THE CULTURAL MANAGEMENT OF FLUE-CURED TOBACCO QUALITY[1]

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The flue-cured variety NC 2326 was grown under 36 management systems comprised of all combinations of two soil types, subsoiled or not-subsoiled, three rates of nitrogen fertilization, and three moisture regimes. Coupled with the dry season of 1980, the cured tobaccos differed widely in quality.

Biochemical observations during the growth of these plants support the conclusion that the key to flue-cured quality is the timing of the metabolic transition from nitrate reduction to starch accumulation. When fertilization has been precise and soil moisture adequate for the timely uptake and reduction of nitrogen, this transition occurs about simultaneously with flowering; leaves fill out, ripen properly, and cure easily. The cured tobaccos have good physical characteristics and are compositionally balanced with respect to sugars and nicotine (ratio, S/N = 6 - 8). Over-fertilization or/and drought delays the transition allowing for more nicotine to be synthesized and, because of rapid shortening daylengths, less starch accumulates subsequently; such tobaccos are chemically imbalanced (S/N < 5). Conversely, underfertilization (or/and leaching) triggers this metabolic shift prematurely thereby restricting nicotine production and permitting much starch to accumulate; these tobaccos too are imbalanced chemically (S/N < 9).

Keywords: quality; nitrogen nutrition; soil moisture; subsoiling.

INTRODUCTION

A general definition of quality is the total properties of any particular entity that adapts it to its intended use. Paraphrasing this definition for flue-cured tobacco, quality is the sum of its physical and chemical attributes that best suits it for the manufacture of cigarettes. But particular characteristics assume greater or lesser importance depending upon who is making this judgment. To the grower, net income is pre-eminent. The federal inspector takes into consideration stalk position, leaf size and intactness, ripeness, color and uniformity of color both within and among leaves, body, texture, and aroma in assigning the Official Standard Grade that will establish the base selling price for each particular lot of tobacco. Tobacco buyers use many of these same criteria in deciding whether or not to compete in the bidding for a particular tobacco. Manufacturers are more thorough in their evaluations, using both constituent analyses—nicotine, reducing sugars, total nitrogen, total ash, Ca, K, Cl, pesticide residues—as well as economic factors—price, strip yield, filling value, hygroscopicity, shatterability, foreign materials—in determining the relative qualities of their tobacco stocks. The ultimate assessment, however, is the consumer's reaction to the flavor and satisfaction of the smoke.

Quality in the commercial sense first become perceptible when flue-cured tobacco is taken out of the curing barn. But quality is not created during curing; it is the product of the cultural environment. Thus, at the moment of harvest, a leaf already contains its maximum potential for quality. The optimum curing schedule merely transforms potential quality into tangible quality. Unfortunately, much quality is degraded by mismanaged curings.

The environmental factor that most frequently causes abberations in tobacco quality is rainfall though, more often, it is poor distribution rather than aggregate insufficiency. The association of high alkaloids and low sugars with droughty tobaccos and, conversely, of low alkaloids/high sugars with wet-weather crops is well known [17].

The magnitude of the effects of inadequate soil moisture on quality depends upon its duration and the stage of growth at which it occurs [9, 10, 13]. Moisture stresses (approximating tissue-water deficits of -12 bars) were induced experimentally by withholding water starting at 14, 31, 42, or 56 days after transplanting [unpublished data]. Young plants subjected to stress had nearly recovered by the time that harvest began. Late stress did not siginficantly affect quality. Withholding water during the period of rapid growth (Drought-31 and Drought-42) adversely affected quality. Yield, grade index, and reducing sugars were lower; alkaloids were higher; and the tobaccos were judged to be less usable for the manufacture of domestic cigarettes [also, 12].

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Table 1. Range in quality assessments among 72 lots of NC 2326 tobacco produced under 36 management systems at the Central Crops Research Station in 1980.

ASSESSMENT	RANGE	NORFOLK	WAGRAM
Yield, kg/ha	Highest	3584	4077
	Lowest	1900	2046
Grade Index	Highest	32.9	26.8
	Lowest	3.7	8.0
Co.A Usability, %	Highest	40.0	61.4
	Lowest	0	0
Co.B Usability, %	Highest	79.7	100
	Lowest	0	0
Co.C Usability, %	Highest	50.9	41.9
	Lowest	0	0
Total Nitrogen, %	Highest	3.37	2.93
	Lowest	1.61	1.51
Nicotine[4/], %	Highest	5.94	5.29
	Lowest	2.33	2.51
Reducing Sugar, %	Highest	25.6	26.8
	Lowest	2.5	9.8
Ratio, Sug/Nic	Highest	11.0	10.7
	Lowest	0.5	1.9

[4/] The Harvey (5) method measures all pyridine-alkaloids as nicotine. Analyses by a more discriminatory method [1,2] revealed that nicotine constituted 93.7% of "total alkaloids" in NC 2326 from the Official Variety Test-1980 [14]. Thus, "nicotine" and "total alkaloids" are sometimes used interchangeably.

Among management options, improper nitrogen fertilization is responsible for much of the poor quality tobacco that is produced every year. Tobacco is unusually sensitive to nitrogen nutrition. Ideally, one supplies precisely the right amount of nitrogen to insure vigorous growth but with no excess, so that the external reserves become exhausted simultaneously with flowering [3, 11]. Plants fertilized excessively with nitrogen produce very large but thin leaves, and ripening is delayed. Overfertilized leaves are difficult to cure and the tobaccos, particularly those from upstalk positions, are usually dark in color, dry, and chaffy. Such tobaccos are high in total nitrogen and alkaloids, are low in sugars, and their smoke is strong and pungent.

The rate of growth of underfertilized plants is retarded. The leaves are smaller but thicker; they are smooth and pale in color and, consequently, are often harvested before they are fully ripe. The cured tobaccos are pale and lacking in texture. They are low in alkaloids, high in sugars, and the smoke is flat and insipid.

Subsoiling or chiseling, viz., the slicing through the soil directly under the row to a depth of approximately 43 cm, is a relatively new tillage option for tobacco, although it has become almost standard practice for corn and soybeans. Many soils develop an impervious traffic pan just below the plow layer. In this situation, the subsoiling blade would rupture this barrier thereby allowing roots (and water) to penetrate more deeply. Then during times of moisture inadequacy, plants may extract water (and possibly nutrients as well) from the larger volume of soil.

Over the past several years, we have investigated the effects of each of the above management options, singly and in binary combinations, on flue-cured quality. Through appropriate combinations of nitrogen applications and moisture managements during culture, tobaccos have been tailored to prespecified alkaloid concentrations [6]; reducing sugars, while shifted in the intended directions, had failed to attain the goals targeted.

This report summarizes a study in which management systems comprised of all combinations of two soil types, two tillages, three rates of nitrogen fertilization, and three moisture regimes were employed to produce tobaccos that differed widely in quality. And, while their effects on quality were

Table 2. Average effects of particular cultural variables on quality assessments. (NC 2326, Central crops, 1980).

Cultural Variable	Yield	Grade Index	Percent Usable CoA	CoB	CoC	Total Nitrogen	Nicotine	Reducing Sugar	S/N Nic
	kg/ha						%	%	
SOILS:									
Norfolk	3008	19.1	5	16	17	2.41^{a}	4.12^{a}	15.4^{a}	4.3^{a}
Wagram	3119	19.6	12	27	18	2.17^{b}	3.67^{b}	18.6^{b}	5.5^{b}
TILLAGE:									
Normal	2904^{c}	17.7^{c}	7	14	17	2.40^{c}	4.09^{c}	15.5^{c}	4.3^{c}
Subsoiled	3224^{d}	21.1^{d}	10	30	19	2.21^{d}	3.71^{d}	18.6^{d}	5.6^{d}
NITROGEN:									
Low	3093	23.9^{e}	18	23	24	2.03^{e}	3.22^{e}	21.6^{e}	7.1^{e}
Normal	3085	20.4^{e}	5	24	16	2.23^{e}	3.88^{f}	17.0^{f}	4.8^{ef}
High	3013	13.9^{f}	5	18	14	2.62^{f}	4.60^{g}	12.5^{g}	3.0^{f}
MOISTURE:									
Normal	3392^{h}	24.3^{h}	14	42	23	2.01^{h}	3.23^{h}	21.3^{h}	7.1^{h}
Stress	2963^{i}	17.4^{i}	4	12	12	2.38^{i}	4.24^{i}	16.7^{i}	4.4^{i}
Ambient	2836^{i}	16.3^{i}	8	13	18	2.49^{i}	4.23^{i}	13.1^{j}	3.4^{i}
CV	8	18	128	60	61	7	9	11	21

Within subgroups, different superscripts indicate significance at $P \leq 0.05$.

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Table 3. Simple correlations, *r*, between pairs of quality assessments. (NC2326, Central Crops, 1980)

	Yield	Grade Index	Usability Co. A	Usability Co. B	Usability Co. C	% T.N.	% Nic.	% R.Sug.	S/N
Yield	1.000	.575	.254	.571		-.560	-.574	.619	.614
Grade Index		1.000	.374	.553	.530	-.811	-.786	.812	.774
Co. A Use			1.000	.283	.272	-.433	-.467	.413	.441
Co. B Use				1.000	.294	-.534	-.561	.532	.568
Co. C Use					1.000	-.442	-.494	.399	.404
% T. Nit.						1.000	.951	-.935	-.937
% Nicotine							1.000	-.887	-.936
% R. Sugar								1.000	.956
S/N									1.000

generally predictable in direction if not in magnitude, other measurements made during growth provided some basis for understanding how these differences had developed.

MATERIALS AND METHODS

The experiment, in a split-plot design, was conducted at the Central Crops Research Station, Clayton, NC, in 1980; the cultivar was NC 2326. All managements other than those imposed experimentally were those believed to be most appropriate for tobacco at this Station. Variables were:

Soils: Norfolk or Wagram. These are very similar sandy loam soils differing mainly in the depth of the topsoil—approximately 23 cm and 60 cm, respectively.

Tillage: Normal (18 cm) or Subsoiled (43 cm). On the shallow Norfolk soil, the subsoiler sliced through the A2 layer and gouged into the clay. On the Wagram soil, subsoiling ruptured the traffic pan.

Rates of Nitrogen: Low, Normal, or High. Because previous experience had indicated the Norfolk soil to be slightly more fertile, an attempt was made to equalize the nitrogen levels of the two soils. The rates of nitrogen applied, in kg/ha, were:

	Low	Normal	High
Norfolk	43	62	82
Wagram	43	66	90

Other nutrients were applied uniformly: P_2O_5, 61; K_2O,

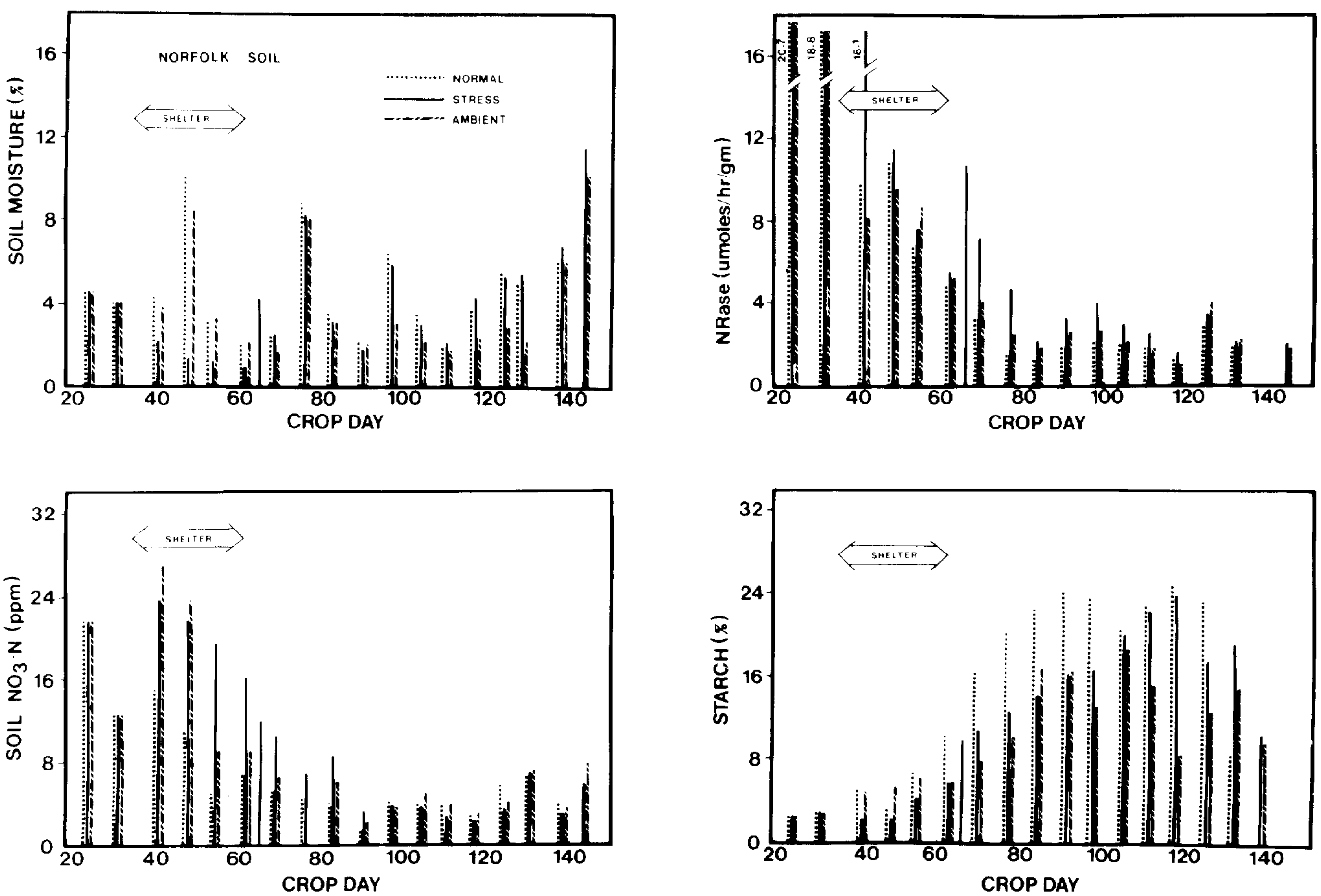

Figure 1. Effect of moisture regimes on soil moisture, soil NO_3-N, NRase and starch on Norfolk soil.

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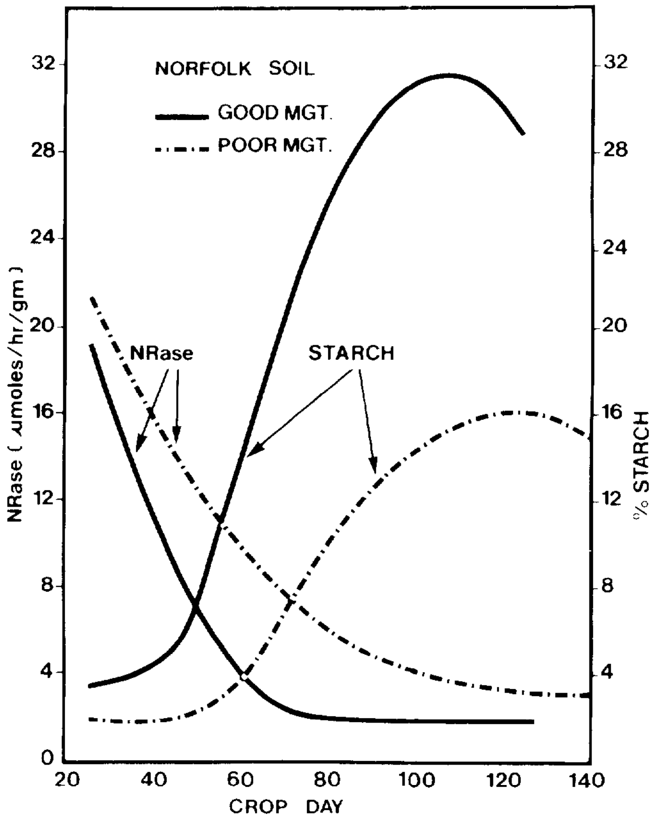

Figure 2. Effects of cultural managements on NRase activities and starch accumulations. The good management combined normal N-fertilization, subsoiling, and normal moisture regime. The poor management consisted of high nitrogen, not-subsoiled, and moisture stress. (NC 2326, Central Crops, 1980).

120; MgO, 22 kg/ha.

Moisture Regimes: Normal, Stress, or Ambient. The normal-moisture plots were irrigated to field capacity whenever the topsoil moisture had been reduced to 2.5% (-15% available water).

Normal soil moisture was maintained in the stress plots until Day 33 (after transplanting) when plastic-covered shelters were installed over the plants to divert rainfall and thus to induce moisture stress. These shelters remained in place for 21 days on the Wagram soil (for 28 days on the Norfolk) at which time the soil moistures under the shelters had been reduced to 0.9 and 1.0% respectively. Immediately following the removal of the shelters, soil moisture was restored by irrigation and, thereafter, was maintained at or above 2.5% moisture.

Ambient plots received rainfall only.

Beginning on Day 24, soil moistures[3], soil nitrate-nitrogen [4], *in vitro* nitrate reductase activities (NRase) in fresh laminae [8], and starch accumulations in freeze-dried tissue [15] were monitored at weekly intervals.

Leaves were harvested when ripe and bulk-cured together. The cured tobaccos, by plot-harvest, were weighed for yield and assigned Official Standard Grades from which a weighted grade index [16] for each plot was computed following the final harvest. Eventually each of these individual plot-harvest tobaccos was evaluated independently by leaf experts from three manufacturers as to its suitability for use in their respective blends. Representative whole-plant laminae samples were analyzed for total nitrogen (Kjeldahl method), and for nicotine and reducing sugars [5].

[3]*Dried overnight in a convection oven at 102°C and computed relative to the wet-weight of the sample.*

RESULTS AND OBSERVATIONS

The season in 1980 was unusually dry and abnormally hot. Between May 1 and September 4, rainfall aggregated only 24.8 cm; this compares with 41.7 cm in 1979, a more normal year. Eight irrigations were required to maintain satisfactory soil moisture in 1980, whereas only one was needed in 1979. During this same period, maximum daytime temperatures exceeded 32°C (90°F) on 55 days as compared with 38 in 1979.

A growth advantage of plants on the subsoiled plots became discernible very early in the season on both soils; on the Norfolk soil, this differential persisted through the final harvest. Among stressed plants, the benefits of subsoiling were especially conspicuous.

The unfavorable season of 1980 superposed upon various combinations of management options produced tobaccos of widely diverse qualities. This diversity is demonstrated by the extremes for each of nine quality assessments (**Table 1**). Yields varied over a twofold range; grade index by a factor of eight; total nitrogen, twofold; a 2.5-fold range in nicotine concentration; tenfold in reducing sugars; 22-fold in sugar/nicotine (S/N) ratio.

Average effects of specific cultural variables on nine assessments of quality are summarized in **Table 2.** Only six of 36 meaningful first-order interactions were significant; the magnitude of the effects of moisture managements on yield, total nitrogen, nicotine, and reducing sugars were larger on the Norfolk than on the Wagram soil (M x S).

Yield: Contrary to expectations, yields did not increase with increasing rates of nitrogen. Yields did decrease significantly with restrictive moisture managements (Stress, and Ambient) and increased with subsoiling.

Grade Index: Grade index is a translation of Official Standard Grades into a numerical description of whole-plant quality, scaled between 1 and 99 [16]. Any tobacco rating a grade index of 60 is fine tobacco indeed. The average grade index of these experimental tobaccos was 19.4; the highest, 32.9. Higher grade indices were associated with normal and low nitrogen fertilization, with normal moisture management, and with subsoiling.

The Official Standard Grades assigned to the 374 individual plot-harvest sublots are also informative. None rated "excellent" or "fine"; only 61 (16%) were graded "good" (Quality 3). Sixty others (16%) were classified as "nondescript", and half or more of these came from moisture-restricted plots (ambient or/and not-subsoiled). Normal and low nitrogen, normal moisture, and/or subsoiling produced more than half of the clear "lemon" (L) or "orange" (F) tobaccos. The color descriptors assigned to 235 (63%) sublots indicated that they were "green" (G), "mixed" (M), or "variegated" (K) and, since these were distributed rather uniformly across all managements, perhaps the hot weather (55 days with highs exceeding 32°C) may have been a principal factor.

Blend-Usability: A leaf buyer's evaluation of a particular pile of tobacco undoubtedly is tempered by his knowledge of that company's specific blend requirements in relation to its current inventories, and by price. When examining these experimental tobaccos, one company's expert could use all of the tobaccos from one particular plot; all companies judged the tobaccos from the same 12 of the 72 plots to be totally unsuitable. All three companies were generally consistent in shunning overfertilized and underwatered tobaccos. Their preferences for tobaccos from subsoiled plots suggests that those plants had been less-stressed than not-subsoiled plants.

Total Nitrogen: Differences in the total nitrogen concentrations among laminae samples are directly relatable to nitrogen fertilizations, to extended durations of uptake as influenced by restrictive moisture managements, and to non-subsoiled tillage. Absolute accumulations of nitrogen however, differed only with the amounts supplied in the fertilizers.

Nicotine: Nicotine concentrations correlate positively with the duration of synthesis as influenced by nitrogen fertilization

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Table 4. Average effects of cultural managements on the timing of the NRase/starch transition, and on maximum starch accumulation. (NC 2326, Central Crops, 1980).

Variable	Steady-State NRase Attained	Max. Starch Accumulation
	Crop Day	%
Soils:		
Norfolk	96	24.2
Wagram	85	23.8
Tillage:		
Normal	95	22.0
Subsoiled	88	24.5
Nitrogen:		
Low	81	28.8
Normal	92	23.8
High	97	19.5
Moisture:		
Normal	86	27.8
Stress	108	24.5
Ambient	98	18.5

and/or restrictive moisture managements.

Reducing Sugar: Glucose is the product of starch hydrolysis during curing and, therefore, its concentration in the cured leaf is directly proportional to starch accumulation in the green leaf at harvest. The conversion factor is approximately 0.6.

Sugar/Nicotine Ratio: S/N is a simple quality index postulated to indicate constituent balance or imbalance (see DISCUSSION).

Statistically significant simple correlations, r, between pairs of quality assessment over the considerable range represented in these experimental tobaccos are summarized in **Table 3.**

Collectively, the results of this experiment strengthen the conclusions that the critical ingredient in the management of flue-cured tobacco is a precisely controlled nitrogen supply and, further, that available moisture regulates the uptake and utilization of that nitrogen. The natural drought of 1980 was more detrimental to tobacco quality than was 22 kg/ha of excess nitrogen; average differences in yield depression, decreases in grade index and reducing sugars, and increases in total nitrogen and nicotine between irrigated versus not-irrigated, normally-fertilized tobaccos far exceeded the differences between irrigated, normal- versus high-nitrogen tobaccos.

Subsoiling was beneficial to tobacco quality in dry 1980. From both visual observations during growth and from quality assessments on the cured tobaccos, it was convincingly evident that plants on the subsoiled plots had been less-stressed for water than those on not-subsoiled plots; the data, however, offer no evidence that the plants had gained access to extra nitrogen as the result of subsoiling.

DISCUSSION

Potential quality is the product of cultural management and environment. The two physiological processes within the plant that predetermine the quality of the cured tobacco are nitrate reduction and photosynthesis.

During growth, metabolic priority is directed to the uptake and reduction of nitrate-nitrogen (NO_3^-). The rate of nitrate uptake is dependent upon the external supply (fertilization) and upon adequate soil moisture (rainfall or/and irrigation). The reduction of nitrate is effected by the enzyme nitrate reductase (NRase). NRase is described as being substrate induced and substrate dependent, that is, its activity increases or declines in relation to the amount of NO_3^- within the tissue. Reduced nitrogen is utilized in the biosynthesis of amino acids, proteins, and nicotine.

Photosynthesis is the source of the energy required for the reduction of nitrate [7]. During early growth when the demands for reduced nitrogen are high, almost all of the photosynthate is utilized for this reduction; there is little surplus to be stored as starch. Only when the pool of NO_3^- within the tissue diminishes —normally as the external reserves approach depletion, or temporarily when drought limits nitrogen uptake—is any excess of photosynthate converted into starch. Thus, physiologically, starch accumulation follows nitrate reduction although the transition is not discrete.

Starch accumulation can be quite rapid; increases of 102 kg/ha (91 lb/A) per day have been measured (unpublished data). Daylength largely determines the amount of starch that will accumulate in a tobacco leaf. Tobacco at Clayton, NC, matures and ripens during shortening days; between July 10 and September 24—the harvest period in this experiment—daylength had shortened by 2.5 high-intensity, midday hours. Accumulated starch adds directly to yield, it fills out the leaves so that they ripen properly; it dilutes nicotine and, during curing, it is hydrolyzed into glucose.

The weekly monitorings of NRase activities and starch accumulations in laminae samples and of soil moistures and nitrate concentrations within the root zones support the above discussion. As an example, the average effects of moisture managements on the Norfolk soil are plotted as bar graphs in **Figure 1.** They show that,

—soil moisture decreased rapidly under the shelters (Upper Left, solid bars);

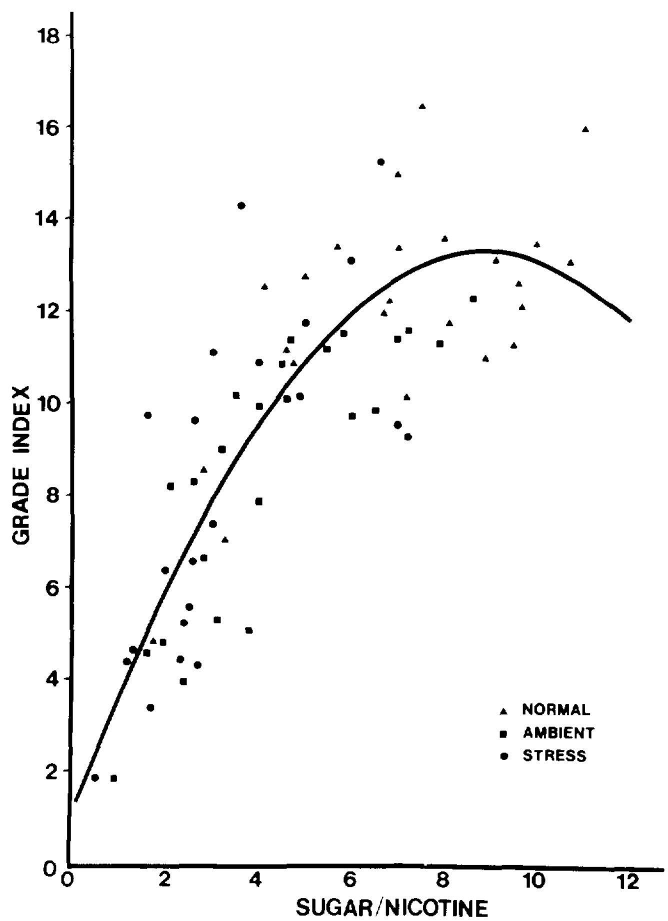

Figure 3. The relationship between physical quality and chemical quality of cured tobacco. (NC 2326, Central Crops, 1980).

—the uptake of nitrate by stressed plants was greatly retarded as the result of low soil moisture (Lower Left, solid bars);

—NRase activity resumed after the shelters had been removed and soil moisture was replenished (Upper Right, solid bars) and "second-growth" followed, and

—starch accumulation was delayed (Lower Right, solid bars).

To illustrate the effects of management variables on growth biochemistries, least-squares polynomial response curves for nitrate reduction and starch accumulation in plants under a "poor" management system (high nitrogen, not-subsoiled, moisture-stressed) and under "good" management (normal nitrogen, subsoiled, normal moisture) are compared in **Figure 2.** Under good management (solid curves), NRase had declined to its low steady state on about Day 70 and starch accumulation ultimately reached 32%. By contrast, the poorly managed plants (broken curves) were still reducing nitrogen (and synthesizing nicotine) on Day 130; maximum starch accumulation was only 16%. Because of the delay in this metabolic transition, the poorly-managed tobacco yielded only 2157 kg/ha as compared with 3583 kg/ha of the "good" tobacco; grade indices were 3.7 and 32.9, respectively; nicotine concentrations, 5.94 and 2.89%, reducing sugars, 5.3 versus 21.7%.

The polynomial regressions for each individual plot were interpolated to approximate the date (Crop Day) of termination of nitrate reduction and for maximum starch accumulations. These interpolated parameters, averaged by management variables, are summarized in **Table 4** and suggest an explanation for the observed quality differences among the tobaccos in this experiment (**Table 2**). Relative lateness of this transition equates to higher nicotine and to lower grade index. Higher starch contributes significantly to yield and is directly proportional to sugar concentrations; it decreases nicotine concentration by dilution.

Sugar and nicotine are the constituents of flue-cured tobacco that contribute most importantly to the character and satisfaction of smoke. The two are inversely related ($r = -.887$); any cultural mismanagement or adverse weather that causes one to increase, also causes the other to decrease. A proper balance between sugar and nicotine is most desirable and, when this prevails, it can reasonably be assumed that other chemical constituents would not be grossly out of balance. Thus the ratio, S/N, is useful as a simple index of chemical quality.

In **Figure 3,** grade index—a numerical appraisal of physical quality based on the assigned Official Standard Grade—is plotted against S/N for each of these experimental tobaccos. The least-squares parabola fitted through these data peaks at S/N = 9.

In retrospect, this particular population of tobaccos was not properly balanced to establish the true relationship between grade index and S/N: (a) the experiment had not included any "too-wet" treatments and (b) the natural drought had caused all ambient-tobaccos to be shifted downscale on both axes. This left only the low-nitrogen, normal-moisture tobaccos to determine the high-ratio downturn of the parabola. We believe that the best tobaccos produced in this area should average about S/N = 7.

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