Nutrient Uptake and Metabolism in Crops

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Summary

Nutrient uptake is the mechanism by which plants capture all those elements that are essential for their growth. Metabolism is a series of chemical processes that occur within a plant that include either synthesis or breakdown of organic compounds. Nutrient uptake depends on a number of factors, including plant species, environmental conditions, nutrient supply and interrelationship among nutrients and between plant and soil, presence of microorganisms (e.g., fungi) in association with plant roots, etc. From a practical perspective, nutrient uptake determines the quantities of nutrients exported from a field via harvest and the requirements for their replenishment.

Introduction

Plant nutrients are chemical elements that are essential for plant growth. For an element to be essential it must be required by the plant to complete its life cycle and no other nutrient can replace it. If an element does not meet all of these requirements, for example, being required by some plants or only enhancing the growth of plants, the element may be a beneficial element. Much interest in plant nutrition lies in the development and use of diagnostic techniques for assessment of the status of plants with respect to plant nutrients and beneficial elements.

Background

Plants have evolved much differently than animals and this is reflected in the way they utilize nutrients. In contrast to animals that are **heterotrophic**, plants are **autotrophic**. What does this mean? Well "hetero", from the Greek word héteros, means other and "trophic", from the Greek word trophé, means food, so in other words animals cannot make their own food and need to rely on synthesized food. On the other hand, plants or "auto" (from the Greek word eautós, which means self) trophic make their own food. Therefore, plants to consume food in very simple forms (i.e., ions and molecules), unlike animals that require complex compounds (often other animals and, of course, plants) to complete their nutrition. Another major difference is that plants can **photosynthesize** and animals cannot. Actually, **photosynthesis** (from the Greek word "phos", meaning light and "synthesis", meaning composition) is a very complex, but at the same time the single most important mechanism, which allows plants to use atmospheric carbon dioxide as well as water and energy from the sunlight to manufacture their own food (please, see **Chapter 6** for more information). Furthermore, plants themselves have

parts that are autotrophic, such as the leaves, and parts that are heterotrophic, such as the roots that depend on the leaves to supply them with their food. Overall, however, plants are autotrophic (please, see **Chapter 1** for more details).

Nutrition is a process by which every living organism, whether plant or animal, ingests and assimilates its food. From a plant perspective, nutrients are all those elements that are **essential** for plant growth (**Table 1**). Nutrient uptake is the mechanism by which plants capture those essential elements. The first experiments to understand nutrient uptake were carried out by Hoagland[2]. To understand nutrient uptake and metabolism by plants, we also need to have a basic understanding of how nutrients enter into the plants; in animal terms, how plants "eat nutrients". Everything starts with the smallest living entity, a **cell** (**Figure 1**). Cells that are responsible for photosynthesis (also known as mesophyll cells) as well as cells of the root cortex are about 20-100 micron (μm) in length; but plant cells include organelles (e.g., mitochondria, chloroplasts, ribosomes, etc.) that are only a few nm in size.

Table 1. Essential nutrients for plant growth

Non Mineral Nutrients		Mineral Nutrients					
		Macronutrients				Micronutrients	
		Primary (Major)		Secondary			
Element	%[1]	Element	%	Element	%	Element	%
Carbon	42	Nitrogen	1.4	Sulphur	0.1	Chlorine	0.01
Hydrogen	6	Phosphorus	0.2	Calcium	0.5	Iron	0.01
Oxygen	48	Potassium	1.0	Magnesium	0.2	Manganese	0.005
						Zinc	0.002
						Boron	0.002
						Copper	0.0006
						Molybdenum	0.00001
						Nickel	<0.00001
Totals	*96*		*2.6*		*0.8*		*0.04*

[1] % denotes percentage concentration or content in plants. These are general numbers to be looked at as guidelines. Actual numbers vary with crops and cultivars (varieties) within crops.

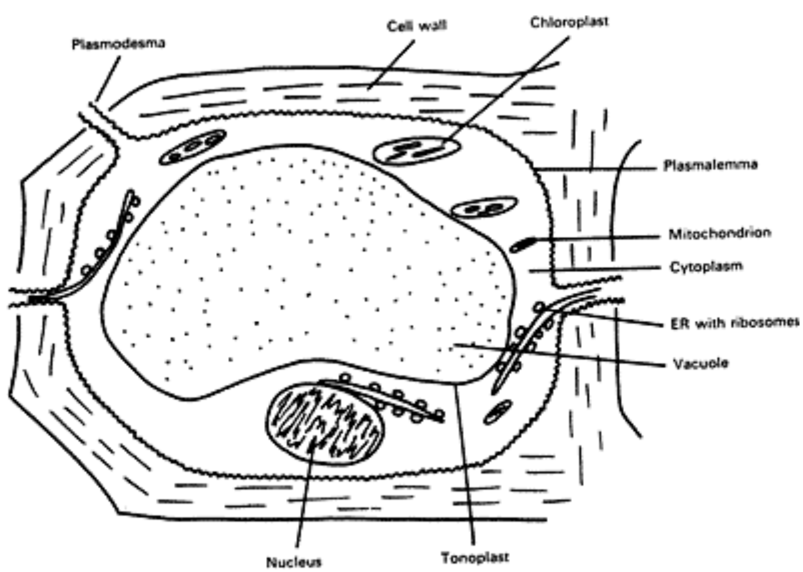

Figure 1. A mesophyll cell that is specialized for photosynthesis

All these are surrounded by membranes, which play a very important role in the transport of both organic and inorganic particles in and out of the cells and, therefore, control nutrient uptake. Details of the intricacy of the plant membranes can be found in earlier pivotal publications (e.g., Singer[16]). A number of important observations on nutrient uptake that impact their metabolism by plants and consequently nutrition are:

1. Plants are able to take up ions selectively, which suggests that plant cells can take up certain ion species from their environment and transport them into the interior of the cell, while excluding others.
2. Nutrients within plant cells move in response to concentration gradients. Gradients are formed from differences in concentration of nutrients not only inside

3. the cells but also between the soil and the plant root (one of the three mechanisms of nutrient movement from the soil to the plant, known as **diffusion**, involves movement of molecules/ions from areas in the soil of high nutrient concentration to the surface of the root that has virtually no nutrients.
4. Nutrient uptake requires energy. That is where metabolism comes into play.

Metabolism (from the Greek word "metabolismos", which means change in movement/form) is a series of chemical processes that occur within an organism, which include either synthesis (anabolism) or breakdown (catabolism) of organic compounds. Whereas anabolism is the set of metabolic pathways that construct molecules from smaller units, catabolism is the set of metabolic pathways that break down molecules into smaller units and release energy. These two mechanisms are interrelated, as anabolism requires energy from catabolism that links ion transport with electron flow in the respiration chain. In aerobic organisms (i.e., organisms that need oxygen to survive, in other words organisms that respire) respiration is directly related to ion uptake[3,14]. In practice, what this means is that the greater the oxygen tension (the more oxygen in other words), the greater the nutrient uptake by plant roots.

Crops differ in their individual nutrient needs and relationships between plant and soil are very complex. If one adds the complexity of the assimilatory pathways and cycling of nutrients within plants, the study of nutrient uptake and metabolism becomes extremely difficult. This has prompted some scientists to develop models to aid our understanding of the acquisition and uptake of nutrients by plants[1,10]. To complicate things further, interactions among or between nutrients influences their uptake by a number of plant species.

The first step in nutrient uptake is their entrance into the plant roots. Before that, a nutrient needs to reach the root surface within the soil. There are three mechanisms by which nutrients move from the soil to the surface of the plant root, namely, mass flow, diffusion and root interception.

- **Mass Flow** is essentially movement of nutrients by water. In other words, dissolved nutrients "along for the ride" in water are taken up by roots; and it is primarily responsible for nutrients such as nitrogen and sulphur.

- **Diffusion**, as we have already mentioned, is movement along concentration gradients (that is from points of high to points of low concentration) and is responsible for nutrients such as phosphorus and potassium.
- **Root Interception -** is when plant roots themselves come into contact with nutrients in the soil and absorb them.

All three processes are in constant operation during plant growth. Independently of the mechanism whereby a nutrient has reached the plant root, it now has to enter through the root "skin", known as the epidermis, and move to the upper parts of the plant (**Figure 1**). Actual uptake of a nutrient at the root surface may be passive (i.e. nutrient enters root with water that is being absorbed) or due to an active process where the nutrient is moved into the root by another molecule or ion called a carrier. This function is often aided by microorganisms that live in association with plant roots. For example, mycorrhizae, which are fungi that live in association with plant roots, can extend the phosphorus uptake range by four times or more[1], since a plant may have mycorrhizal hyphae (filaments) that are 100 to 1000 times longer than its roots. However, not all plants are mycorrhizal. For example, canola does not establish a mycorrhizal association. Once a nutrient enters the plant through the root, it will be subject to translocation within the plant.

Nutrient uptake by field crops means that a portion of the nutrient will be removed in the harvested part(s) of the crop (see examples in **Table 2**; or the crop removal/uptake charts for western Canada at: http://www.cfi.ca/_documents/uploads/elibrary/d161_NU_W_01[1].pdf.).

[1](https://www.ipni.net/ppiweb/agbrief.nsf/5a4b8be72a35cd46852568d9001a18da/9161f81419741d648525690a0068c8d7!OpenDocument)

Table 2. Nutrient uptake in the straw and grain portion of crops commonly grown in western Canada.

Crop (Yield)	Plant Part	Typical Nutrient Uptake (lb/ac)			
		Nitrogen (N)	Phosphorus (P_2O_5)	Potassium (K_2O)	Sulphur (S)
Spring Wheat	Seed	60	23	17	4
(40 bu/ac)	Straw	25	9	55	5
	Total	85	32	71	9
Barley	Seed	78	34	25	7
(80 bu/ac)	Straw	28	9	68	5
	Total	106	43	93	12
Canola	Seed	68	41	21	12
(35 bu/ac)	Straw	44	17	72	10
	Total	112	58	93	22

For crops that are grown for their seed, this portion is limited to the seed, whereas for those grown for above-ground biomass (forage, hay, cellulosic feedstock, etc.) it extends to the whole plant. Different nutrients have different mobility within plants, so they will also tend to accumulate in different plant parts. Uptake patterns of three major crop categories grown in western Canada are illustrated in **Figures 2 to 4** (adapted from Malhi et al.[11,12]; see Appendix for growth stage description).

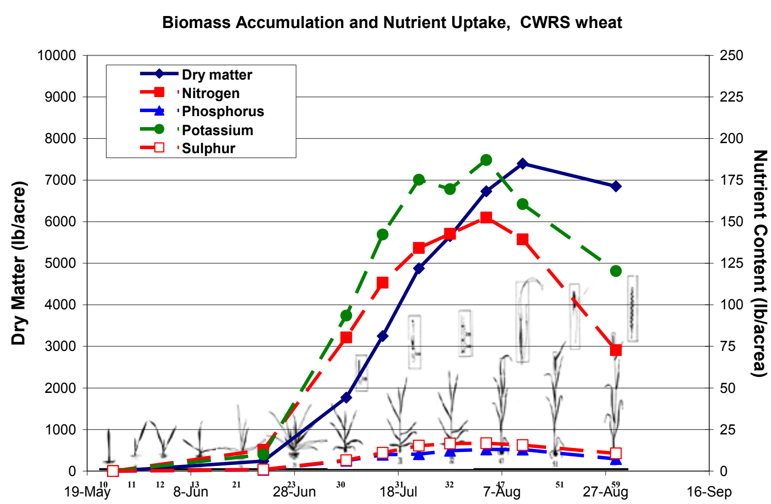

Figure 2. Plant biomass and nutrient accumulation in wheat (adapted from Malhi et al.[11]; growth stages shown on the graph are approximations).

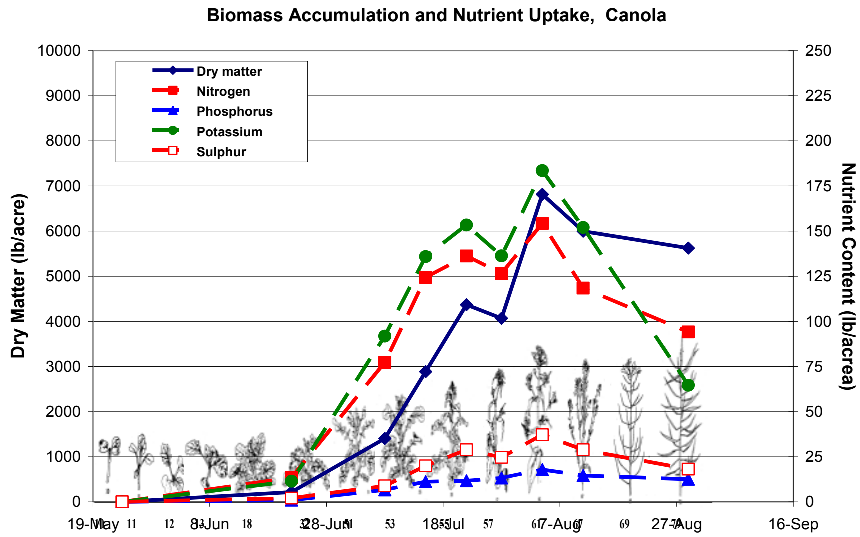

Figure 3. Plant biomass and nutrient accumulation in canola (adapted from Malhi et al.[12]; growth stages shown on the graph are approximations).

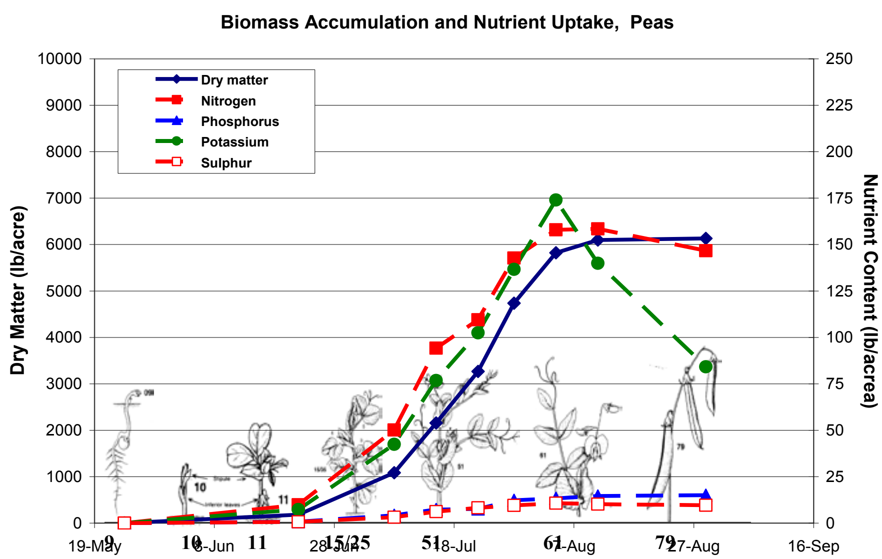

Figure 4. Plant biomass and nutrient accumulation in peas (adapted from Malhi et al.[12]; growth stages shown on the graph are approximations).

Nutrient Uptake by Crops

Nitrogen (N)

✶ **<u>Key Practical point</u>:** Crops use more N than any other mineral nutrient (see **Table 2**).

- Nearly all plant N is found in the proteins.
- In mature plants, the bulk of the N (60% to 80%) is found in the seeds.
- Total N removal by crops relates to the amount of material removed and the protein concentration of the harvested material.
- Nitrogen consumption by crops relative to other macronutrients is illustrated in **Table 2**.
- Rate of N consumption by healthy plants is not consistent over the growing season.
- A large portion of the total N requirements of a plant is taken up early in its growth cycle.
- As shown in **Figure 5**, nearly 70% of the crop's total N requirement is taken up by the late tillering stage. At this point in time, only 30% of the total above-ground dry matter has been produced.

✶ **<u>Key Practical point</u>:** Effective nitrogen fertilizer placement is critical for ensuring that an adequate supply of N will be available to the crop early in the growing season.

✶ **<u>Key Practical point</u>:** Nitrogen taken up later in the growing season will be less effective for increasing yield but may have a significant impact on grain protein concentration[8].

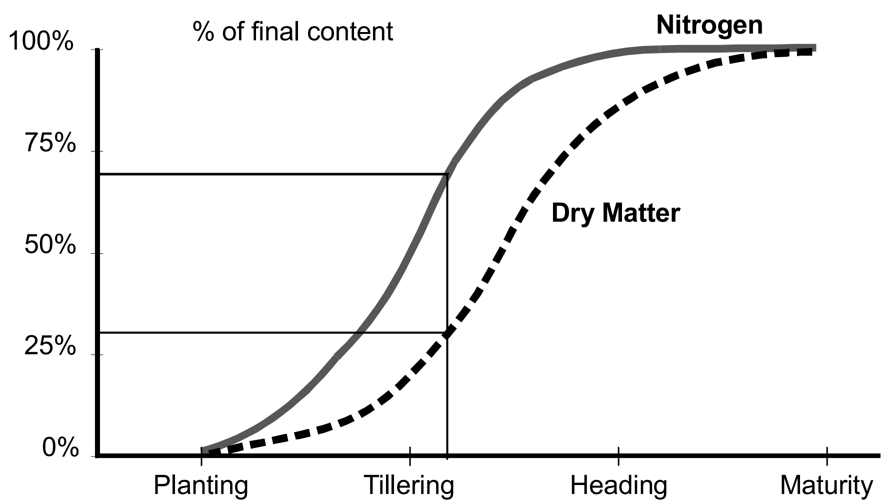

Figure 5. Growth of wheat and final yield strongly influenced by rate of early season nitrogen uptake

Phosphorus (P)

- After N, P is the second most frequently limiting macronutrient for plant growth[15].
- Applying N fertilizer in a common band with P helps improve P availability and uptake[13].
- Anything that reduces aeration (e.g., poor drainage, compaction) will reduce P availability and uptake. Excess moisture excludes oxygen (aeration) which limits root growth and uptake. The reduced soil pore space caused by compaction slows diffusion and the uptake of P (see **Table 3**).

Table 3. Increasing bulk density of soil (i.e., compaction) decreases crop uptake of soil P.

Soil Texture	Bulk Density (g/cm^3)	P Uptake (mg/pot)
Loamy Sand	1.30	63.7
	1.60	47.5
	1.90	12.2
Silty Clay	1.10	78.1
	1.35	48.4
	1.50	29.6

✶ **Key Practical point:** Cool temperatures slow diffusion (mechanism of P uptake by plants) which could create a P deficiency. Presence of small amounts of P fertilizer at or near the seed depending on the sensitivity of crops to P, even on P sufficient soils, ensure that plants have adequate supply of P at the start of their growth by taking advantage of the well know "pop-up" effect, i.e., temporary solubilization of P fertilizer in cool soils.

- Fungi can also compete for available P supply, but in some cases fungi can act as an extension of the rooting system and increase P uptake (e.g., mycorrhizae fungi).

✶ **Key Practical point:** Since P fertilizers are more rapidly modified (i.e., made less available for plant uptake) when thoroughly mixed with the soil, some types of band application (seedrow, deep-band, side-band) are usually most effective.

- Root proliferation in the area of band results in higher uptake of both P and N.

✶ **Key Practical point:** Fertilizer P application at the time of seeding approximately 1½″ below and 1½″ to the side of the seedrow, or applied 1/3 in the seedrow and 2/3 in a shallow band, thereby ensuring early crop uptake, while providing protection against the risk of germination damage associated with seedrow P, has been shown to be very effective[9].

Sulphur (S)

- In small grains, S uptake is most rapid up to the flowering stage. In canola, maximum S uptake and accumulation occurs between 5 and 6 weeks after seeding[7].

Potassium (K)

- Potassium is essential for improving N uptake and protein synthesis (**Figure 6**).

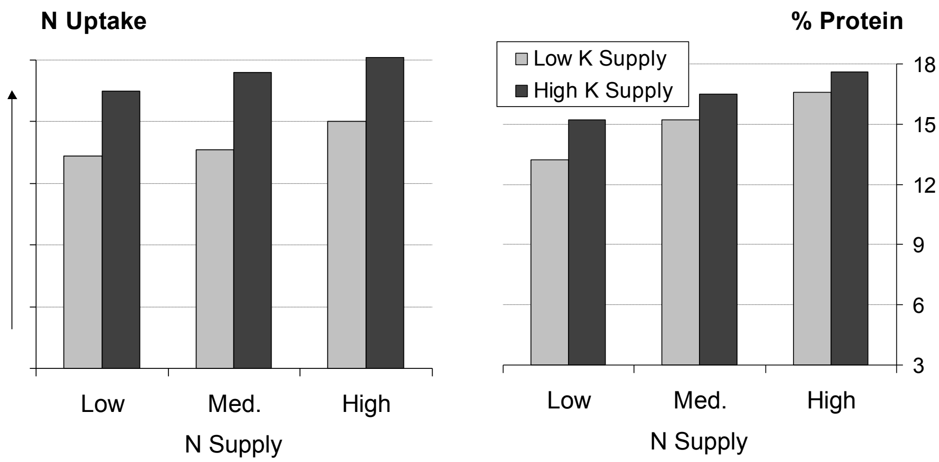

Figure 6. Plants adequately supplied with K have an increased uptake of N and produce higher protein contents.

- Additional N within the plant translates into higher protein content.
- Higher levels of N mean more K is required to help the plant convert the N into protein.
- High soil calcium levels can interfere with K uptake by plants. This is highly unlikely in crops grown on western Canadian soils because of the generally high amounts of K present.

✶ **<u>Key Practical point</u>:** Since K has limited movement in the soil, placement of potash supplying fertilizer near the seed can improve uptake of fertilizer K.

Secondary Nutrients and Micronutrients

- Micronutrients can react with other nutrients to form insoluble compounds (i.e., become unavailable) for plant uptake.
- High soil P can depress zinc (Zn) uptake. Singh et al.[17] attributed this effect in cereals to suppression of mycorrhizae that live in association with plant roots in the presence of high levels of P. The same authors attributed the same phenomenon in peas to plant dilution effects and reduced translocation of Zn from roots to tops[18].
- Excess K can reduce the uptake of magnesium (Mg), if grasses are being grazed by livestock.
- Low soil temperatures and plenty of soil moisture in the presence of only moderate amounts of K can result in higher K uptake compared to Mg and the development of tetany-prone forage grasses.
- Manganese (Mn) is involved in metabolism by influencing uptake and assimilation of other nutrients. Karamanos et al.[4,5,6] demonstrated a manganese × copper interaction in wheat and barley.
- Heavy P applications increase molybdenum (Mo) uptake by plants.
- Heavy S applications decrease Mo uptake by plants. This interaction was assessed in a study by Karamanos et al.[5], who showed that lowering Mo levels in canola by heavy S application eliminated a molybdenum × copper antagonism and led to alleviation of a copper deficiency.
- Molybdenum enhances the uptake of N, K and calcium (Ca).
- Chloride (Cl) may compete with nitrate uptake, tending to promote the use of ammonium-N rather than nitrate-N; this has been observed with winter wheat.

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Appendix
Growth Staging – Canola
Extended BBCH Scale

Principal growth stage 1: Leaf Development	
10	Cotyledons completely unfolded
11	First leaf unfolded
12	2 leaves unfolded
13	3 leaves unfolded
14	4 leaves unfolded
15	5 leaves unfolded
16	6 leaves unfolded
17	7 leaves unfolded
18	8 leaves unfolded
19	9 or more leaves unfolded
Principal growth stage 2: Formation of side shoots	
20	No side shoots
21	Beginning of side shoot development; first side shoots detectable
22	2 side shoots detectable
23	3 side shoots detectable
24	4 side shoots detectable
25	5 side shoots detectable
26	6 side shoots detectable
27	7 side shoots detectable
28	8 side shoots detectable
29	End of side shoot development: 9 or more side shoots detectable
Principal growth stage 3: Stem elongation	
30	Beginning of stem elongation: no internodes ('rosette')
31	1 visibly extended internode
32	2 visibly extended internodes
33	3 visibly extended internodes
34	4 visibly extended internodes
35	5 visibly extended internodes
36	6 visibly extended internodes
37	7 visibly extended internodes
38	8 visibly extended internodes
39	9 or more visible extended internodes
Principal growth stage 5: Inforescence emergence	
50	Flower buds present, still enclosed by leaves
51	Flower buds visible from above ('green bud')
52	Flower buds free, level with the youngest leaves
53	Flower buds raised above the youngest leaves
55	Individual flower buds (main inflorescence) visible but still closed
57	Individual flower buds (secondary inflorescences) visible but still closed
59	First petals visible, flower buds still closed ('yellow bud')
Principal growth stage 6: Flowering	
60	First flower opens
61	10% of flowers on main raceme open, main raceme elongating
63	30% of flowers on main raceme open
65	Full flowering: 50% of flowers on main raceme open, older petals falling
67	Flowering declining: majority of petals fallen
69	End of flowering
Principal growth stage 7: Development of fruit	
70	
71	10% of pods have reached final size
73	30% of pods have reached final size
75	50 % of pods have reached final size
76	
77	70 % of pods have reached final size
79	Nearly all pods have reached final size
Principal growth stage 8: Ripening	
80	Beginning of ripening: seed green, filling pod cavity
81	10% of pods ripe, seeds black and hard
83	30% of pods ripe, seeds black and hard
85	50% of pods ripe, seeds black and hard
87	70% of pods ripe, seeds black and hard
89	Fully ripe: nearly all pods ripe, seeds black and hard
Principal growth stage 9: Senescence	
92	
93	
95	
97	Plant dead and dry
99	Harvested produce

Growth Staging – Peas
Extended BBCH Scale

Code	
00	Dry seed
01	Beginning of seed imbibition
03	Seed imbibition completion
05	Radicle emerged from seed
07	Shoot emerged from seed
08	Shoot growing towards soil surface
09	Emergence; shoot emerges through soil surface
Principal growth stage 1: Leaf Development	
10	Pair of scale leaves visible
11	First leaf (with stipules) unfolded or first tendrils developed (leafless cultivars)
12	2 leaves (with stipules) unfolded or 2 tendrils developed (leafless cultivars)
13	3 leaves (with stipules) unfolded or 3 tendrils developed (leafless cultivars)
14	4 leaves (with stipules) unfolded or 4 tendrils developed (leafless cultivars)
15	5 leaves (with stipules) unfolded or 5 tendrils developed (leafless cultivars)
18	Stages continuous till…
19	9 or more leaves (with stipules) unfolded or 9 or more tendrils developed (leafless cultivars)
Principal growth stage 2: Formation of side shoots	
21	1st primary side shoot visible
22	2nd primary side shoot visible
2.	Stages continuous till…
29	9 or more primary side shoots visible
	1st secondary side shoot visible
	Xth apical side shoot of the Nth order visible
Principal growth stage 3: Stem elongation (main shoot)	
30	Beginning of stem elongation
31	1 visibly extended internode*
32	2 visibly extended internodes*
3.	Stages continuous till…
39	9 or more visible extended internodes*
Principal growth stage 4: Development of harvestable vegetative plant parts	
Principal growth stage 5: Inflorescence emergence	
51	First flower buds visible outside leaves
55	First individual flower buds visible outside leaves but still closed
59	First petals visible, many individual flower buds, still closed
Principal growth stage 6: Flowering	
60	First flowers open (sporadically)
61	Beginning of flowering: 10% of flowers open
63	30% of flowers open
64	
65	Full flowering: 50% of flowers open
66	
69	End of flowering
Principal growth stage 7: Development of fruit	
71	10% of pods have reached typical length; juice still issuing out if pressed
72	20% of pods have reached typical length; juice still issuing out if pressed.
73	30 % of pods have reached typical length; juice still issuing out if pressed. Tendrometer value: 80TE
74	40 % of pods have reached typical length; juice still issuing out if pressed. Tendrometer value: 95TE
75	50 % of pods have reached typical length; juice still issuing out if pressed. Tendrometer value: 105TE
76	60 % of pods have reached typical length; juice still issuing out if pressed. Tendrometer value: 115TE
77	70% of pods have reached typical length. Tendrometer value: 130TE
78	
79	Pods have reached typical size (green ripe); peas fully formed
Principal growth stage 8: Ripening of fruit and seed	
81	10% of pods ripe, seeds final color, dry and hard
83	30% of pods ripe, seeds final color, dry and hard
85	50% of pods ripe, seeds final color, dry and hard
87	70% of pods ripe, seeds final color, dry and hard
89	Fully ripe: all pods dry and brown. Seeds dry and hard (dry ripe)
Principal growth stage 9: Senescence	
97	Plants dead and dry
99	Harvest product

Growth Staging – Cereals
Extended BBCH Scale

Code	
00	Dry seed
01	Beginning of seed imbibition
03	Seed imbibition completion
05	Radicle emerged from seed
06	Radicle elongated, root hairs and/or side roots visible
07	Coleoptile emerged from seed
09	Emergence; coleoptile penetrates soil surface (cracking stage)
Principal growth stage 1: Leaf Development	
10	First leaf through coleoptile
11	First leaf unfolded
12	2 leaves unfolded
13	3 leaves unfolded
14	4 leaves unfolded
15	5 leaves unfolded
16	6 leaves unfolded
17	7 leaves unfolded
18	8 leaves unfolded
19	9 or more leaves unfolded
Principal growth stage 2: Tillering	
20	No tillers
21	Beginning of tillering: first tiller detectable
22	2 tillers detectable
23	3 tillers detectable
24	4 tillers detectable
25	5 tillers detectable
26	6 tillers detectable
27	7 tillers detectable
28	8 tillers detectable
29	9 or more tillers detectable
Principal growth stage 3: Stem Elongation	
30	Beginning of stem elongation: pseudostem and tillers erect, first internode begins to elongate, top of inflorescence at least 1 cm above tillering node
31	First node at least 1 cm above tillering node
32	Node 2 at least 2 cm above node 1
33	Node 3 at least 2 cm above node 2
34	Node 4 at least 2 cm above node 3
35	Node 5 at least 2 cm above node 4
36	Node 6 at least 2 cm above node 5
37	Flag leaf just visible, still rolled
39	Flag leaf stage: flag leaf fully unrolled, ligule just visible

Principal growth stage 4: Booting	
41	Early boot stage: flag leaf sheath extending
43	Mid boot stage: flag leaf sheath just visibly swollen
45	Late boot stage: flag leaf sheath swollen
47	Flag leaf sheath opening
49	First awns visible (in awned forms only)
Principal growth stage 5: Inflorescence Emergence, Heading	
51	Beginning of heading: tip of inflorescence emerged from sheath, first spikelet just visible
53	30% of inflorescence emerged
55	Middle of heading: half of inflorescence emerged
57	70% of inflorescence emerged
59	End of heading: inflorescence fully emerged
Principal growth stage 6: Flowering, Anthesis	
61	Beginning of flowering: first anthers visible
65	Full flowering: 50% of anthers mature
69	End of flowering: all spikelets have completed flowering but some dehydrated anthers may remain
Principal growth stage 7: Development of Fruit	
71	Watery ripe: first grains have reached half their final size
73	Early milk
75	Medium milk: grain content milky, grains reached final size, still green
77	Late milk
Principal growth stage 8: Ripening	
83	Early dough
85	Soft dough: grain content soft but dry, fingernail impression not held
87	Hard dough: grain content solid, fingernail impression held
89	Fully ripe: grain hard, difficult to divide with thumbnail
Principal growth stage 9: Senescence	
92	Over-ripe: grain very hard, cannot be dented by thumbnail
93	Grains loosening in day-time
97	Plant dead and collapsing
99	Harvested product