

Systems Analysis in Alfalfa Production

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Plant growth and development depends upon physiological processes such as photosynthesis, and it is the integration of such processes which leads to the accumulation of biomass and crop yield. Knowledge of the processes involved helps us in two ways. On one hand, we can do a better job of farming since we have a rational basis for diagnoses and decisions on cultivar, spacing, timing and inputs of nutrients. On the other hand, we can use the information for designing improvements in the farming system.

Our understanding of some production processes is very advanced. Photosynthesis, plant nutrition and microclimatology can be placed in that category. In other areas, such as plant development and temperature responses, the information is still very primitive. Weaknesses also exist in our abilities for detailed integration of the cause-effect relations which determine yield. New methods are gradually emerging for prediction of yield from holistic analyses of component physiological processes. These methods have been termed "integrative physiology" (Loomis, Rabbinge, and Ng, 1979) and are one example of the increasing importance of "systems analysis" in agriculture. Other examples are found in nutrient cycling (Frissel, 1977), grazing studies (Innis, 1978), and pest management (Ruesink, 1976). Systems analysis has come to have two connotations: analysis of the cause-effect pathways in a complex system (Watt, 1966); and the construction and use of simulation models of complex systems (de Wit and Goudriaan, 1974).

Systems Analysis as a Way of Problem Solving

Systems analysis is not limited to the more formal aspects of model conception and development. In fact, the idea of systems analysis as a cause-effect assessment of a complex system, is part of the everyday efforts of agriculturalists. Our group at Davis used that approach in recent work aimed at characterizing the growth and development of alfalfa under California conditions.

The main issues in our research were to determine the factors affecting productivity and stand persistence over years. The basic problem is defined by the fact that record yields of alfalfa run to 30 mt of hay per hectare (ca. 15 tons per acre) while the average yield in California is less than half of that. Some of the difference can be laid to management practices (poor soils, harvester damage, poor irrigation practices). We concentrated on the question of whether growth processes were also limiting or contributed to managerial problems. We adopted a two-tiered approach: at one level, we focused on specific issues such as leaf photosynthesis and root-crown anatomy which were known to be important; at a second level, we attempted an ecological description of what the crop does during regrowth after cutting. This was done through harvests at 5 to 7-day intervals in a commercial field to establish growth curves over several cutting cycles. Separation of plant parts at each harvest provided a view of photosynthate partitioning. The idea of this "nonexperiment" was to establish a baseline picture of regrowth from which we might draw ideas regarding the controls of productivity.

The results of dry matter sampling for one of the cutting cycles in 1980 is illustrated in Figure 1. The yield of oven-dry forage for this late-summer cycle was 2950 kg·ha⁻¹. Earlier cycles gave heavier yields while later ones were lower, following the pattern of solar radiation and the tendency for alfalfa to become dormant in the fall. Total yield for five cycles over the entire growing season was near 20 mt·ha⁻¹.

In addition to stem and leaf fractions, we found nearly 4000 kg·ha⁻¹ of biomass in above- and belowground "crown" tissues (regrowth occurs by activity of axillary and adventitious buds on these stem and rhizomatous structures), and the central tap root. Only the upper 5 cm of the tap root was sampled in this first year. Fibrous roots and deep tap root fractions were sampled in the 1981 season. This small portion of tap root totaled 1500 kg·ha⁻¹ in 1980 so we estimate that the actual yield of the entire root

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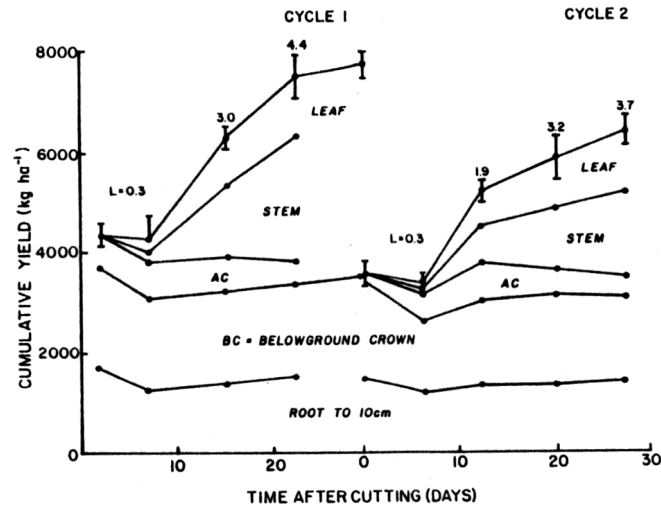


Figure 1. Regrowth of 3-year old commercial stand of 'WL508' alfalfa during two cutting cycles in July and August at Davis, California. Above- and belowground biomass of various plant fractions are plotted versus time after cutting. Forage yield is composed of stem and leaf fractions; above- (AC) and belowground crown (BC) and the central tap root represent parts of the continuing "perennial" structures.

L = 0.3, 3.0, etc. indicates the leaf area index ($1000 \text{ kg}\cdot\text{ha}^{-1}$ corresponds to nearly 900 lbs. per acre).

system may range upwards from $3500 \text{ kg}\cdot\text{ha}^{-1}$

These rather simple results reveal a number of points:

1. Lag period. There was no net production during the first 7 days after cutting. During this first quarter of the regrowth cycle, buds were opening and cover was being reestablished. The crown and root system showed negative growth. Analyses showed that this was due mainly to a decline in starch content and to the death of stem branches from which no regrowth occurred. The content of nonstructural carbohydrates in woody parts of the tap root declined from over 17 to about 12 percent of dry weight during the first 2 weeks after cutting and then returned to the original level during the last 2 weeks. (The anatomical study is aimed at clarifying the role of the root cambium in providing new wood and bark tissues for carbohydrate storage.)

2. Size of the perennial structures. Clearly, a very large amount of biomass is given to perennial structures. Much more definition of the root system is required and that has been given priority in recent work. Since the total of perennial structures seems to amount to above $6000 \text{ kg}\cdot\text{ha}^{-1}$, they represent a considerable reservoir of carbohydrates and nitrogenous materials to support regrowth. They also represent a potentially large cost in maintenance--at a relatively low maintenance requirement of 1 g glucose respired per 100 g root-crown material per day, as much as $70 \text{ kg photosynthate}\cdot\text{ha}^{-1}\cdot\text{day}$ may be expended in maintenance respiration.

3. Peak growth rates. After the 7-day lag, "crop growth rates" (slope of the total biomass curve) were positive, and biomass accumulated. The peak growth rate occurred during the second week and, for this cycle, reached $185 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{day}^{-1}$. (Other cycles approached $300 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{day}^{-1}$.)

Remarkably, these growth rates occurred with considerably less than full leaf cover. Many experiments with various crops have shown a linear relation between crop growth and

percent of ground covered by leaves. Since cover increased from 12% to only 50% (0.3 to 1.9 leaf area index) during the second week, we expected the growth rate to increase above $185 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{day}^{-1}$ during the 3rd and 4th weeks as leaf area index increased to 3.7 and cover approached 100%. But that did not occur. Rather, growth rate declined to $77 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{day}^{-1}$. The cumulative difference between 77 and $250 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{day}^{-1}$, which might reasonably be expected during the last 15 days, is $2600 \text{ kg}\cdot\text{ha}^{-1}$. That behavior seemed general for this field and is also seen in data from other locations.

Our attention quickly focused on possible explanations for the 2600 kg of "missing yield." This exercise in systems analysis led us to the following possibilities:

1. Water shortage. A growth decline of this sort would occur during drought. But heavy irrigations were applied in the first and third weeks. Measurements of plant water status were not made, but no signs of stress were evident and the plants used the soil moisture freely.

2. Nutrient shortage. Nitrogen, phosphorus and potassium are possible candidates as limiting nutrients. It is common for alfalfa forage to contain over 3% N, 2% K and 0.2% P so the nutrient removal by a 20 mt crop can be very large. We do not expect deficiencies of K and P on this site but soils analyses for P were marginal and we are now checking that possibility through analysis.

The nitrogen analyses are presented in Figure 2. The standing crop of nitrogen and its distribution among plant parts followed a pattern very similar to that shown for dry matter. The main difference is the large proportion of nitrogen in leaves (5% D.W.) at final harvest compared to stems and roots (2% D.W.). The peak increase in nitrogen corresponds to peak growth rate (2nd week). Here, we need data for the balance of the root systems and the nodules to establish a complete story. But it appears that the crop receives a single major contribution of about $60 \text{ kg N}\cdot\text{ha}^{-1}$ during the second week, and very little thereafter. Whether that nitrogen is from the soil, roots, or nodules, is yet unclear. The nitrogen content of the crowns and sampled portion of the tap root declined from 2.0 to 1.8% during this time. If the whole perennial structure (estimated at $6000 \text{ kg}\cdot\text{ha}^{-1}$) declined as much, that would account for only $1 \text{ kg N}\cdot\text{ha}^{-1}$ (0.002×6000). Perhaps cutting causes nodule and fibrous root decay, providing a single major release. The small gain in nitrogen during the last 2 weeks might reflect a reestablishment period for those structures.

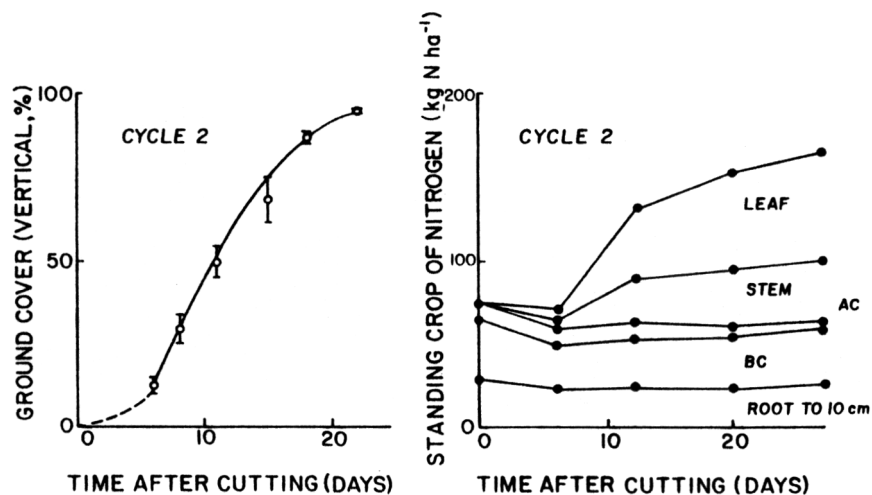


Figure 2. Percent of ground cover by leaves (viewed vertically) (left) and nitrogen content of plant fractions (right) for Cycle 2. Coding is the same as in Figure 1. ($100 \text{ kg}\cdot\text{ha}^{-1}$ corresponds to about 90 lbs per acre).

Whatever the mechanisms, pulsations in nitrogen supply could account for the growth plateau seen in Figure 1 so nitrogen economy was given a major emphasis in the 1981 work.

The diversion of photosynthate to replacement of nodules and to support nodule activity could contribute to the observed plateau effect in Figure 1. The actual cost of fixation, however, would not be great. The conversion of N to NH involves reduction of nitrogen by the addition of three electrons to each atom. Since respiration of a mole of glucose (180 g) yields the equivalent of 24 moles of electrons, the ratio of assimilate use will be 3/24 mole glucose per mole NH or $\frac{3 \times 180}{24 \times 14} = 1.6$ g glucose per g nitrogen. For

the 60 kg N which appeared in this cycle, only 96 kg of photosynthate would be required. Even if we double that to account for nodule maintenance, the result is only a small fraction of the "missing" 2600 kg of yield. So we have to consider that fibrous root and nodule replacement as well as wasteful hydrogen production by the nodules would be the major factors. Even if that accounts for the missing yield, one can still draw the interpretation that shoot growth came to be limited by nitrogen supply.

It is strange to think of a vigorous legume crop encountering a deficiency of nitrogen. This field appears to do very well in nitrogen fixation. With 20 mt of hay containing over 3% N harvested each year for 3 years, more than 1800 kg N ha has been removed. That amount is vastly greater than natural inputs through rainfall and dust. It also greatly exceeds the nitrogen which could be supplied from organic matter by this desert soil. The high apparent rate of fixation plus the repeated failure of agronomists to obtain alfalfa yield responses through additions of fertilizer nitrogen leads one to skepticism regarding nitrogen limitations. But small amounts of fertilizer nitrogen seem to simply replace an equal amount of fixation. Nodulation and fixation are both repressed in the presence of inorganic nitrogen (Evans and Barber, 1977). So, to be effective in increasing yield, considerably more than 600 kg N ha⁻¹ would have to be supplied as fertilizer. Such rates have seldom been employed with alfalfa, i.e., the possibility exists that the nitrogen responsiveness of alfalfa has not really been tested.

3. Net photosynthesis decline. Leaf photosynthesis rate sometimes decline dramatically with age. This seemed unlikely as an explanation for the missing yield, however, since alfalfa stems elongate indeterminately until slowed by heavy flowering. At final harvest, our canopy was dominated by recently expanded young leaves in the upper strata. In addition, laboratory studies revealed that the difference in maximum net photosynthesis rates of the youngest and oldest mature leaves was only about 25%.

The photosynthesis measurements were generally made on leaves grown at moderate light levels in glasshouses, and at high nutrition. If a shortage of nitrogen did occur, one would expect carbohydrates to accumulate in stems and leaves. Chemical analyses showed that sugars and starch did increase with time in the field. As a result, some type of "feedback inhibition" of photosynthesis (Neales and Incoll, 1968) might be expected under high-light conditions in the field. An additional possibility is that "photorespiration" might be increased in the presence of high levels of carbohydrate. Both possibilities have been investigated with plants grown under conditions with high light and restricted growth sinks. It appears that net photosynthesis declines with increasing carbohydrate content and that increased photorespiration is the cause.

Accumulated dry matter, as observed in Figure 1, integrates leaf net photosynthesis with respiratory activities of the whole plant. As noted earlier, maintenance respiration would be expected to increase as biomass increased and that could be a significant drain on yield. There are also possibilities that maintenance respiration increases as carbohydrate supply increases or that wasteful, "uncoupled" respiration may occur in high-carbohydrate roots. Again, we see the need for a great deal more information about the underground structures before one really understands an alfalfa crop.

Summary

Our work is concerned with developing a better understanding of how an alfalfa crop accumulates forage yield. I have presented a sample of our findings from growth and analysis studies in the field and from laboratory studies of photosynthesis. Other aspects of the work have centered on a reinvestigation of root anatomy and an examination of sunlight interception by alfalfa leaves. The work has provided a number of exciting leads which may help explain the generally poor performance of commercial stands of alfalfa in California. That kind of understanding is a first step towards improved

cultivars and improved farming practices

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