NITROGEN (N)

Cotton is grown on fertile clay soils in Australia, which have become depleted in N and organic matter over time. They are no longer able to supply the cotton crop's need for N. Because of the direct effects of N on crop development, it is imperative to apply adequate N fertilizer. To achieve maximum yield, cotton growers may need to supply N fertilizer to each crop at rates up to 200 kg N/ha. **Over supply of N** will encourage rank growth and fruit shedding, reduce lint yield, hamper defoliation, encourage insects and diseases and delay maturity.

THE ROLE OF NITROGEN IN THE PLANT

Nitrogen is an integral component of proteins, which are essential for healthy crop growth and physiological development. Nitrogen is also needed to synthesise the chlorophyll required for photosynthesis. New leaves may contain up to 6% N. It is a very mobile nutrient and moves from older to newer leaves as the plant ages. Nitrogen is taken up throughout the growing season and is transported and stored in the leaves. The N requirements for boll development are partially met from N stored in the leaf canopy.

UPTAKE AND REMOVAL OF NITROGEN

To achieve optimum cotton yields an uptake of about 180 kg N/ha is needed. Most N taken up by the crop comes from the surface (0 to 50 cm) soil from where organic matter is mineralised and fertilizer is applied.

Cotton prefers to take up nitrate-N (rather than ammonium-N) and does so in phase with crop dry matter production; as the crop matures N uptake slows. Most of the N is transported to the leaves (hence the use of petiole nitrate testing). A young cotton plant can take up more N than it needs and excess N is remobilised from the leaf canopy later if uptake does not meet the crop's requirements. The production of new leaves and squares slows at 'cut out' which should coincide with the exhaustion of the soil N supply. Thus, low soil N can hasten cut out and limit yield. Most N is taken up between 50 and 110 days after sowing and about 60% of this N is removed in the seed cotton (Table 3-1).

NITROGEN DEFICIENCY SYMPTOMS

Deficiency symptoms include small, pale yellow leaves. N deficient plants are stunted with few vegetative branches and fruiting branches will be fewer and shorter. As N deficiency progresses, older leaves become yellow, as N is remobilised to new growth. Leaves with severe N deficiency turn various shades of autumn colours.

Crops that are adequately fertilised will exhaust the pool of available N in the soil as bolls start to open, when the lower leaves begin turning yellow. This is a good indication that the crop has received adequate N fertilizer. Mobilisation of N from older leaves, stems and roots is a feature of normal growth. Crops that are over-fertilised with N will remain green throughout the growing season, hence crop maturity, defoliation and picking are delayed.

NITROGEN FERTILIZERS AND APPLICATION

The major N fertilizers used in cotton production are anhydrous ammonia (82% N) and urea (46%N). The N released from both fertilizers becomes available to plants quickly. Urea and anhydrous ammonia perform similarly in an agronomic sense and are normally equally well recovered by cotton.

Anhydrous ammonia (NH_3) is the most popular option for irrigated cotton, especially where high rates of N are needed. About 80% of N fertilizer is applied as anhydrous ammonia. It is as effective and no more expensive than other N fertilizers, and most growers possess the equipment needed for its application. Loss of ammonia is negligible when anhydrous ammonia is applied deeper than 15 cm. However, the soil water content is important: ammonia applied to very dry soil may allow ammonia to escape through the voids between large clods, or in very wet soils, ammonia may escape via the slot made by the fertilizer shank if not covered over with loose soil.

Urea ($CO[NH_2]_2$) is normally hydrolysed to ammonium within days of application. It is then nitrified in the soil and assimilated by the crop. Urea can be dissolved in the irrigation water (water-run urea), side-dressed or aerially applied (in which case it must be quickly incorporated or watered-in). Urea should not be applied to the surface of wet or moist soil where volatilisation losses can reach 75% of N applied. Urea can be applied to a dry soil surface but it should be incorporated as soon as possible using cultivation or irrigation.

Water-run urea works efficiently as the N is distributed throughout the soil volume from which the crop extracts water. The N does not volatilise from the water and is delivered evenly to the length of the field. However, some N will be unavoidably wasted as supply channels and tail drains are fertilised, hence, tail water should be recirculated.

Water-run anhydrous ammonia does not work efficiently, as the ammonia is distributed poorly down the field and severe losses occur via ammonia volatilising from the irrigation water (up to 25% per hour).

	Lint yield (bales/ha)				
	6	7	8	9	10
N removed (kg/ha)	43	54	68	87	116

Table 3-1. Nitrogen removed in seed cotton from an experiment at Narrabri where yields ranged from 5.5 to 10.4 bales/ha.

The three methods for applying urea with irrigations are:

- applied to dry soil surface by either spreader or aircraft then irrigated in as soon as possible. Avoid applying to moist soil and/or allowing a delay before irrigation as shallow incorporation in moist soil can lead to losses with ammonia volatilisation
- supply of urea solutions is possible in some regions that allow metering of the solution via a constant head tank and float valve. Application rates can be altered by adjusting the flow of the irrigation water or the flow of the fertilizer solution
- solid urea can be applied via N buggy type equipment that dispenses urea directly to the water flowing through the irrigation channel

Urea is best added to the water at a drop structure or culvert to improve the mixing process. The efficiencies of the three methods are similar.

Starter fertilizers, such as mono ammonium phosphate (MAP) and diammonium phosphate (DAP), supply a small amount of N to cotton seedlings.

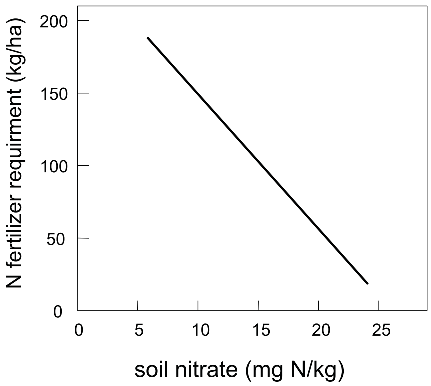


Figure 3-1.
The relationship between N fertilizer requirement and soil nitrate-N concentration in an unfertilized clay loam soil, sampled in September, one month prior to sowing cotton.

DETERMINING NITROGEN FERTILIZER REQUIREMENTS FOR COTTON

Most growers use rates based on their experience from previous cotton crops but also consider soil condition and previous rotation crops. The N fertilizer required by cotton can be predicted with greater precision by using pre-sowing soil nitrate analyses (figure 3-1) . N fertilizer rates can be modified, as indicated by petiole nitrate analyses. Dryland cotton commonly requires about half the N rate applied to irrigated crops.

NutriLOGIC

NutriLOGIC is a module of the CottonLOGIC computer program available through the Australian Cotton Cooperative Research Centre's Technology Resource Centre at the Australian Cotton Research Institute, Narrabri.

NutriLOGIC allows the grower to enter soil nitrate-N and petiole nitrate-N data and estimates the N fertilizer required for cotton based on this data, the cotton-growing region and the month the sample was taken. The NutriLOGIC program makes allowance for soil factors (texture, compaction and predisposition to waterlogging), the time the soil was sampled and the district in which the cotton is grown. Hotter areas require slightly more N to maximise lint yield. The program does not contain a calibration for soil sampled earlier than July.

The N fertilizer rate indicated by NutriLOGIC allows for an average loss of N through denitrification and leaching during the crop-growing season based on soil type. Soil texture impacts substantially on N fertilizer losses, which are lower in lighter clays than in heavy clays. Greater losses occur from poorly structured or poorly drained soils compared to well-structured and well-drained soils.

SOIL NITRATE ANALYSIS

Pre-sowing (September) soil nitrate content is closely related to crop N uptake and ultimately, yield. N fertilizer requirements can be estimated from soil nitrate-N (figure 3-1). High levels of soil nitrate indicate a high level of N fertility. If fertilizer has been applied before sampling in September, nitrate test values will be extremely high and variable and are not suitable for estimating N fertilizer requirement.

PETIOLE NITRATE ANALYSIS

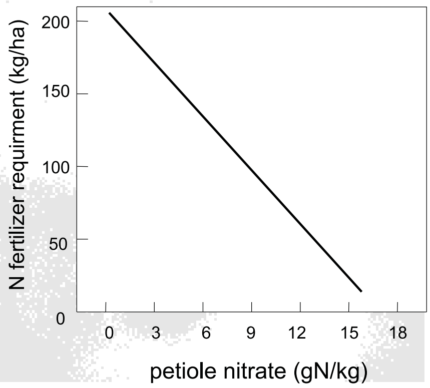
Petiole nitrate analysis allows growers to determine whether a crop has received sufficient fertilizer N to produce its optimum yield. Monitor N status early in the growing season so that any N deficiency can be rectified before growth is severely affected.

The critical value for petiole nitrate at first flower (750 day degrees from sowing) is about 20,000 ppm. Below this value, nitrogen applications may be necessary. The NutriLOGIC computer program can be used to help estimate this requirement (see NutriLOGIC chapter in this manual).

Sampling procedures are detailed in the *leaf and petiole analysis* section of this manual.

The relationship displayed below in Figure 3-2 will change slightly for different soil types, but moreso for time of petiole sampling. The NutriLOGIC program adjusts the N fertilizer recommendation by accounting for the day degrees since the crop was sown.

Figure 3-2.
The N fertilizer requirement for cotton grown on a clay loam soil as related to petiole nitrate-N concentration at 750 day degrees from sowing (first flower).



NITROGEN FERTILIZER MANAGEMENT

TIMING OF N FERTILIZER APPLICATION

Growers should aim to apply N fertilizer as close as practical to sowing in order to reduce N losses and maximise the effectiveness of N fertilizer. Often, N losses are substantial when fertilizer is applied before July. Growers should apply their N fertilizer into cool soil in the three months prior to sowing to reduce N losses. Applying N in warm/moist soil during the summer/autumn months before the crop is sown can be wasteful and costly for the grower. Early application unnecessarily exposes fertilizer to N loss episodes over many months, when soil conditions favour denitrification.

Severe N losses (primarily through denitrification) can occur between the time of fertilizer application and the crop being sown, particularly during wet winters. The practice of applying N fertilizer in the summer while preparing fields after cereal cropping is not recommended because of the potential for much of this N to be lost (see Figure 3-3).

SIDE-DRESSING N FERTILIZERS

When side-dressing N fertilizer, growers must take into account the time for fertilizer N to become available to the plant. Most growers aim to side-dress N prior to flowering, when the crop may take up as much as 4 kg N/ha/day. By applying N early to the crop, the damage caused by fertilizer tynes pruning the roots is minimised. As the plant ages, its ability to take up N decreases, even if N deficient. However, nitrogen taken up before this period and stored within the plant can be relocated within the plant.

Side-dressing can produce comparable responses to N compared with pre-plant applications, assuming there is sufficient N in the seed bed to allay N deficiency. Side-dressing can be a problem in wet summers when soil structure can be damaged. In these cases, water-run urea is often a better option than applying urea or anhydrous ammonia.

TIMING N FERTILIZER APPLICATION TO AVOID CROP DAMAGE

Where growers opt to place anhydrous ammonia (or urea) below the plant line prior to sowing, they should ensure sufficient time has elapsed for the ammonia to dissipate from the soil where the root system will develop. This may take up to three weeks for high N application rates.

Nitrogen applied more than three to four months before sowing is subjected to greater N loss through denitrification and leaching.

Nitrogen side-dressed after squaring may not be as well recovered by the crop as N applied pre-sowing.

PLACEMENT OF N FERTILIZER

N fertilizers should be placed a short distance from where seedling roots will grow, especially when N is applied close to sowing. Generally, the best responses and recoveries are achieved from urea or anhydrous ammonia either placed:

- under the row if more than one month before sowing, or
- to the side of the crop row, if close to sowing

Depth of N fertilizer application is important. The developing seedlings may become N deficient where they cannot access N fertilizer placed too deeply. Shallow placement of N fertilizer may result in damage to the developing seedlings. Also, substantial N losses can be experienced during application of anhydrous ammonia (or urea). Further, N may be washed down the furrows from the head to the tail of the field during flood irrigation, especially where high nitrate concentrations persist following shallow N fertilizer application.

N fertilizer needs to be placed near the developing cotton roots, but not so close that ammonia toxicity will damage the root system. Ideally, the fertilizer band should be below and to the side of the developing roots, allowing the root system to grow into the band. Roots will proliferate through the fertilizer band as the ammonia is nitrified.

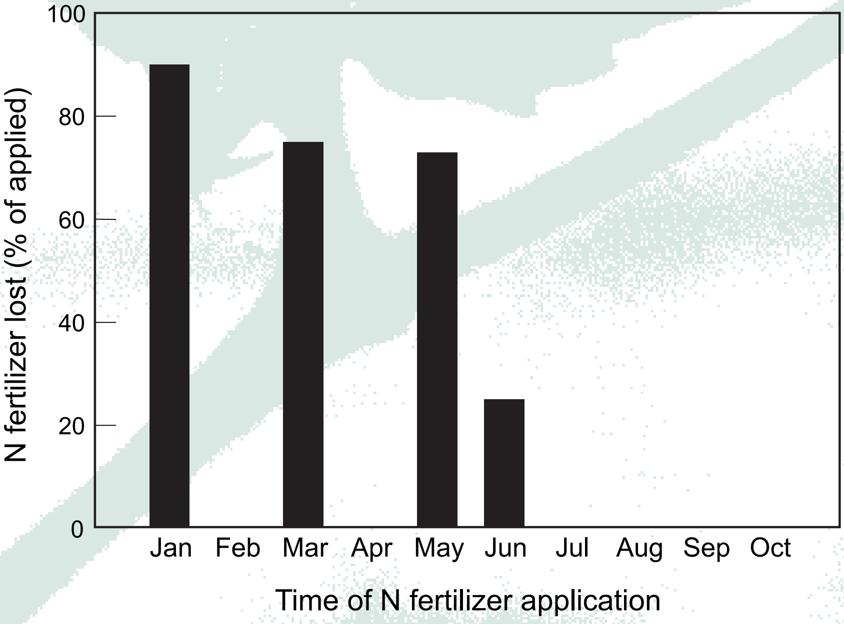


Figure 3-3.
Percentage of N lost from early fertilizer applications as determined by fertilizer remaining in October. Almost complete loss of fertilizer N may eventuate from early applications in years having above average winter rainfall. (Source: Freney – Australian Cotton Conference 1992).

Band placement of N fertilizer reduces N loss. Where 2-metre beds are used, the centre of the bed is the ideal position for N application. Placement of N in the furrow often achieves poor responses to fertilizer.

Urea should not be placed with the seed. Urea is extremely soluble and if applied near the crop row prior to sowing and watered-up, it may be moved into the seedling root zone. This can result in seedling damage, especially where high N rates are used. Water-run urea does not cause this problem.

FOLIAR APPLICATION OF N FERTILIZERS

Crops experiencing difficult growing conditions may respond to foliar applications of N, particularly when irrigating poorly drained fields. Poor soil aeration and waterlogging can limit nutrient uptake for some days after irrigation.

Foliar applications of soluble N fertilizers have been used to overcome N stress caused by short-term waterlogging from early crop irrigations. As the plant rapidly absorbs foliar N such applications can overcome a deficiency faster than soil applied N.

Waterlogging due to irrigation or rainfall often creates a short-term deficiency as roots lose their ability to absorb N when the soil is saturated. In these conditions denitrification loss is also increased. Foliar application is most effective when applied a day before the waterlogging event (irrigation). Applications of 8 to 10 kg N/ha (before first and/or second irrigation) at early squaring and early- to mid-flowering, can overcome the effects of waterlogging. Urea -ammonium nitrate solution used at 20 litres/ha is generally sufficient to meet plant requirements for the 3 or 4 days until the waterlogging event to pass. Application of foliar N fertilizer in wet cloudy weather is unlikely to benefit the plants, as they require sunlight to metabolise the nitrogen.

Higher rates of N can burn the foliage, consequently applications should occur in the late evening as cool humid conditions lessen this risk. Foliar N applications are not recommended after flowering (mid to late January). Little or no yield response is achieved, although the crop may become visibly greener. Little loss of N via volatilisation occurs with foliar applications of ammonium sulfate, ammonium nitrate and urea-ammonium nitrate solutions to advanced crops.

APPLYING N FERTILIZER NEAR SOWING

In winters with above average rainfall, growers may not be able to apply fertilizer prior to sowing. In this situation growers need to explore other options available for N application, including side-dressings of ammonia and starter fertilizers (MAP) and other fertilizer management practices.

Mono-ammonium phosphate (MAP) rates of up to 40 kg /ha can be safely applied with seed where seedbed moisture is good. Because of the phosphate's acidifying effect, the alkalising effect of the ammonium is neutralised, thereby reducing the ammonia concentration within the seed-fertilizer band. Applications of di-ammonium phosphate (DAP) do not produce enough acid and should not be substituted for MAP applications with seed.

FERTILIZER DAMAGE CAUSED THROUGH AMMONIA TOXICITY

The most influential factor in fertilizer injury of seedling cotton is the presence of gaseous ammonia near developing roots. When ammonia-producing fertilizers (urea, anhydrous ammonia, MAP) are applied in alkaline soils, a proportion of the N remains as ammonia in the soil water and air spaces within the soil. The pH of the soil within a band of ammonium-producing fertilizer increases towards the centre of the band, causing the ammonium-ammonia equilibrium to increase the ammonia concentration.

Crop root systems are extremely sensitive to ammonia and patches of dead seedlings may become evident where N has been applied too close to the plant row. As the ammonium is nitrified, the soil pH declines, commonly below that of the soil surrounding the fertilizer band.

COST OF OVER-FERTILISING WITH NITROGEN

Too much N and water can cause rank vegetative growth and shedding of young bolls. This will delay full fruit load and crop maturity. The fruit will be smaller and the fibre more immature, largely because leaves and bolls are shaded by the excess vegetative growth. Diseases, such as boll rots, may be more common.

Minor effects of increased N supply are increased boll size and increased seed/boll numbers. The effect of N on lint quality is variable. A rank crop resulting from too much nitrogen can create problems for insecticide application, defoliation and aggravate some diseases such as boll rots and Verticillium wilt. Over fertilized cotton maybe more attractive to insects which can be more difficult to control.

The application of growth regulators (such as mepiquat chloride) may reduce the problems associated with rank growth in over-fertilised cotton.

EFFICIENCY OF N FERTILIZER USE BY COTTON

The most efficient use of N fertilizer is achieved by applying the correct rate at a time when N loss will be minimal, *ie* after June when cooler conditions slow the nitrification and denitrification processes.

The crop uses less than half the fertilizer N applied. Large quantities are lost from the system through either leaching or biological denitrification (the process where soil nitrate N is converted into gaseous forms of N and returned to the atmosphere).

Cotton crops recover about 33% of N applied on average; about 25% remains in the soil at crop maturity, but in an unavailable (organic) form. The remainder of N applied (*ie* 42% of N applied) is assumed lost from the system through denitrification and leaching.

About two-thirds of N taken up by cotton is derived from the soil organic N pool (*ie* non-fertilizer N). This N is mineralised from soil organic matter before and during crop growth. The N fertilizer applied meets only about one-third of the crop N requirement.

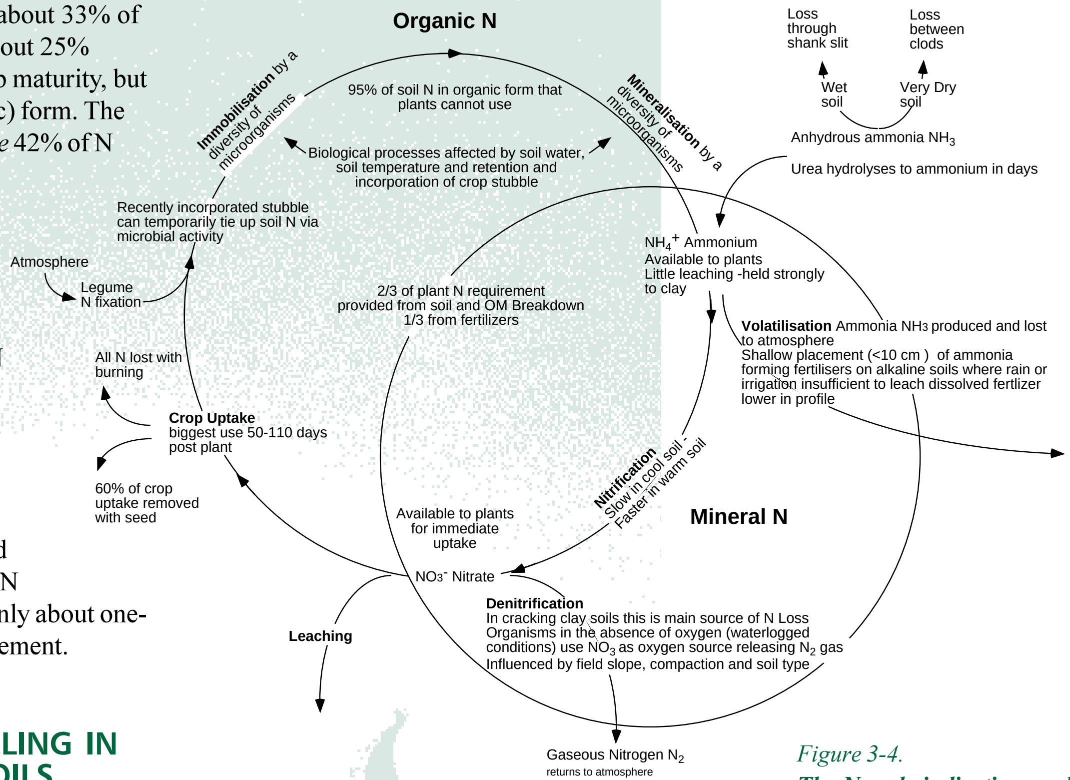


Figure 3-4.
The N cycle indicating pools and processes of relevance to cotton production

NITROGEN CYCLING IN COTTON SOILS

A complex cycle exists in the soil, where N is transformed through numerous pathways, converting organic matter (*eg* crop stubbles) into plant-available forms of N (*ie* nitrate and ammonium). N can be added to the system as N fertilizer or by growing legume rotation crops, and can be removed by nitrate leaching, denitrification and in harvested seed cotton. The cycle in Figure 3-4 is not closed as various processes are constantly adding or removing N.

ORGANIC N AND MINERAL N

Normally, more than 95% of soil N is in an organic form which plants cannot use. Organic N must first be 'mineralised' before it becomes available to the plant. This is a biological process performed by diverse microorganisms present in the soil. Ammonium (NH_4^+) and nitrate (NO_3^-) are available to the crop for immediate uptake.

organic N ⇒ *mineralisation* ⇒ plant-available (mineral) N

Because soil organisms also require N, they compete for the available mineral N and convert a portion of this N back into organic forms. The process where plant available (mineral) N is converted into an unavailable organic form by the soil's microbial populations is called 'immobilisation'**.**

mineral N ⇒ *immobilisation* ⇒ organic N

These two opposing processes operate continually within the soil, creating a balance between plant available (mineral) N and organic soil N. Mineral N converted into organic N is not lost from the system, but becomes available as other soil organisms recycle the organic N back into a plant available N**.**

While some organic N is readily decomposed, much organic N is highly resistant to decomposition. Because these processes are biological, the balance is affected by the soil water content, soil temperature and particularly, the retention and incorporation of crop stubbles. The N fertility of soil can be improved by legume cropping as well as N fertilizer application. This is covered in depth in the section on legume rotation crops.

The nitrification process involves the conversion of ammonium (whether from anhydrous ammonia or urea) to nitrate. This process may take two months after fertilizer application in cool soil, but only two to three weeks in warm soils. Nitrification will proceed more slowly where N is applied at high rates, because of the high pH and ammonia concentration in the soil around the fertilizer band. In unfertilised soils, very little ammonium normally exists because of the dominance of the nitrification process.

Nitrate (NO_3^-) is the most common form of mineral N in alkaline soils. Ammonium (NH_4^+) derived from the fertilizer or organic matter is quickly oxidised to nitrate by nitrifying microorganisms. Mineral N levels fluctuate throughout the year, with concentrations lowest in August/September. This corresponds to the recommended sampling time for soil nitrate analysis.

LOSSES OF N FROM THE SYSTEM

Nitrogen can be lost from the system in various ways:

- removal of produce – (seed cotton)
- denitrification – (especially through waterlogging of irrigated soils)
- leaching – (nitrate washed through soil profile - especially sandy soils)
- volatilisation – (ammonia lost from soil surface after fertilizer application – especially urea)
- burning stubble (see Cotton stubble management chapter)

Denitrification is a biological process whereby nitrate-N is converted to nitrogen gases and N is lost to the atmosphere. It is the most significant N loss process in clay soils. High soil temperatures and saturated soil encourage denitrification. Following flood irrigation and/or heavy rainfall, the soil profile may become waterlogged. The pore spaces in the soil become devoid of oxygen as air is forced from the profile. Increased soil water content may also stimulate mineralisation of organic N, which also consumes oxygen. Under these circumstances, the denitrifying microorganisms start to use nitrate as a source of oxygen. This reduces the amount of mineral N available for the cotton crop.

The loss of fertilizer N during crop growth is variable and is site dependent. In several experiments at Narrabri, between 12% and 65% of N applied was lost from the system, as well as some non-fertilizer N. Fields with poor drainage, low slope, poor soil structure, compaction, high organic matter content etc. may be predisposed to severe denitrification losses. Soil clay content (texture) is closely related to denitrification loss. Australian research has shown that inhibitor chemicals applied with the fertilizer can reduce the loss of N fertilizer through denitrification in cotton-growing soils.

NITRATE LEACHING

The nitrate ion, NO_3^- is not strongly held to clay and organic matter and is subject to movement within the soil profile. Downward movement of ions (leaching) is a problem in coarse-textured soils (loams and sands) in well structured clay soils. In clay soils where movement of soil water is slow, nitrate movement is also slow. During flood irrigation, surface soil high in nitrate is washed into cracks with the irrigation water, thereby transporting nitrate (and soil) into the subsoil.

High levels of nitrate at depth are commonly reported in dryland cropping soils where long fallows are used. This nitrate may have accumulated over many years, even before the soil was cultivated. Most N taken up by the crop is derived from the surface 50cm of soil. The use of deep nitrate by cotton has not been measured, but roots will take up nitrate in proportion to the use of water from deeper in the profile.

Ammonia volatilisation can result in significant N loss from alkaline soils. Where high concentrations of ammonium exist at the soil surface, ammonia gas can escape into the atmosphere. Volatilisation is a purely chemical process driven by environmental parameters, such as soil pH, temperature and ammonium concentration and wind speed. Ammonium-forming fertilizers (eg urea) applied to the surface of alkaline soils, or at shallow (<10cm) depth, may be lost as ammonia gas.

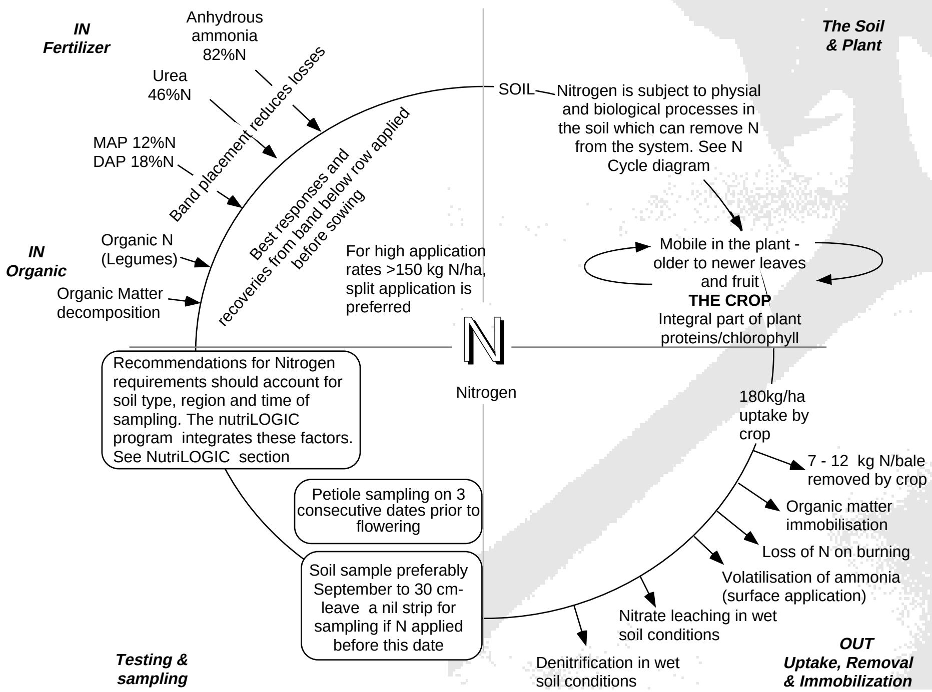


Figure 3-5.
Summary of Nitrogen management issues.

IMPROVING SOIL N FERTILITY WITH LEGUME CROPS

N FIXATION BY LEGUME CROPS

All legume crops have the capacity to 'fix' atmospheric nitrogen (N_2) and incorporate this N into their tissues via an association with bacteria (*Rhizobium* spp.) that normally exist in the soil. As legume seedlings develop their root system, the Rhizobia bacteria infect the root hairs. Nodules form on the roots as the bacteria reproduce. The Rhizobia contain an enzyme (nitrogenase) that converts N_2 into a plant-available form of N. The conversion process requires a high input of energy in the form of carbohydrate which is 'donated' by the plant. In turn, the plant is rewarded with a supply of N from the nodules. Both partners benefit from this symbiotic relationship.

INOCULATE LEGUME SEED BEFORE SOWING

Cotton-growing soils often contain low amounts of these Rhizobia bacteria, hence selected strains of the bacteria should be applied when the legume crop is sown. As most legumes are quite specific in the strain of Rhizobia that can infect the root, growers should apply the appropriate Rhizobia inoculum at the recommended rate. The inoculum can be applied either to the seed just before sowing or diluted and injected into the soil with the seed at sowing.

SOIL NITRATE IN LEGUME SEEDBED

Because soil nitrate-N concentrations are normally low following a cotton crop, a legume crop sown after cotton will need to derive most of its N requirement from N fixation. Where high levels of plant-available N (nitrate) are present in the soil, the crop will use that N in preference to fixing N.

WATER STRESS

Legume crops grown under moisture stress from either waterlogging or drought will not fix as much N as crops grown in good soil moisture conditions. Nutrient deficiencies in the legume crop will also affect N_2 fixation. Similarly, soil salinity drastically reduces N_2 fixation.

SOIL STRUCTURAL IMPROVEMENT

Legume crops offer other beneficial effects, such as improving soil structure (tilth) that makes ploughing and root growth of following crops easier. Green manuring of some legume crops may also reduce the effects of some cotton pathogens. Legume crop stubble should be incorporated into the soil to reduce the incidence of seedling diseases (such as *Pythium* and *Rhizoctonia* spp.) which may be encouraged by the presence of stubble left on the soil surface.

Faba beans

SLOW-RELEASE OF NITROGEN

Because legume-N is added to the soil in an organic form, it must go through the mineralisation process before that N is available to the following crop(s). As this may take several years or several crops, the addition of legume-N can be thought of as a slow-release form of organic N fertilizer. Losses of N from legume stubbles are substantially less than from the equivalent input of chemical fertilizer-N.

COMMERCIAL LEGUME CROPS

Surveys of commercial legume crops grown in rotation with cotton indicate that high levels of N_2 fixation are possible in this system. Although substantial quantities of N can be removed in grain, normally there is a net input of N into the system (Table 3-2).

Species	No. of crops	Prop. crop N fixed (%)	N fixed (kg/ha)	Residual fixed N (kg/ha)
		mean	mean	mean
Summer				
soybean	6	83	371	194
peanut	2	80	273	168
(late sown)	3	40	84	33
(saline)	1	14	37	-20
adzuki bean	4	20	12	5
mung bean	5	51	47	12
pigeon pea	5	14	16	
cowpea	3	74	160	
lablab	9	73	140	
Winter				
faba bean	35	74	177	113
lupin	3	71	176	97
field pea	5	75	161	
lentil	1	61	169	
Winter forage				
clover	9	86	118	
medic	3	84	149	
vetch	4	89	171	

Table 3-2.

Means and ranges of the proportion of crop N fixed, N_2 fixation and residual fixed N (including estimates of below ground N) in 98 legume crops grown in rotation with cotton. Where no estimates of residual fixed N are provided, no grain was harvested and the crops were green manured (all fixed N was returned to the soil). Data from Rochester et al. 1998.

NITROGEN MANAGEMENT

CHAPTER 3

Damaged roots of cotton seedlings caused by placement of the fertilizer band too close to the seed. Photo Stephen Allen.

Uneven nitrogen fertilizer application and/or soil compaction can produce stripes (waves) across cotton fields. Photo Ian Rochester.

Over use of nitrogen fertilizer can delay maturity of cotton, hamper defoliation and reduce yields. Photo Ian Rochester.

Cotton growing on soil of high (left) and low (right) nitrogen status. Photo Ian Rochester.

CHAPTER 3

IMPROVING SOIL WITH LEGUME CROPS

Nodules formed on faba bean roots by nitrogen-fixing Rhizobia bacteria. Photo Ian Rochester.

Faba beans are commonly used as a winter grain legume in cotton systems. Photo Ian Rochester.

Vetch is a highly efficient nitrogen-fixing winter legume cover crop. Photo Ian Rochester.

Vetch is mown and incorporated into the topsoil prior to sowing cotton. Photo Ian Rochester.

Peanuts can be grown in rotation with cotton. Photo Ian Rochester.