ALFALFA AS A SOIL BUILDER

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Concern about legumes as soil builders has been out of style for some decades, so that the relevant information pertains to older agricultural systems less intensive than ours. It seems necessary to bolster the data with what I hope are accurate informed guesses. This article is mainly about additions to soil nitrogen, but it also considers some other effects of alfalfa on soil.

Capability of Alfalfa as a Nitrogen Fixer

Nodulation of the roots of legumes results from infection by appropriate root nodule bacteria, the rhizobia. If the nodules are effective, the rhizobia within them fix nitrogen, i.e., they convert atmospheric nitrogen gas (N_2) to ammonia (NH_3) which can be assimilated by the plant.

Nitrogen fixation in alfalfa nodules can support very high growth rates. This has been shown in greenhouse experiments comparing plants supplied with adequate nitrate nitrogen and plants supplied with no combined nitrogen at all. In both cases the plants, after the initial seedling lag stage, were able to double their size every 6-7 days, the kind of growth that would give 2 tons/acre 30 days after emergence. The implication is that nodules are capable of supplying nitrogen fast enough to meet the demands of the highest growth rates likely to be achieved in the field. How well they in fact do meet these demands in the field is another question. We need first to consider some of the variables of soil and management that affect nitrogen fixation.

Variables that Influence Nitrogen Fixation

Plant growth rate. This sets an upper limit on the rate of nitrogen fixation in legumes, because it limits the ability to assimilate fixed nitrogen. There appears to operate a feedback control mechanism whereby any accumulation of ammonia resulting from fixation inhibits further fixation. Thus alfalfa rarely exceeds 3-4% N in the tops. A small amount of fixed nitrogen can be excreted from the roots, especially under conditions that favor fixation more than they favor growth. Some of this excreted nitrogen can be recovered in systems where the legume is grown in association with a grass and the mixture is harvested. Alfalfa is rather better than other legumes (e.g., clovers) at transferring nitrogen directly to associated grasses in this way, but even so the amount excreted is only a small percentage (about 5%) of the amount fixed and assimilated directly by the alfalfa (Simpson, J.R. Aust. J. Agr. Res. 16, 915 (1965)). In a pure alfalfa stand nitrogen excreted is probably of little benefit since it will be volatilized, leached, or recycled through the alfalfa at the expense of fixation at a later time.

Soil factors. The most important nutritional deficiencies, namely water, phosphorus, potassium and sulfur, strongly limit nitrogen fixation because they limit the growth of the alfalfa plant. For salinity the same appears to be true, in alfalfa. In some other legumes salt directly inhibits nodulation or nodule function, and reduces growth as a result of this Evidence that salt stops alfalfa nodulation has also been obtained, in laboratory experiments. However greenhouse experiments in sand culture at Riverside and in soil culture at Davis contradict this. Salt levels in solution in the soil up to 1% slowed germination and reduced growth, but had little effect on the number, size, or effectiveness of nodules or on the plants' color or nitrogen content. Although the interference with nitrogen fixation is indirect, via plant growth, it is nonetheless important practically.

Certain other environmental factors reduce legume growth by directly interfering with nodulation or nodule function. The most clearcut case is molybdenum deficiency, which may occur in certain Californian upland and Terrace soils but is evidently rare in valley agricultural soils.

Soil acidity inhibits nodulation of alfalfa, but because its effects on nodulation don't usually become significant unless the soil pH is below 5.6 we have tended to downgrade its importance in California. However, recent field experimentation in highly weathered acid soils, where calcium is also deficient, show clearly that alfalfa growth may respond to lime up to pH 6.8, because this improves nitrogen fixation even though the nodules are abundant and healthy looking. This finding may apply to older, red-colored soils in California, some of which are going into alfalfa production.

High soil temperatures may sometimes slow down nitrogen fixation. Even a few hours' exposure to temperatures much in excess of 35C (95F) permanently incapacitates alfalfa nodules. But against this, field observations at Davis indicate that almost all the nodules in well established stands were too deep in the soil to get overheated.

Soil nitrogen and nitrogen fertilization. Alfalfa ike other legumes, will not bother fixing nitrogen if the soil supplies enough Nitrate in particular inhibits nodule formation and nodule function.

Nitrogen fertilizer trials are the best test of the adequacy of nitrogen fixation in a legume. A large nitrogen response indicates that fixation is being impaired by inadequate nodulation or by acidity, molybdenum deficiency or some such condition that directly inhibits fixation. Nitrogen trials done for this purpose should always include high rates of application: low rates may produce no response simply because the supplied nitrogen is compensated by reduction in nitrogen fixation.

In general, well-nodulated established alfalfa stands give small or only transitory nitrogen responses. Greenhouse and field trials at Davis have given yield increases ranging from 0 to 15%, not enough to make the fertilization worthwhile; and in this they agree with almost all published research on the subject.

High levels of soil nitrogen may be beneficial where alfalfa and grasses are deliberately grown together. Here the grass can "mop up" available soil nitrogen and minimize its adverse effects on nitrogen fixation, and high nitrogen helps keep the grass in a desirably high ratio to the legume. However this is not relevant to most current practice in California, where grass in alfalfa is a weed.

Rhizobia in the soil and inoculation. Rhizobial types capable of nodulating alfalfa are widespread in Californian agricultural soils. Greenhouse tests with soils from 20 northern California alfalfa fields have shown little response to inoculation of seed with rhizobial cultures. In one soil from an orchard, uninoculated plants nodulated slowly because the soi had enough rhizobia to establish nodulation promptly, and the indigenous rhizobia were nearly as effective as the commercial inoculant bacteria, or in two cases slightly more effective. A field trial with commercial inoculants and with inoculants made from our most effective isolates has given no evident response. Inoculant bacteria with only slightly superior effectiveness tend to have little effect unless they have remarkable ability to compete during infection with the large population of indigenous bacteria. It appears that under most Californian alfalfa-growing conditions, inoculation is not likely to be of great benefit.

However, in land that has not recently grown alfalfa, or in acid soils, inoculation may be considered a cheap worthwhile insurance against delayed nodulation or nodulation failure. The signs of nodulation failure include nitrogen deficiency symptoms, nitrogen response, and virtual absence of nodules (these nodules present may become very large). These signs are of course observed after the event. Inoculation is also beneficial where the naturally occurring rhizobia are ineffective. This situation is indicated by the same signs as nodulation failure except that the plants have abundant nodules, usually small and white. Ineffectiveness problems have not arisen in California alfalfa, though they are the rule in our sub-clover rangelands.

Estimates of Nitrogen Fixation by Alfalfa

A 12 ton/year alfalfa has to assimilate a little over 1000 lb nitrogen per year. There is no evidence that fixation cannot supply this amount. But in practice it rarely does if only because 12 ton stands and completely nitrogen deficient soils are rare.

The table below gives estimates of nitrogen assimilated and fixed at different yield levels. These estimates assume a ratio of root production to shoot production of 1:4, with nitrogen contents of 3.5% in shoots and 2% in roots. For the amount of nitrogen obtained yearly from the soil, a good round figure of 100 lb is probably fairly representative of a typical unfertilized reasonably fertile Californian agricultural soil.

yearly production	lb N assimilated / acre				
	shoots	roots	total	from soi	lb N fixed
2 tons	150	20	170	100	70
4 tons	300	40	340	100	240
6 tons	450	70	530	100	430
10 tons	770	110	880	100	780

These estimates agree with measurements made from long term nitrogen balance studies in lysimeters in New York and Arizona, and with estimates from a survey of fields with different cropping histories in Kansas.

	annual production tons/acre	lb N fixed lb/acre/yr	increase in soi N, lb/acre/yr
Kansas, semiarid	2.5	160	35
New York, 2-yr stands	3.5	200	50
Arizona, 2-yr stands	6	470	160

Alfalfa is no slouch at fixing nitrogen, provided the conditions allow it to grow wel However only a small fraction of the fixed nitrogen is added to the soil

Addition of Fixed Nitrogen to the Soil

The immediately preceding table lists measurements of soil nitrogen accumulation under alfalfa cut for hay. These measurements are uncertain: they depend on small analytical differences and may reflect gains and losses not related to nitrogen fixatio by alfalfa. They imply a direct relationship with productivity; and in this respect and in their magnitude they are reasonably consistent with the following considerations

Fixed nitrogen is certainly added to the soil in the form of roots, crowns, and nodules left at the end of the stand's life. Figures for the amount of roots and crowns range from 2000 to 6000 lb/acre, of material which contains about 2% N. This gives a quantity of between 40 and 120 lb N added to the soil, per acre. The average long term effect of this kind of addition is probably greater the higher the productivity, since productivity probably relates to root weight, but it would become smaller as stand life was increased.

In addition to this end-of-stand accession of nitrogen there are very uncertain yearly accessions during thelife of the stand, in the form of leaf drop and loss of nitrogen from roots and nodules by excretion and decay. The following table lists estimates of these accessions based on assumptions that 10% of the above-ground nitrogen is returned to the soil by leaf drop and that about 5% of the total nitrogen fixed is lost to the soil by excretion and sloughing of roots and nodules.

nnual production	lb N in leaf drop	lb N lost from roots	total
4 tons	30	12	42
6 tons	45	20	65
8 tons	60	30	90

These generous estimates are likely to be reduced, perhaps to zero, by volatilization, leaching, and uptake of released nitrogen by the alfalfa itself.

Grazing increases the return of nitrogen to the ground. Dairy cattle, for instance, may return as much as 50% of the standing nitrogen in feces and urine. Thus grazing of a 1-ton stand could add 40 lb N to the soil per acre, and repeated grazing 5 or 6 times a season could add 200 lb. The net benefit would be reduced somewhat as mineralization of the returned nitrogen inhibited fixation by the alfalfa.

Green manuring of course returns to the soil all the nitrogen currently standing above ground, as well as the nitrogen below ground. This makes sense only at the end of the stand's life, and even then alfalfa hay is an expensive fertilizer at present prices

Hay cutting, by contrast with grazing and green manuring, harvests nitrogen most efficiently and therefore returns the least to the soil. This should be no cause for distress, because nitrogen is worth a good deal more in alfalfa hay than it is in the soil

Effects of Alfalfa not related to Nitrogen Fixation

Other plant nutrients, besides nitrogen, are harvested with prodigious efficiency in alfalfa hay production. The following table lists the minimal take-off of potassium, phosphorus, and sulfur, assuming the alfalfa contains these elements at levels nearly deficient for its own growth.

		P	
% in alfalfa tops	2	0.2	0.2
lb/ton alfalfa	28	4.5	4.5
lb/4-yr stand, 25 tons	680	10	110
lb readily available in top acre foot of Hanford soil	320 (exchange)	200 (sorbed)	80 (inorganic 800 (organic

Depletion of any of these nutrients is serious if the soil happens to be near to deficiency of any one of them. Potassium (K) is removed in the largest quantity: if replacement became necessary, the cost would greatly exceed the value of nitrogen added to the soil.

Subsoil water is also harvested efficiently by alfalfa, sometimes to the detriment of later deep-rooted crops, such as alfalfa itself. Observations in dryland conditions in Nebraska have shown a 40% reduction in yield of alfalfa attributable to this effect, while shallow-rooted crops like clover were almost unaffected. The detriment is of course minimized if rainfall or irrigation are sufficient to resupply the subsoil water.

Soil structural benefits are possible under alfalfa, as under any crop that maintains cover and minimizes cultivation. In a commonly cited example, the percentage of the top soil aggregated into water-stable aggregates bigger than 0.25 mm was reduced to 33% under continuous corn, but held at 60% under alfalfa.

On the other hand, soil structural damage is likely to result from traffic associated with alfalfa operations, especially when these are done with the soil wet Even on a sandy textured soil (Hanford) increases in soil strength sufficient to impair root growth have been measured. The greatest effect occurred at depths between 3 and 15 inches, but there was measurable effect down to at least 2 feet. Such compaction effects are not necessarily overcome by subsequent cultivation. Disking, for instance, did not eliminate adverse effects on barley growth resulting from just two passes with a tractor on a wet Hanford soil.

In Conclusion

The alfalfa-rhizobium combination is a powerful nitrogen fixing system. It is less successful at improving soil N because the nitrogen is efficiently harvested. Nitrogen benefits to the soil are variable and uncertain. They range from as low as a few pounds of nitrogen per acre per alfalfa year up to 200 lb or higher under highly productive grazing systems. (Observed benefits to crops following alfalfa hay production are commensurate with nitrogen additions in the lower part of this range).

Apart from needed attention to soil fertility, acidity, and inoculation in some areas, the nitrogen fixing system in alfalfa needs little management. Increasing the productivity of alfalfa entails large removals of soil nutrients and may entail structural damage, but it is the most effective way to increase both nitrogen fixation and nitrogen addition to the soil.