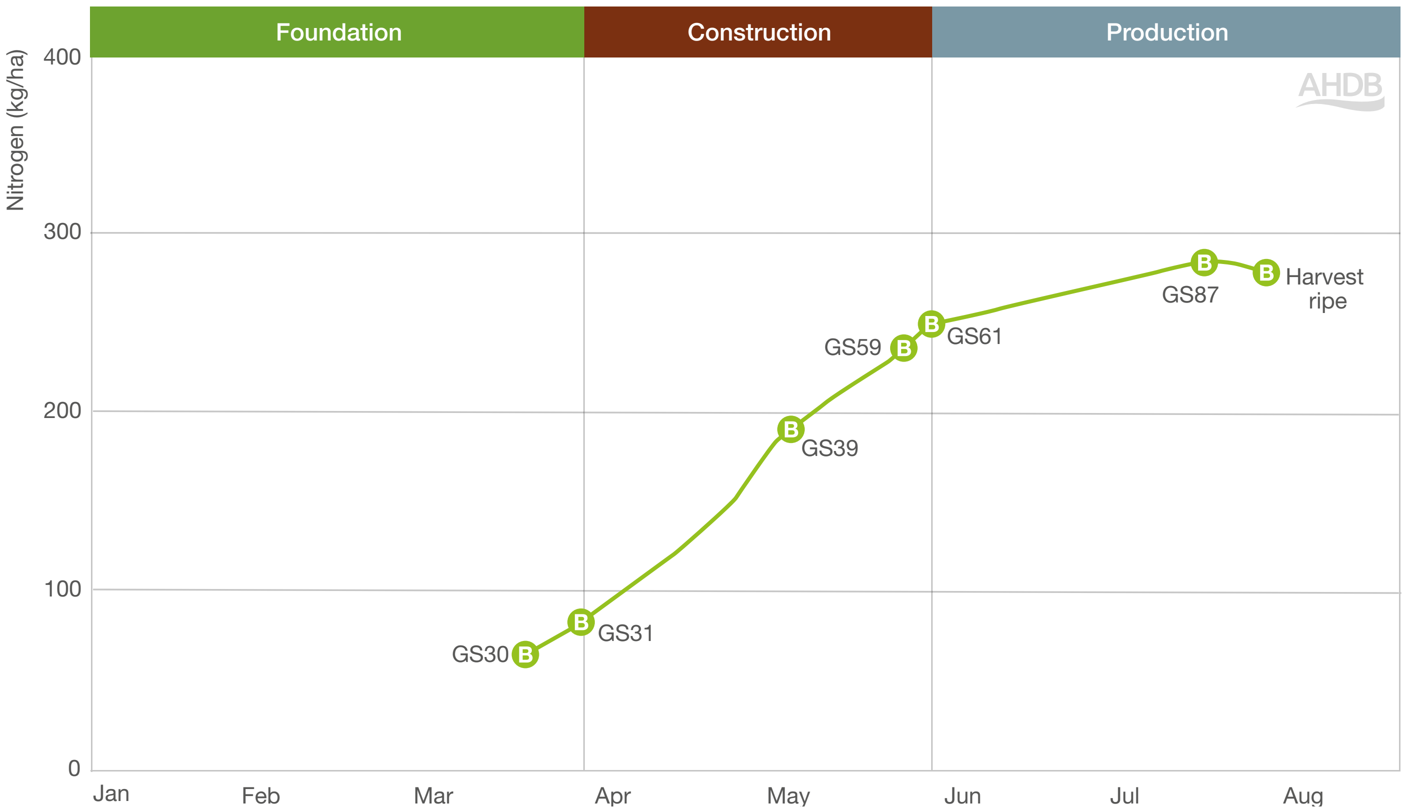


Figure 15. Crop nitrogen uptake during different growth stages in winter wheat

This graph shows a pattern of nitrogen uptake compatible with other benchmarks. These values, and those for canopy nitrogen requirement and nitrogen distribution, are greater than for most UK crops.

How to measure crop nitrogen uptake

Nitrogen uptake can be measured at any time during the season using a quadrat – see Establishment section for details. For each quadrat, cut the plants at ground level, dry them and weigh them, then send a subsample to a lab for grinding and percentage nitrogen determination. To determine the total amount of nitrogen on an area basis, the percentage nitrogen in the crop needs to be multiplied by total dry weight of the crop. To determine the nitrogen redistribution to the grain, this assessment needs to be done just before harvest, the grain separated from the straw or chaff and percentage nitrogen measured for both samples.

Implications for management

Where soil nitrogen residues may be large (>120 kg nitrogen/ha) or are uncertain, SMN analysis is a better predictor of available soil nitrogen than the field assessment method. It should include an estimate of crop nitrogen content at the time of soil sampling.

- Obtain a good estimate of eventual soil nitrogen supply by estimation or soil analysis

Where soil nitrogen uptake over winter may be limiting and the farm is outside a Nitrate Vulnerable Zone (NVZ), autumn nitrogen may be justified occasionally.

- Consider autumn nitrogen only where nitrogen availability may be inadequate over winter, e.g. on light soils with large amounts of surface straw (>120 kg nitrogen/ha), and after minimal cultivation

Early spring nitrogen is important for some crops.

- Apply early nitrogen to encourage tillering after poor establishment or to overcome root restrictions, where there is soil compaction or a risk of take-all

Late-spring nitrogen after tillering is needed by most crops. It encourages rapid canopy expansion, mainly through better tiller survival.

- Use late-spring nitrogen before the canopy turns pale, unless canopy size is excessive

Early summer nitrogen around GS39 helps optimise canopy expansion and survival during grain filling.

- Use early summer nitrogen, particularly for crops with pale, small canopies or with high yield potential

Late-summer nitrogen ensures canopy survival through grain filling as well as adequate grain protein concentration for breadmaking.

- Consider late nitrogen (summer-applied urea), particularly for crops intended for breadmaking, where yield potential is high and where field history indicates a need

Access the ***AHDB Nutrient Management Guide (RB209)*** at **ahdb.org.uk/rb209**

Canopy expansion and senescence

Managing canopy expansion and senescence is key to optimising crop output.

Key facts

- Canopies go through three distinct phases:
  - Slow expansion (foundation phase)
  - Rapid expansion (construction phase)
  - Senescence and death (production phase)
- Canopy size determines the proportion of sunlight intercepted and subsequent dry matter increase
- Canopy growth and lifespan is responsive to crop management

Canopy expansion starts at crop emergence and stops shortly after ear emergence, see Figure 16 for further detail. The canopy dies before harvest. Canopy size can be expressed as GAI – the ratio of total green area (one side only) to the ground area occupied.

Foundation phase – slow canopy expansion

B GAI = 2.0 by GS31

Varietal influence: Low

Other influences: Shoot count, nitrogen supply

From emergence to early April, ground cover increases. Cover increases as leaves and tillers emerge during early autumn and winter but GAI rarely exceeds 1 before March (Figure 16).

During this phase, photosynthesis and growth are slow because ground cover is incomplete, and because light levels and temperatures are relatively low.

Construction phase – rapid canopy expansion

B 1 GAI unit increase in every nine days

Varietal influence: Medium

Other influences: Nitrogen supply

Light interception is sufficient for rapid growth when GAI ≥3.

Canopy expansion accelerates in late April as temperatures rise and the largest leaves emerge, as shown in Figure 16. As stems and leaf sheaths extend, they contribute to GAI. The benchmark rate of canopy expansion is 0.1 GAI/day, hence crops expand by 3 GAI units during May.

Nitrogen availability controls canopy expansion quite closely because crop nitrogen for each unit of green area remains constant at 36 kg/ha – the canopy nitrogen requirement. Nitrogen shortage curtails rapid canopy expansion and advances senescence.

At flag leaf emergence, leaf blades comprise about 85% of total GAI. The benchmark date for maximum canopy size, which occurs between flag leaf emergence and ear emergence, is 26 May. The benchmark maximum GAI is 6.9. Maximum canopy size occurs earlier in nitrogen-starved crops, as lower leaves begin to die.

Third and fourth leaves from the ear significantly increase GAI, but contribute little to grain filling.

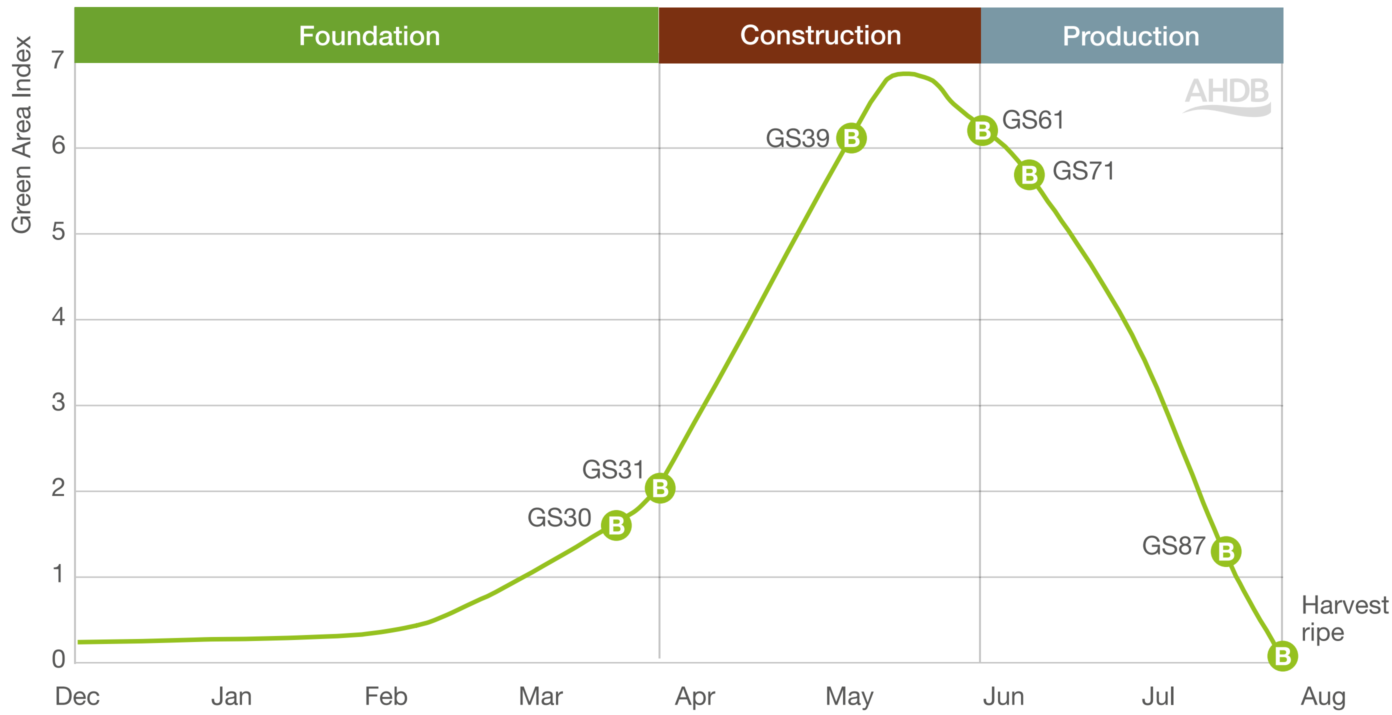


Figure 16. Change in Green Area Index (GAI) over the growing season

Production phase – canopy senescence and death

B GAI falls to <2 by GS87

Varietal influence: Medium

Other influences: Nitrogen supply, disease

The canopy senesces from June onwards. Lowest leaves die first, unless disease intervenes. Leaf sheaths usually die last. GAI drops below 2 at the end of July, causing the end of rapid crop and grain growth. The canopy continues to respire, losing greenness and weight.

Canopy size and light interception

B GAI at GS61 = 6.3

Varietal influence: Low

Other influences: Nitrogen supply, shoot number, disease

The crop canopy comprises all green surfaces – mainly leaf blades (Figure 17). At flowering, fertile shoots have a GAI of 6.0 and infertile shoots 0.3. The benchmark maximum green area for each fertile shoot is 130 cm^2.

GAI 0.5 – GS24

GAI 0.9 – GS26

GAI 1.4 – GS30

Figure 17. Green Area Index at various growth stages in wheat

Husbandry has little effect on leaf number or size, so canopy management focuses on shoot number.

As shoot number and GAI increase, the extra light intercepted decreases, e.g. an increase from GAI of two to three captures 15% more light, whereas only 2% extra is captured as GAI rises from six to seven.

Upper leaves become more important for light interception as GAI increases (Figure 18).

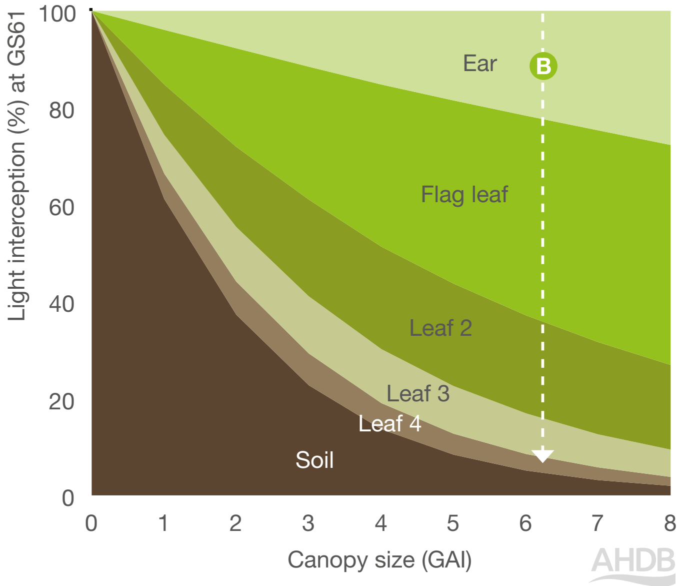


Figure 18. Light interception by crop increases with canopy size
Source: ADAS

The optimum canopy size at flowering is GAI of 6.3.

- Small canopies (GAI <4), which can result from inadequate shoots or nitrogen deficiency, waste sunlight
- Large canopies (GAI >7), which can result from high seed rates and high nitrogen supplies, cost more than is necessary to intercept all available sunlight. They are also at a higher risk from foliar disease and lodging

Optimum canopy size for varieties with erect leaves or low canopy nitrogen requirement only differ slightly from varieties with lax leaves. Differences in leaf greenness have little effect on photosynthesis.

Full light capture is hastened by early sowing, warm winters and springs, and adequate moisture and nitrogen.

Implications for management

Achieving optimum canopy size is important for good yields. Eventual canopy size tends to be increased by pre-sowing management.

- Early sowing
- High seed rate
- Plentiful soil nitrogen
- Adequate phosphorus and potassium, and correct pH

During the growing season, canopy can be managed by:

- The amount and timing of fertiliser nitrogen applied
- Disease control measures

Often, canopy growth needs to be kept in check to avoid exceeding target GAI.

How to measure GAI

GAI can be measured in several ways. The simplest is to assess the green leaf area compared to the ground area by eye. A more accurate method involves cutting a known area of crop (e.g. 1 m^2), removing the leaves and feeding them through a leaf area machine.

Some apps are now able to measure GAI from a photo taken vertically above the crop as shown in Figure 19. Multiple photos should be taken to get an average for a field. Apps are most accurate for growth stages up to early stem extension (around GS32).

Sensors (handheld, tractor-mounted, on drones or satellites) measure reflectance of different wavelengths of light. Various vegetation indices are then calculated, usually using near infrared or red wavelengths, which indicate crop cover.

GAI 2.0 – GS31

GAI 2.3 – GS31

GAI 4.0 – GS31

Figure 19. Photos can be taken from vertically above to measure the Green Area Index (GAI) using online apps

Biomass growth

Biomass growth represents the net effect of photosynthesis after losses from respiration and leaf fall.

Key facts

- 90% of final crop dry matter is formed after GS31
- The crop grows by 0.18 t/ha/day (1.3 t/ha/week) from May to July
- Crop growth on dull days is less than half that on bright days
- Grain dry matter accumulates during the production (50–80%) and construction (20–50%) phases. No grain dry matter accumulates during the foundation phase

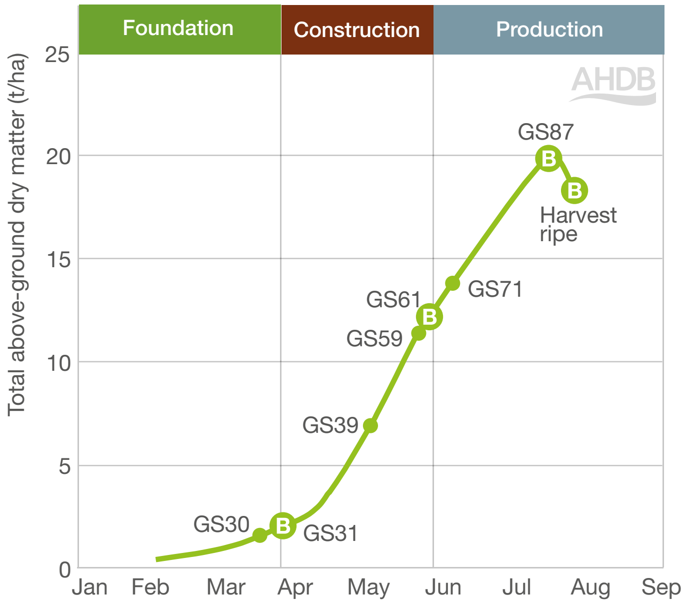


Figure 20. Changes in crop dry matter over a growing season

Foundation phase

B 1.9 t/ha above-ground growth by GS31 (10 April)

Varietal influence: High

Other influences: Nitrogen supply, shoot number

Growth is slow over winter, as canopy cover is incomplete and sunlight is limited (Figure 20). In fact, just 10% of total growth occurs by GS31 (six months after sowing). Dry matter formed in the initial period produces leaves that are all lost before flowering, with only their nitrogen being redistributed in the plant.

Construction phase

B 10.2 t/ha increase in above-ground growth from GS31 to GS61

Varietal influence: High

Other influences: Nitrogen supply, shoot number

Rapid growth starts in late April as internodes start to extend, and light interception approaches 100% as sunlight intensity increases (Figure 20). Over half of total growth occurs in this phase. Dry matter produced in this period supports at least 0.6 t/ha extra root growth and the formation of all the organs vital to grain production.

Stem reserves act as a buffer and accumulate when photosynthetic rate is adequate and fall when photosynthesis is inadequate (e.g. on dull days).

Each fertile stem has a finite storage capacity for grain dry matter, determined by fertile floret numbers. The amount stored depends on how much dry matter is partitioned to the ear during booting and ear emergence. Partitioning differs between varieties.

Growth may slow towards the end of crop construction if storage capacity is already full.

Production phase

B 7.5 t/ha increase in above-ground growth from GS61 to GS87, then 1.2 t/ha loss to harvest

Varietal influence: High

Other influences: Nitrogen supply, disease

Rapid growth continues, although it slows slightly as leaves age and larger organs respire more in warmer weather (Figure 20). Soil water may also become limiting.

Only grains accumulate dry matter after flowering. Other plant parts (e.g. stems and leaves) lose weight, although chaff remains constant. As most soluble stem reserves produced pre-flowering are redistributed, grain growth always exceeds total crop growth during this phase.

Canopy senescence occurs as leaf and stem nitrogen moves to the grain. Thus, as grain proteins form, photosynthesis progressively slows. Senescence can be delayed if nitrogen and water uptake continue.

Rapid grain filling starts at GS71 and ends at about GS87, even if green tissues remain. Early canopy senescence, often due to drought or disease, brings grain filling to a premature end.

Crop dry weight often decreases from its maximum, mainly owing to ongoing respiration, but also through leaf loss (Figure 20). Dry matter is rarely lost from grain.

Understanding growth

(B) 0.18 t/ha/day from May to July

Varietal influence: High

Other influences: Water, light, canopy size

Rapid growth arises from complete interception of intense sunlight. Slow growth results from incomplete light interception or dull conditions.

Respiration reduces dry matter, particularly when tissues are senescing. Respiration rate is increased by temperature and continues during the night, so high night-time temperatures result in increased reductions in dry matter.

Resources for growth

Assuming a full canopy, growth may be limited by the availability of solar energy, carbon dioxide or water – see introductory section. Low winter temperatures can also limit growth.

Solar energy: Dry matter growth in the UK usually relates directly to solar energy intercepted by the green canopy. About half of this radiation is photosynthetic.

Factors affecting interception of solar radiation are:

- Region
- Canopy size
- Leaf posture
- Foliar disease

Light levels reach a maximum during May to July (Figure 21). On sunny summer days, growth can be as much as 0.25 t/ha. As clouds reduce light energy by about two-thirds, growth can fall to just 0.1 t/ha on dull days.

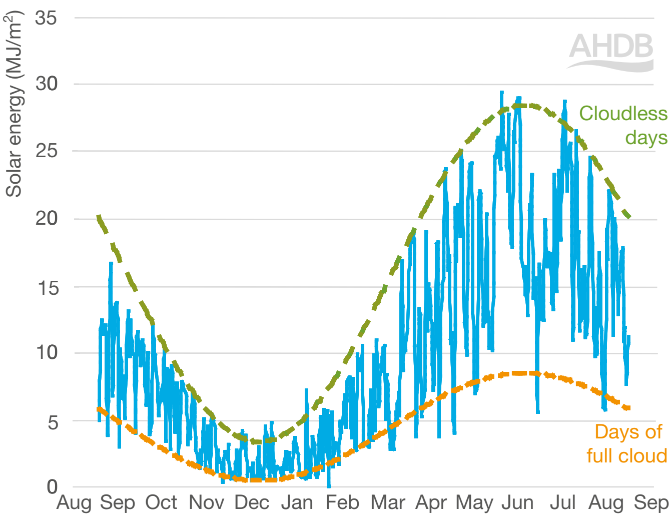


Figure 21. Season and cloud cover affect the amount of solar energy received by a crop

Source: ADAS

Carbon dioxide: Atmospheric carbon dioxide is about 400 parts per million (ppm) and is increasing at about 21 ppm per decade. In this range, crop growth relates almost directly to carbon dioxide concentration, so atmospheric change is increasing growth by about 5% per decade. Variation in carbon dioxide concentrations is not significant on a regional or seasonal scale.

Water: To absorb carbon dioxide, leaves must lose water to the air in transpiration. On an average summer day, transpiration uses about 3 mm of water. For each tonne per hectare of dry matter formed, the crop transpires about 20 mm of water. Drought restricts growth.

Factors affecting water availability for transpiration are:

- Region – rainfall amounts and distribution
- Soil type – moisture retention through summer, when transpiration generally exceeds rainfall
- Soil depth and rooting
- Take-all and other diseases: reducing root function

How to measure dry matter

Crop dry matter can be measured any time during the season.

Sample, dry and weigh the crop from a 0.5 m x 0.5 m (0.25 m^2) quadrat (see Establishment section on page 11) and multiply the weight by four to determine the weight in 1 m^2.

Alternatively, crop vegetation indices (calculated from spectral reflectance measurements taken by crop sensors) can be used as a proxy for crop dry matter. See Canopy expansion and senescence section on page 22.

Implications for management

Growth can be managed mainly through the size of the crop's green canopy, taking light conditions and water availability into account.

- Target fungicides to protect the top leaves until grain filling is complete

Stem elongation

Crop height is a reflection of variety and growing conditions.

Key facts

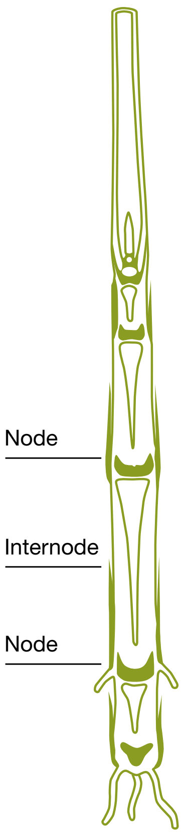
- Stem height is determined by extension of the last five or six internodes
- Crop height is affected mainly by variety, sowing date and plant growth regulator (PGR) use
- Crop height is only one of several determinants of lodging risk in wheat

The extended stem

B Five internodes measuring 69 cm, excluding ear

Varietal influence: High

Other influences: Sowing date, PGR use, nitrogen supply



Height before stem extension is related to leaf sheath length and reaches only 9 cm by GS31.

Each internode starts to extend when the previous one has reached half its final length. The benchmark number of nodes in a wheat stem is four, giving five internodes as illustrated in Figure 22. Crops sown earlier can have an extra internode and may be taller.

With a full PGR programme, the benchmark final height is 69 cm to the base of the ear. Without PGRs, crops can be as much as 20 cm taller.

By flag leaf emergence (GS39), stem height is 34 cm (50% of final height). Stems extend to 53 cm by full ear emergence (GS59) and reach their final height around the time of flowering (GS61) as shown in Figure 23.

Stem height does not reflect stem reserves, as taller stems have a greater proportion of structural materials that cannot be redistributed.

Figure 22. Final crop height results primarily from internode extension
Source: Hillary Broad, Annals of Applied Biology

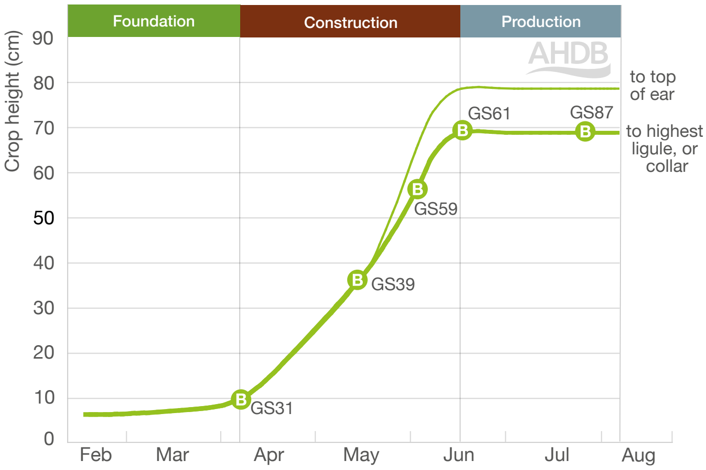


Figure 23. Crop height increases rapidly during construction phase

The extended stem

B Five internodes measuring 69 cm, not including ear

Varietal influence: High

Other influences: Sowing date, PGR use, nitrogen supply

Varieties and stem extension

Height is highly dependent on variety. Varieties contain different combinations of dwarfing genes. In the AHDB Recommended Lists, height is measured to the top of the ear (Figure 23).

Agronomy and stem extension

The benchmark heights are for crops receiving applications of PGR during both early and late stem extension. Early sowing, high nitrogen residues or lack of PGR contribute to tallness. Fertiliser nitrogen extends the penultimate internode and peduncle.

Lodging risk

In tall crops, the aerial parts of the plant impose a large force on the stem base and root system, but variation in crop height is only a minor contributor to lodging risk. Other factors are weight distribution along the shoot, root anchorage and stem strength. All components of lodging risk can be altered by choice of variety and husbandry.

The earlier that lodging occurs during grain filling, the greater the yield loss. Lodging can also adversely affect quality characteristics, such as Hagberg Falling Number and specific weight.

How to measure height and lodging

Use a metre ruler to measure the height from the ground to the top of the stem, base of ear or top of ear. Take an average of at least 10 shoots. Before GS39, the main stem (largest stem) of a plant should be measured, but after this, any tiller can be measured.

The proportion of a crop that is lodged can be assessed from its first occurrence. A percentage lodging index can be calculated:

Lodging Index =% Crop leaning (10 to 45° from vertical) ÷ 3 +% Lodging (>45° from vertical but not flat) ÷ 2 +% Lodged flat to ground

Stem carbohydrate storage

Stem reserves contribute 20–50% of grain yield.

Key facts

- Carbohydrate reserves are the major part of the dry matter redistributed from stems and leaves during grain filling. Protein is also redistributed
- Soluble carbohydrate stem reserves reach a maximum of 2.7 t/ha between late booting and early grain filling
- Variety and growing conditions can cause stem reserves to vary from <2 t/ha to >4 t/ha
- Grain filling normally depends on stem reserves and photosynthesis. By harvest, almost all stem reserves have been relocated to the grain or lost through respiration

Accumulation of stem reserves (GS31 until early grain filling)

More assimilate is produced during the construction phase than is needed for structural tissues (Figure 24). The surplus is stored in stems as fructan sugar, mainly in the pith of upper internodes – about 25% is in the peduncle, 30% in the penultimate internode and 45% in lower internodes.

Stem storage capacity is set by stem number and structure. Maximum capacity can be reached by late booting (GS47). Reserves may be utilised during temporary shortages, caused by factors such as dull weather, before and after flowering. Reserves fluctuate with growing conditions, from booting to early grain filling; they then decrease as shown in Figure 24.

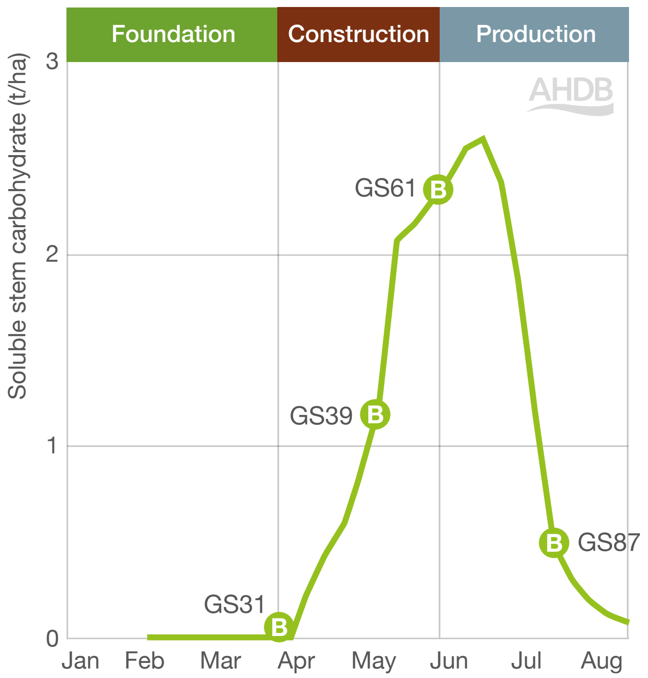


Figure 24. Stem reserves during the foundation, construction and production phases

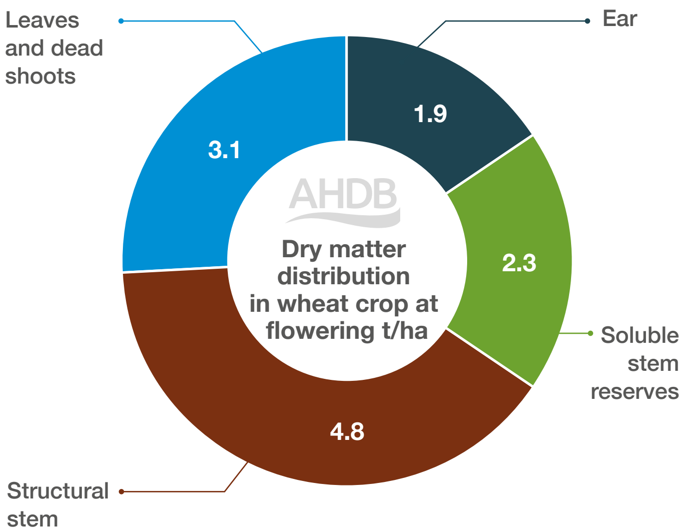


Figure 25. Dry matter distribution in wheat crop at flowering

Maximum stem storage

B 2.7 t/ha soluble carbohydrate

Varietal influence: High

Other influences: Shoot number

The benchmark amount of soluble stem reserves at flowering is 2.3 t/ha (Figure 25). An additional 0.4 t/ha accumulates by early grain filling. Sometimes, the maximum is reached before flowering.

Both variety and growing conditions can affect stem reserves by about 2 t/ha. Some crops can store more than 4 t/ha. Varietal differences may be due to both total stem weight and percentage of soluble material.

Recent UK varieties have 25–35% of stem biomass as soluble reserves. Environmental differences in stem reserves commonly relate to differences in stem number. Soluble stem carbohydrate is not affected by PGR applications.

Dry matter redistribution during grain filling

B 2.9 t/ha, of which 1.9 t/ha soluble carbohydrate

Varietal influence: High

Other influences: Redistribution of soluble reserves lasts from 26 days after flowering to the end of grain filling. The loss in straw dry matter between flowering and harvest is 2.9 t/ha, comprising 1.9 t/ha soluble stem reserves and protein from leaves and stems.

Reserves contribute significantly to yield under all post-flowering conditions. Varieties with highest yield potential tend to be those that accumulate greatest amounts of stem soluble carbohydrate. Stem carbohydrate storage is not included in the Recommended List but wheat breeders may be able to provide information on varietal differences.

Stem reserves contribute similar amounts of assimilate in stressed or unstressed crops. However, because yields are reduced in stressed crops, reserves contribute a higher proportion.

How to measure stem reserves

After stems are fully extended, pull up at least 10 stems (taking care not to break them) and remove leaf laminae, roots and ears. Dry the whole stems rapidly (at around 100°C), weigh them and send them for analysis by an appropriate laboratory. To determine the soluble stem reserves on an area basis, you will need to know the number of tillers in an area and multiply this by the Water Soluble Carbohydrates (WSC) per stem.

AHDB RECOMMENDED

For current information on wheat yields associated with commercial varieties, see the AHDB Recommended Lists. **ahdb.org.uk/rl**

Ear formation

Capacity for grain filling is set by grain number per unit area and the storage capacity of each grain.

Key facts

- Ear weight increases rapidly during booting
- Ear weight at flowering is the same as the weight of chaff at harvest. It relates closely to final grain number and hence storage capacity of the ear
- Grain number per ear is largely controlled by survival of flower initials (florets) while the last leaves and ear are emerging

Ear development

B 18 days from flag leaf to ear emergence

Varietal influence: High

Ears are initiated during the foundation phase and spikelet initiation is completed as stem extension starts (GS31). Floret initiation and development then proceed until flowering. The number of potentially fertile florets depends on assimilate supplies to the ear, particularly during booting, and is affected by shoot numbers. At shoot numbers of over 400/m^2, mutual shading results in fewer grains in each ear.

Weather affects ear development, especially during booting and ear emergence. Cool, bright conditions one or two weeks before flowering can prolong or enhance the ear formation period and increase grain number per ear. However, inclement weather at flowering, such as heavy rain, heat or drought, can impair pollination and reduce the number of fertilised florets.

Grain number

B 48 grains/ear – 22,000 grains/m^2

Varietal influence: High (grains/ear)

Other influences: Shoot numbers, pests

The benchmark for grain number per ear is 48. With 460 surviving fertile shoots/m^2, this gives 22,000 grains/m^2, illustrated in Figure 26.

Varieties with smaller culm leaves tend to have more shoots/m^2 and fewer grains/ear. Breadmaking varieties tend to have fewer grains/ear than other varieties.

Some insects, such as orange blossom midge, can reduce grain numbers and feed on developing grains.

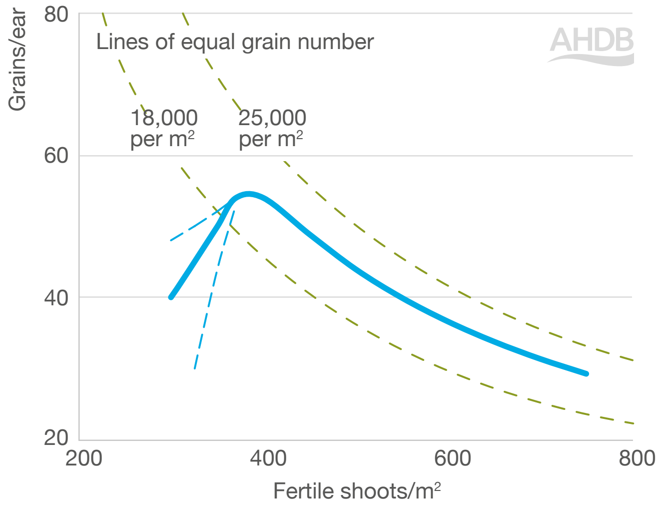


Figure 26. Grain numbers in the ears can compensate above 400 shoots/m^2

Ear weight at flowering

B 420 mg/ear (dry weight)

Varietal influence: High

Other influences: Photosynthesis during the construction phase

By flowering, the benchmark ear weight is 420 mg/ear, comprising glumes, florets and rachis. These components remain of similar weight throughout grain filling and become the chaff at harvest. As a result, ear weight at flowering multiplied by fertile ear number per unit area can indicate yield potential.

Photosynthesis in the ear contributes significantly to grain growth. The benchmark final ear weight at harvest is 2.8 g, 15% of which is chaff.

Implications for management

In wheat, yield variation due to region, soil type and early crop management is more strongly related to grain number rather than the weight of each grain. Hence, to realise potential yield, it is usually essential to maximise grain numbers. Severe disease or drought can significantly reduce grain size.

Grain filling and ripening

Grain filling depends on ear and leaf photosynthesis, as well as redistribution of stem reserves.

Key facts

- Grain filling starts when flowering is complete and continues until grain reaches about 45% moisture
- After flowering, grains swell (largely by water uptake). Rapid dry weight growth continues with starch and protein deposition in expanded grain cells – these are supplied by both photosynthesis and redistribution of reserves
- Ripening and moisture loss continue after grain filling until the grain is dry enough to harvest

Grain filling

B 43 mg dry matter per grain in 45 days from flowering to 26 July

Varietal influence: Medium

Other influences: Water availability, disease

Grain filling determines final dry grain weight. This final stage in yield formation influences grain appearance and specific weight.

Grains accumulate more water than dry matter for about four weeks after flowering, when water content is at its maximum. Water enables cells first to divide, then expand. As water uptake stops, dry matter accumulation accelerates.

Suboptimal photosynthesis during the first two or three weeks of grain growth will reduce the cell number and potential weight of each grain.

The benchmark period from flowering until maximum dry weight (the grain filling period) is 45 days, but it varies considerably; it can be just 28 days in severe drought conditions. The benchmark weight/grain is 43 mg dry matter, which equates to a 'thousand grain weight' of 50 g at 15% moisture. Varietal differences in average grain weight are shown in the AHDB Recommended List.

Canopy survival during grain filling

B GAI <2 after maximum grain weight achieved

Varietal influence: Medium

Other influences: Nitrogen supply, foliar disease

Canopies start to senesce rapidly from GS71, about nine days after flowering. Most remaining greenness is lost just after grain weight reaches its maximum.

High nitrogen uptake, fungicide use or cool, moist weather all tend to delay senescence. Crops at northerly latitudes generally have high grain weight because cooler temperatures prolong grain filling. Hot weather reduces grain weight by shortening the period of grain growth, even in bright and moist conditions. Grain weight is also reduced by leaf or root disease, pest infestation or early lodging.

Ripening

B 45 to 20% moisture content in two weeks

Varietal influence: Low

Other influences: Lodging

After grain filling, moisture content provides the best indication of ripening until grains are dry enough to harvest. On average, grain takes about two weeks to dry, from 45 to 20% moisture. Frequent rain re-wets grain and slows moisture loss, especially at low moisture contents. Lodged crops dry slowly.

How to measure grain filling, moisture and ripening

The grain filling period can be estimated by counting the number of days between GS65 and when the gain reaches 45% moisture content. Grain moisture can be determined by weighing grain threshed from around 20 ears, drying at 80–100°C until no further weight loss and weighing again.

Moisture content = 100 - (grain dry weight ÷ sampled grain weight) x 100.

The grain ripening period is then the number of days from 45% moisture until it reaches 20% moisture.

If a grain sample is taken at the end of the grain filling period, the dried and weighed grain can then be counted and divided by the number of grains to determine the dry matter per grain.

Implications for management

No further grain filling occurs once grain moisture is below 45%, at around GS87, so yield cannot be affected by any treatment applied at or after this stage.

- Consider using a desiccant (approved for use at less than 30% moisture, GS91) if harvest timing is threatened by inclement weather

Yield

Yield depends on the number of ears per unit area and the weight of each grain.

Key facts

- Grain dry weight usually constitutes about half of final crop dry weight
- Grain yield is the product of three components: ears/m², grains/ear and individual grain weight

Grain yield

B 11.0 t/ha at 15% moisture

Varietal influence: Medium

Other influences: Radiation and rainfall, soil type, soil depth and condition, all aspects of husbandry

Grain is the principal product of crop growth, especially in June and July. Yields, therefore, depend on the state of the crop leading into this period and then on growing conditions during this period.

There is also an important genetic component to yield. The AHDB Recommended Lists can be used to understand performance of varieties.

Yield components

B 460 ears/m²

B 48 grains/ear

B 50 mg/grain

Varietal influence:

- Ear number – Medium
- Grains/ear – High
- Grain weight – Medium

Other influences: All aspects of husbandry, weather

Ear number/m², grains/ear and grain weight are key yield-determining attributes at harvest. Their values are related to the success of different growth phases:

- Ear number reflects growth from the start of tillering to flag leaf appearance (GS39)
- Grain number/ear reflects growth from GS39 to flowering (GS61)
- Individual weight/grain reflects growth after flowering

Each phase partially compensates for the outcome of earlier phases. A crop with a sparse shoot density tends to produce more grains/ear and heavier grains than a thick crop. Conversely, poor performance in one phase increases reliance on good growing conditions in later phases, so the yield is at greater risk from adverse weather.

Final distribution of dry matter

B 18.4 t/ha dry matter with 51% Harvest Index

Varietal influence:

- Total crop dry matter – Medium
- Harvest Index – High

Other influences: All aspects of husbandry

The Harvest Index is the proportion of total dry crop biomass growth (dry matter) that is harvested as grain (Figure 27).

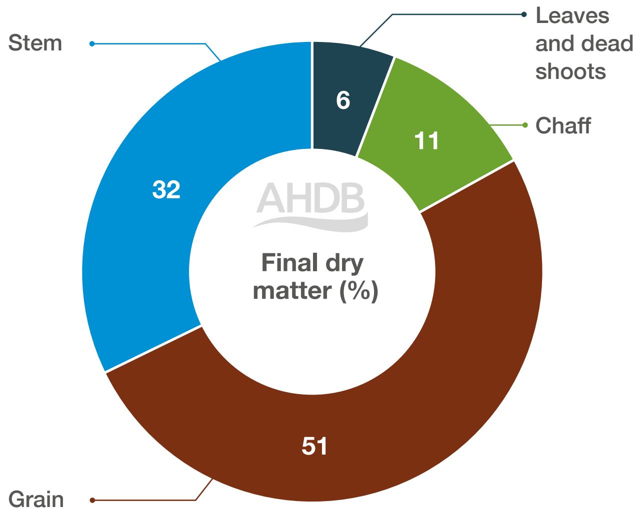


Figure 27. Percentage final dry matter distribution in wheat

The benchmark dry matter of the harvest-ripe crop is 18.4 t/ha, of which 9.4 t/ha is grain (equivalent to 11.0 t/ha at 15% moisture).

The remaining 9 t/ha of dry matter includes straw, chaff and stubble (Figure 27). Only about half of this can be baled as straw, even when the height of the combine cut is low. Much variability in crop dry weight comes through changeable production of non-harvestable material. Plant breeders have been most successful in increasing Harvest Index; growers have been most successful in increasing total crop dry matter.

Nitrogen redistribution

Most grain protein is formed from redistributed nitrogen. Around 158 kg/ha of nitrogen comes mainly from stems, leaves and roots as they die. Only an additional 31 kg/ha of grain nitrogen comes from uptake after flowering.

The straw and chaff contain 90 kg/ha nitrogen at harvest – 32% of total crop nitrogen – making the nitrogen harvest index 68%.

Protein deposition

B 189 kg/ha nitrogen or 1.1 t/ha protein

Varietal influence: Low

Other influences: Nitrogen rate and timing

The weight of grain protein relates directly to the weight of nitrogen, with a ratio of 5.7 to 1. The benchmark amount of grain nitrogen is 189 kg/ha, equating to about 1.1 t/ha protein. Soil type, season and husbandry all influence grain protein deposition.

Generally, the later nitrogen fertiliser is applied, the more grain nitrogen is increased. Applying urea as a spray when grain is milky ripe (GS75) has the largest effect on grain nitrogen, but normally has little effect on yield.

Implications for management

Accurate measurement of yield is essential to assess the success of husbandry and plan approaches for future yield enhancement.

- Ensure combine yield monitors are calibrated to manufacturer's instructions

High levels of grain nitrogen are essential for wheat destined for breadmaking.

- Consider an application of urea at GS75 to increase grain nitrogen

On-farm trials

Split field or tramline trials can be used to test the success of management strategies, including:

- Fertiliser rates, timings or products
- Varieties
- Cultivation or establishment practices
- Fungicide programmes

To draw valid conclusions, it is necessary for trials to be fair and to test only one factor at a time. To conduct fair tests, consider:

- Using past yield maps to pick equivalent areas of a field to compare
- Replicating treatments in more than one tramline within a field
- Replicating a trial in more than one field
- Excluding headlands from 'trial' areas – harvest the headlands first, then measure the size of the treatment areas accurately. Finally, harvest the treatment areas and determine the grain weight from each

How to measure grain yield

Grain yield can be determined in a number of ways. Yield mapping combines are now common, but it is important that these are set up appropriately and calibrated. If mapping is not available, grain can be weighed over a weighbridge. The moisture content of the grain must be known so that yields can be adjusted to 85% dry matter.

On a smaller scale, yield and Harvest Index (HI) can be determined from quadrat samples (as per the method in the How to measure dry matter section on page 25) taken just before harvest. To determine the HI, after weighing the whole dried sample, the grain should be threshed and weighed separately.

HI (%) = (Dry weight of grain ÷ Dry weight of whole plant (grain, straw, chaff) × 100

It is important to know the moisture content of grain to determine yield at 85% dry matter and to store grain effectively (including drying strategies). Most farms have handheld moisture meters and grain intake labs also boast this facility. If meters are unavailable, a grain sample can be taken, weighed, then dried and weighed again to calculate the moisture content.

For the grain weight, the thousand grain weight (TGW) is the commonly used metric measurement. Weigh out 40 g of dried grain as accurately as possible. Count the number of grains in this sample, then calculate the TGW using:

TGW (g) = (Weight of dried grain sample (g) ÷ Number of grains in sample) x 1,000

Grain quality

Quality characteristics are highly heritable. Values published in the AHDB Recommended Lists should be used as benchmarks for specific varieties.

Key facts

- Specific weight partly depends on grain size, grain density and grain packing characteristics
- Hagberg Falling Number, which reflects the gelling properties of flour made from whole grain, is affected mainly by variety rather than husbandry
- Grain protein is related directly to grain nitrogen: it is increased by protein deposition and diluted by other grain growth
- Grain protein levels acceptable for breadmaking are usually more consistently achieved in second (rather than in first) wheat crops

Grain protein concentration

Varietal influence: High

Other influences: Nitrogen rate and timing, grain yield

Protein concentration (and protein quality) is highly dependent on variety and determines the variety's end-use suitability. Weather and management of the crop, however, are also very influential.

High concentrations of grain protein can arise either from large nitrogen uptake or poor starch formation during grain filling. Providing both are fertilised optimally, first wheats tend to have grain percentages below those of second wheats. Protein contents of first wheats are usually diluted by their greater yields.

Conversely, factors that reduce yield without affecting nitrogen transport to grain, such as drought, early lodging or some diseases*, may raise protein.

*Powdery mildew is an exception, as it lowers protein percentage by interfering with nitrogen transport.

Specific weight

Varietal influence: High

Other influences: Delays to harvest, lodging

Crops with a large grain weight tend to have a high specific weight. It is also influenced by:

- The range of grain sizes
- The density of individual grains
- Characteristics of grain surfaces that affect packing

Specific weight indicates the weight of grain that can be loaded onto lorries or ships. A typical requirement for milling or export is 76 kg/hl. Samples below this requirement are likely to incur price penalties or be excluded from the intended market.

Late harvests can reduce specific weight through weathering.

Hagberg Falling Number

Varietal influence: High

Other influences: Delays to harvest, lodging, pests

Hagberg Falling Number (HFN) is a measure of hot paste viscosity, expressed as the number of seconds (s) taken for a plunger to fall through a wholemeal water suspension. The minimum value possible is 60s. The minimum value required for breadmaking is 250s, and for soft wheat for export, 220s. Lower viscosity results from starch breakdown by alpha-amylase. This enzyme may form during or after ripening.

Enzyme activity is associated with initiation of germination and hence with sprouting. Alpha-amylase may also form in cool, wet weather during ripening, even in the absence of visible sprouting. Green grains on late tillers or grains damaged by orange blossom midge also have high alpha-amylase.

Effects of husbandry on HFN tend to be small and inconsistent compared to the effects of variety and weather. Varietal differences in HFN are indicated in the AHDB Recommended Lists. Group 1 wheats are generally classed as 'very high'.

How to measure grain quality

Specific weight can be measured by hand using a chondrometer. Grain is, however, routinely measured at intake labs, using an NIR grain analyser, which can also give readings for moisture content and protein concentration. Grains can also be sent to a specialist lab for protein determination by methods such as Dumas or Kjeldahl.

There is an international standardised method for determining HFN. This requires specialist equipment, which many intake labs have.

Implications for management

By GS91, management can only protect against losses of yield or quality.

- Depending on intended market and likely risks, consider:

  Harvesting as soon as the crop is ripe

  Assessing HFN pre-harvest on hand-threshed, air-dried grain

  Harvesting at high moisture to optimise chances of high HFN

Glossary

Anthesis In wheat, anthesis is normally recognised by appearance of pollen sacs (anthers) from florets within the ear. This signifies pollination. Anthesis is also known as flowering

Assimilate The product of the crop's synthetic processes, mainly photosynthesis. Measured as dry matter

Benchmark A quantitative reference point against which a crop's performance can be compared

Canopy The above-ground parts of wheat plants capable of photosynthesising

Carbohydrates Synthesised entirely from carbon dioxide and water, these are mainly starch and cellulose, which are not 'soluble' or mobile, and sugars (e.g. fructan), which are 'soluble' as they dissolve in water and are mobile in the plant

Chondrometer A machine used to measure specific weight

Coleoptile The first leaf structure to emerge from the seed at germination. It protects the first true leaves during emergence of the seedling. It has little chlorophyll but may give rise to tillers

Culm An alternative term for stem

Development Changes in crop structure, as defined by the decimal Growth Stage (GS) code

Day degrees See thermal time

Dormancy A condition in which grains do not germinate in the presence of adequate moisture, temperature and air

Dry matter Crop constituents other than water, left after tissue has been dried. Often, 'total dry matter' refers to just the above-ground parts of the crop

Floret The primary sub-component of a spikelet. Each floret bears one grain; while they retain this potential, they are termed fertile florets

Frost heave Lifting of the soil surface, caused by freezing of moisture in the topsoil and expansion, often leading to stretching and breaking of roots and other sub-surface structures

Fructan A form of sugar, a polymer of fructose (the main component of soluble carbohydrate), used by wheat and other grass species as storage assimilate in stem tissues

GAI Green Area Index. The ratio between the total area of all green tissues, one side only, and the area of ground from which they came

Growth Changes in crop size or weight

Growth phase Period during which a specific crop structure is produced

Growth stage A finite point in a crop's development

Hagberg Falling Number A measure of the hot paste viscosity of a wholemeal suspension in water. In the laboratory, a suspension of flour is heated in water for a fixed period. The time in seconds taken for a plunger to fall through the resultant gel is recorded as the 'Hagberg Falling Number'

Harvest Index The ratio between grain yield on a dry basis and the total crop dry weight at harvest

Internode The section of stem between two adjacent nodes

Leaf blade The upper portion of a leaf, from the tip to the ligule (junction with the sheath)

Leaf sheath The basal portion of a leaf that encloses the stem and sheaths of younger leaves

Ligule A small structure at the junction of leaf sheath and leaf blade

Lodging Permanent displacement of a stem or stems from a vertical posture. Lodging can be considered as an event occurring within one day, although lodged stems may initially lean rather than lie horizontally

Main shoot The primary axis of the plant on which the primary tillers are borne

Mean The average. The sum of all the values divided by the number of values

Median The middle value when all values are ranked by size. Medians may provide more robust summaries than means because they are not influenced by exceptional values

NVZ Nitrate Vulnerable Zone. Areas determined to pose a risk of nitrates leaching into watercourses. These areas are subject to regulations that must be complied with by farmers

Node The point at which a leaf sheath is attached to a stem

Partitioning The division of dry matter between organs

Peduncle The topmost internode, between the flag leaf node and the base of the ear (the collar)

PGR Plant growth regulator. The 'full PGR programme' used to grow the benchmark crops included chlormequat at the end of tillering and GS31 and Terpal at GS37 to GS39

Photosynthesis Formation of carbohydrates by green tissues from absorbed carbon dioxide and water, driven by energy from sunlight

Phyllochron The interval in thermal time from emergence of one leaf tip on a shoot to emergence of the next. Phyllochron is the reciprocal of leaf emergence rate

Pollination Reception by the stigma of pollen produced in the anthers and bearing the male genetic complement, leading to fertilisation of the ovum, which bears the female genetic complement. Fertilisation of wheat normally occurs within one floret, rather than between florets

Rachis The portion of the stem within the ear (above the collar) bearing the spikelets

Respiration Degradation of sugars and the associated absorption of oxygen and emission of carbon dioxide (and water) to yield energy for crop metabolism

Ripening The changes that occur in the grain between completion of growth and maturity. These include drying, development and loss of dormancy. Grain is considered 'ripe' when it is ready for harvest – at less than 20% moisture

Senescence Loss of greenness in photosynthetic tissues, normally brought about by ageing, but also by diseases or drought

Shoots All the axes of a plant with the potential to bear an ear. The main shoot and all tillers are included. Shoots retaining the potential to form grain are termed 'fertile shoots'

Soil stability The tendency for soil aggregates to retain their integrity when wetted and disturbed. It is measured by assessing how easily aggregates break up into fine particles

Specific weight The weight of grain (corrected for variation in moisture content) when packed into a standard container. It is expressed in kilograms per hectolitre (100 litres)

Spikelet The primary sub-component of the ear. About 20 spikelets are borne on alternate sides of the ear stem or 'rachis', and there is one 'terminal spikelet'. Each spikelet is contained within two glumes and consists of several fertile florets

Thermal time The sum of all daily temperatures (mean of maximum and minimum) above a base temperature below which the process in question stops. In the case of leaf development, this is 0ºC. Results are expressed in 'day degrees' (ºC days)

Tiller A side shoot. Thus 'tillers' do not include the main or primary shoot

Transpiration Loss of water vapour from a crop's green surfaces, mainly through leaf pores (stomata)

Vernalisation A change in the physiological state of a plant from vegetative to reproductive brought about by a period of cold – can be applied to seeds or (in the case of wheat) to the young plant

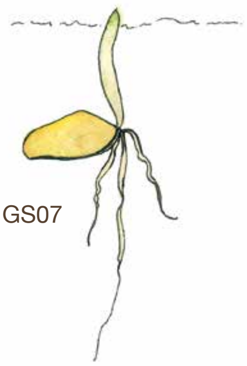
Waterlogging Filling of soil pores with water to the extent that there is insufficient oxygen for normal root function

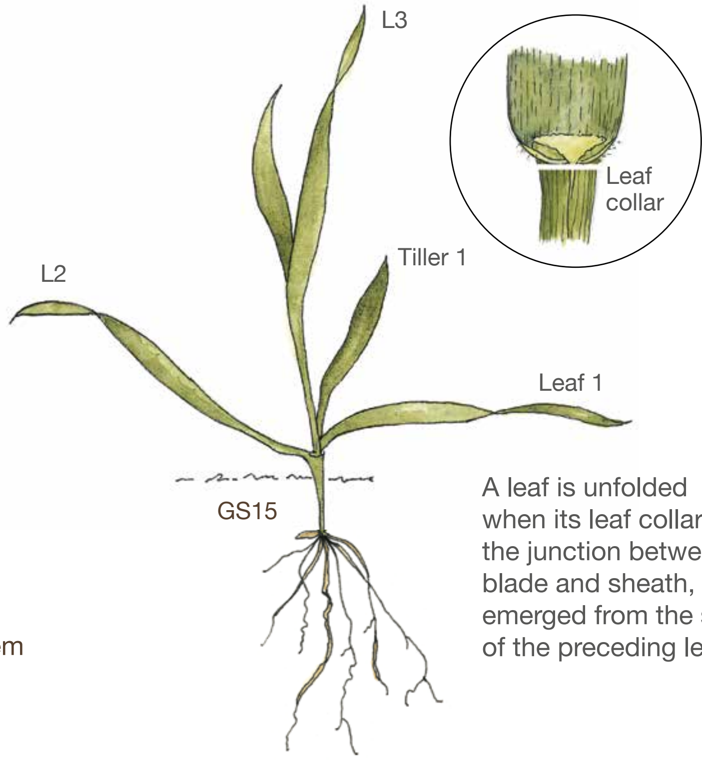
Cereal growth stages and benchmarks

Decimal growth stages (GS) can be used to identify the most appropriate benchmark during the season. The stages can also be used to guide spray timings.

Germination

GS07 Germinating seed with root (which forms first) and shoot

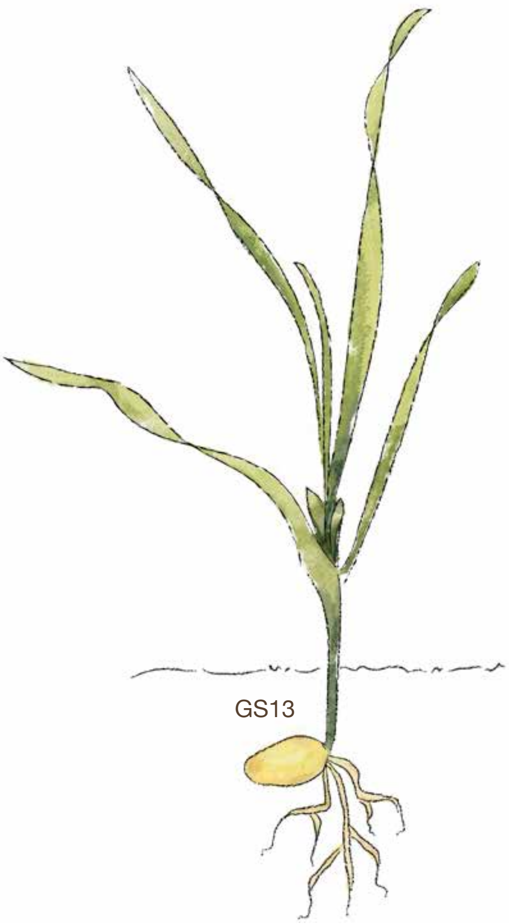


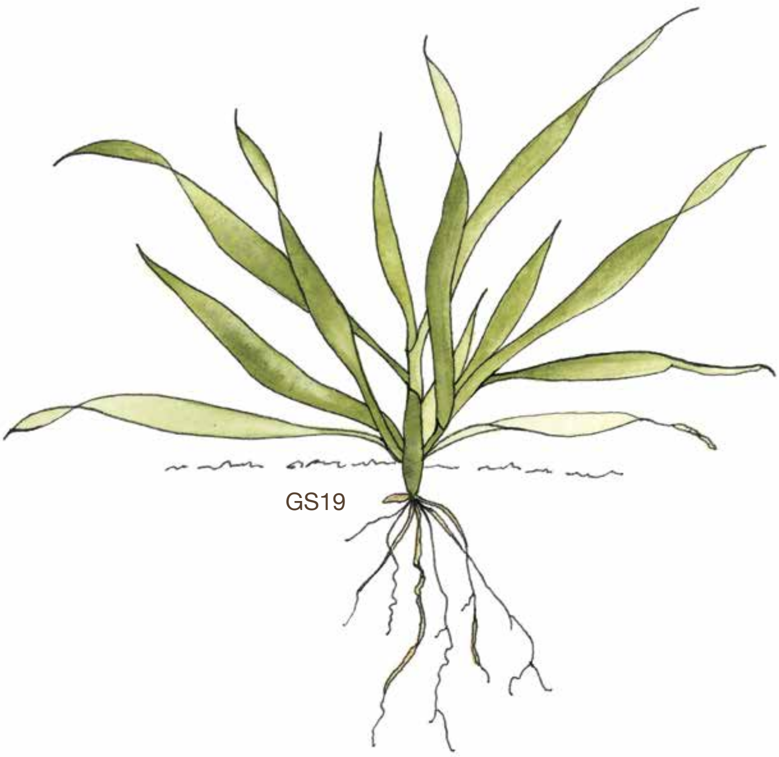


Seedling growth

GS10 First leaf through coleoptile
GS11 First leaf unfolded (ligule visible)
GS13 Three leaves unfolded on the main shoot
GS15 Five leaves unfolded
GS19 Nine or more leaves unfolded on the main stem

A leaf is unfolded when its leaf collar, at the junction between blade and sheath, has emerged from the sheath of the preceding leaf.





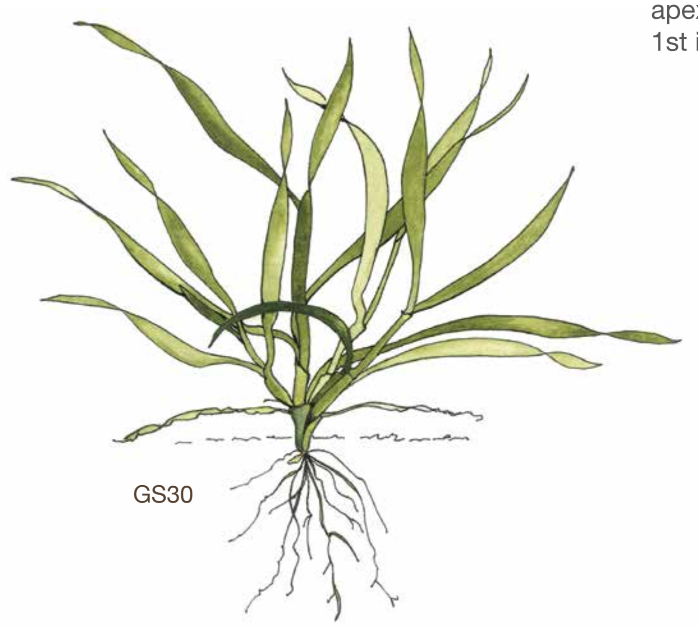
Tillering

GS20 Main shoot only
GS21 Main shoot and one tiller. (See Fig.10, page 13)
GS23 Main shoot and three tillers
GS25 Main shoot and five tillers
GS29 Main shoot and nine or more tillers

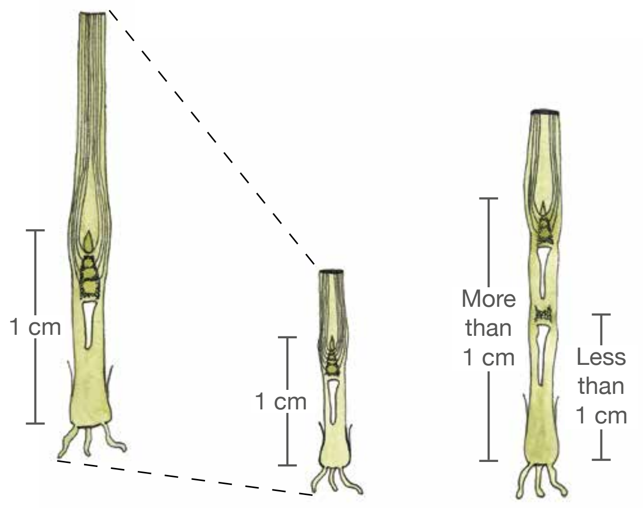
Stem elongation

GS30 Ear at 1 cm (pseudostem erect)
GS31 First node detectable
GS32 Second node detectable
GS33 Third node detectable
GS37 Flag leaf just visible
GS39 Flag leaf blade all visible

GS30	31 March	Ear at 1 cm
Plants	260/m^2	70% of seeds sown
Shoots	941/m^2	Tillering ceases when GAI >1
Roots	0.4 t/ha; 12 km/m^2	Little of the soil is fully rooted
GAI	1.6	Only enough to intercept 45% of light


GS30

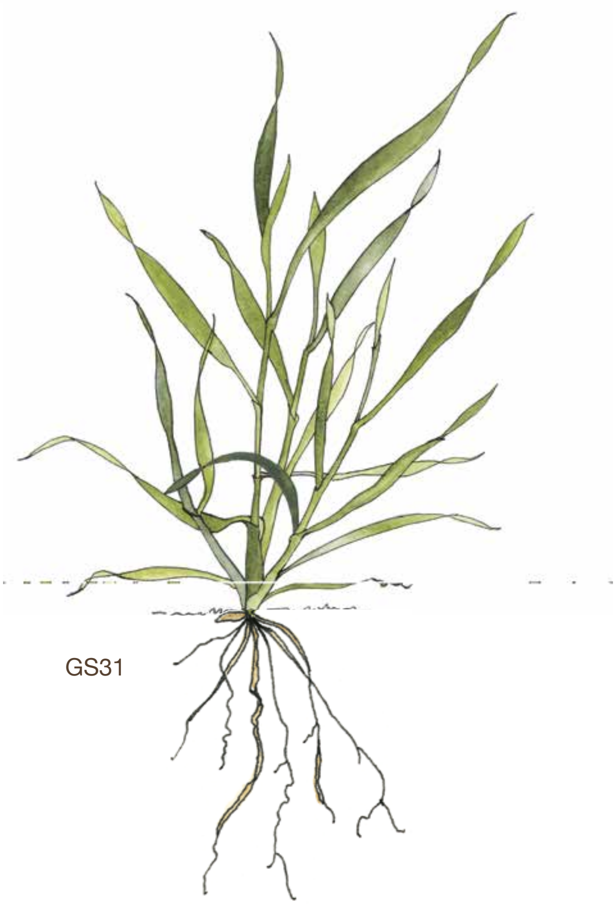
Distance between base of the plant and the top of the shoot apex on the main stem is 1 cm or more, but the length of the 1st internode is less than 1 cm.



When stem elongation begins it is necessary to split the main shoot to determine the correct crop Growth Stage.

For a quick, but crude assessment, fold back the leaf sheaths then count the slight 'bumps' caused by each node.

The exact stage is revealed by stripping off leaves and cutting the main stem longitudinally with a sharp knife.


GS31

GROWTH STAGE 31

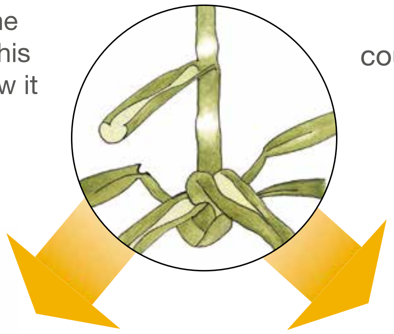
1st node detectable An internode is 1 cm or more but the internode above is less than 2 cm

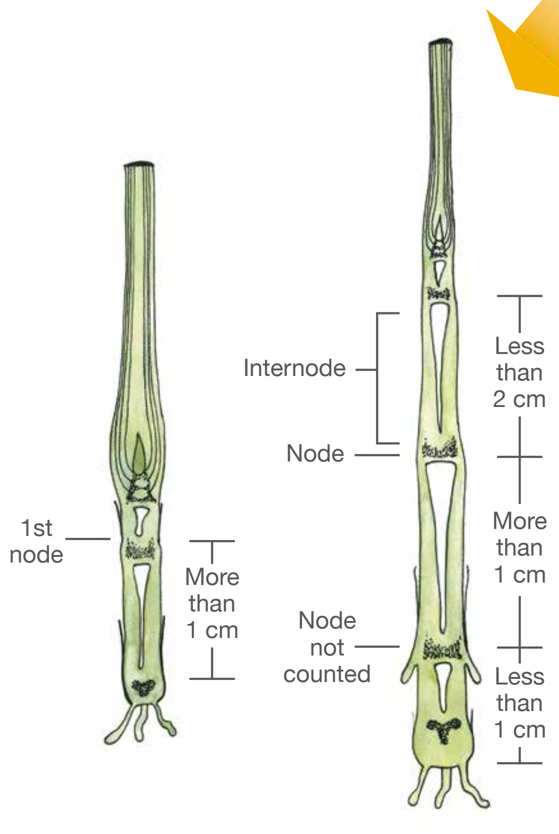
Sometimes a node may be below the ground and may bear roots. Even if this occurs, as long as the internode below it exceeds 1 cm it is still counted.

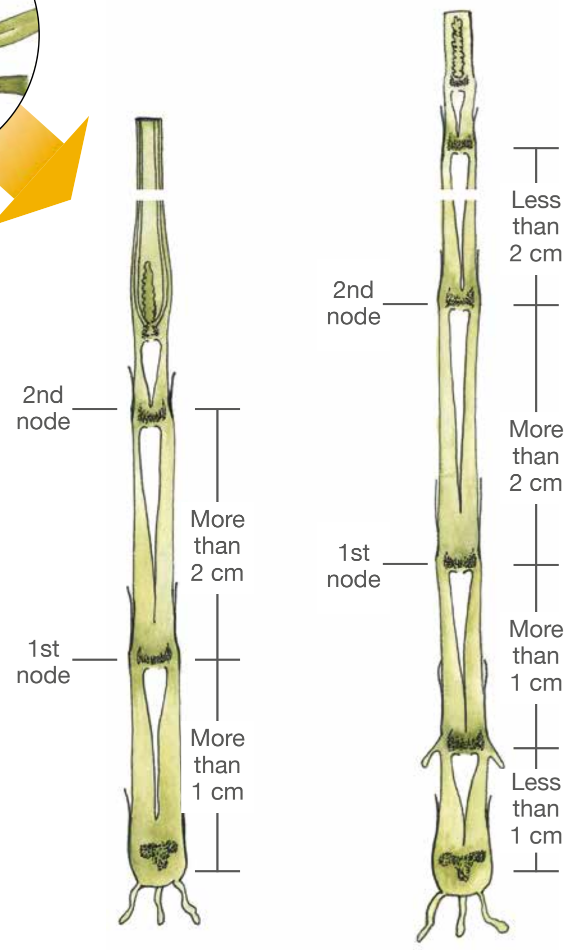
GROWTH STAGE 32

2nd node detectable

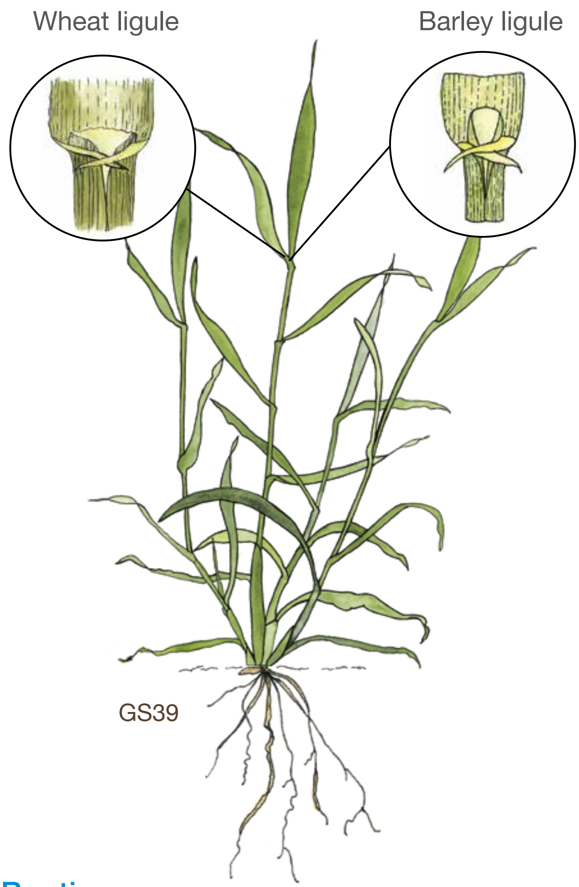
2nd and subsequent nodes counted when the internode below them exceeds 2 cm.







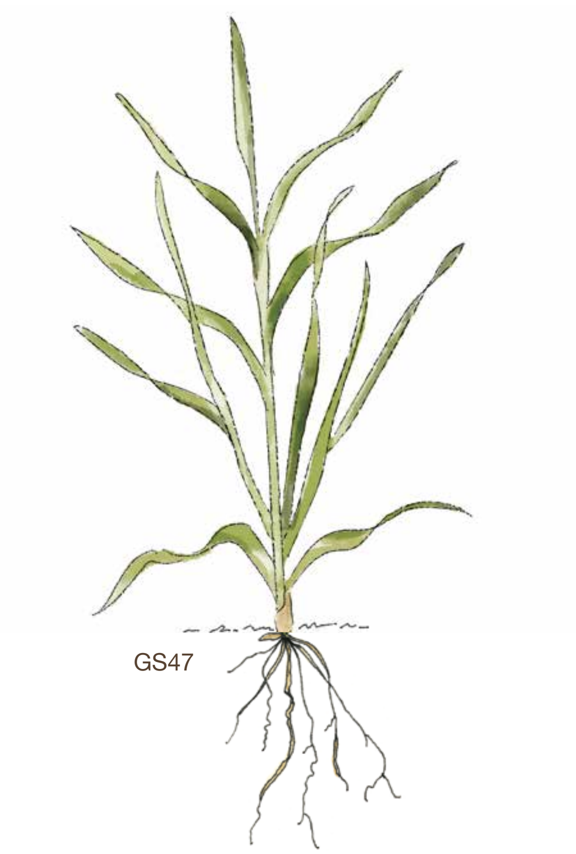
GS31	10 April	First node detectable
Shoots	902/m^2	Shoot numbers usually decrease from GS31
Three leaves yet to emerge	28 April 9 May 19 May	One leaf emerges every 122 degree days
Roots	0.5 t/ha; 15 km/m^2	Roots now reach to about 1 m depth
Nitrogen uptake	81 kg/ha	About 30% of final uptake
GAI	2.0	Only enough to intercept half the light
Above-ground dry weight	1.9 t/ha	Only 10% of final dry weight
Growth rate	0.16 t/ha/day	During the construction phase (GS31 to GS61)
Height to top ligule	9 cm	Stem extension just starting



GS39	19 May	Flag leaf blade all visible
Fertile shoots	655/m^2	Some young shoots are still dying
Total leaf number on main shoot	14	No further leaves emerge
Nitrogen uptake	189 kg/ha	Increasing by 2.5 kg/ha/day
GAI	6.2	Enough to intercept 95% of light
Above-ground dry weight	6.9 t/ha	About 35% of maximum growth
Height to top ligule	34 cm	Subsequent extension

Booting

GS41 Flag leaf sheath extending
GS43 Flag leaf sheath just visibly swollen
GS45 Flag leaf sheath swollen
GS47 Flag leaf sheath opening



Ear emergence

GS51 First spikelet of ear just visible above flag leaf ligule
GS55 Half of ear emerged above flag leaf ligule
GS59 Ear completely emerged above flag leaf ligule

GS59	6 June	Ear completely emerged
Fertile	495/m^2	Little further shoot death occurs
Nitrogen uptake	230 kg/ha	36 kg nitrogen/ha per unit GAI
GAI	6.4	GAI is falling from its maximum of 6.9 in late May
Above-ground dry weight	11.4 t/ha	Growth may slow if flowering is delayed
Height to collar	53 cm	Five internodes extend

Flowering

GS61 Start of flowering
GS65 Flowering halfway
GS69 Flowering complete

GS61	11 June	Start of flowering
Fertile shoots	460/m^2	150 additional infertile shoots/m^2 remain until harvest
Roots	1.0 t/ha; 31 km/m^2	Sufficient for full moisture capture to 70 cm depth. Deepest roots reach to ~1.5 m. Maximum root system size reached
Nitrogen uptake	248 kg/ha	Only 30 kg/ha further uptake occurs
GAI	6.3	Canopy senescence is slow
Above-ground dry weight	12.1 t/ha	About two-thirds of final dry weight
Growth rate	0.18 t/ha/day	During most of the production phase (GS61 to GS87)
Height to collar	69 cm	Little further extension occurs
Stem dry weight	7.1 t/ha	33% is soluble, giving 2.3 t/ha for redistribution
Ears	1.9 t/ha	Ears have 48 grain sites after flowering. Each ear weighs 420 mg (dry) both now and as chaff at harvest


Wheat


GS65


Barley

Milk development

GS71 Grain watery ripe
GS73 Early milk
GS75 Medium milk
GS77 Late milk

GS77

GS71	20 June	Grain watery ripe
GAI	5.7	Rapid senescence now starts
Stem dry weight	7.6 t/ha	Now at its maximum. Rapid redistribution of soluble reserves begins at GS73
Above-ground dry weight	13.7 t/ha	All further increase occurs in the grain

Dough development

GS83 Early dough
GS85 Soft dough
GS87 Hard dough (thumbnail impression held)

GS85

GS87	29 July	Grain at 'hard dough'
GAI	1.3	All greenness will be lost in the next few days
Above-ground dry weight	19.6 t/ha	About 1.2 t/ha is subsequently lost, mainly from the straw
Grain filling	Lasts 45 days	Grain filling stopped at about 45% moisture, about 3 days before GS87

Ripening

GS91 Grain hard (difficult to divide)
GS92 Grain hard (not dented by thumbnail)
GS93 Grain loosening in daytime

GS91

Harvest ripe	9 August	
Ears (fertile shoots)	460/m^2	At least 400 shoots/m^2 required to avoid yield loss
Nitrogen uptake	279 kg/ha	68% of final crop nitrogen is in grain, 32% in chaff, straw and stubble
Above-ground dry weight	18.4 t/ha	51% grain, about 10% chaff, the rest as straw and stubble
Straw dry weight	7.3 t/ha	Includes stems and leaves; only 0.2 t/ha soluble sugars remains
Chaff dry weight	2.0 t/ha	Chaff is 420 mg/ear
Grain weight	50 mg at 15% moisture	Specific weight 78 kg/hl
Grain protein	11.5% (dry basis)	Calculated as 2.0% nitrogen x 5.7
Grain yield	11.0 t/ha at 15% moisture	Shedding losses are 0.03 t/ha

Further reading

Barley growth guide
ahdb.org.uk/barleygg

Nutrient management guide (RB209) and RB209 app
ahdb.org.uk/RB209

Field drainage guide
ahdb.org.uk/drainage

Recommended Lists for cereals and oilseeds
ahdb.org.uk/rl

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