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SOIL MOISTURE-BASED SIMULATION OF FORAGE YIELD

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ABSTRACT

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A simulator of seasonal forage yield (SIMFOY) was developed for a 'dry weather-forage crop' insurance plan in Ontario, Canada. Growth is assumed to follow an idealized sigmoidal curve with time. Departures from the potential daily growth increment are determined from an estimate of the soil moisture regime and degree-days above 5°C. The harvestable dry matter at the end of each growth cycle depends on the accumulated daily growth increments. Daily soil moisture is estimated in each of several soil zones using potential evapotranspiration calculated from a modified energy budget approach, and an extraction pattern that depends on soil moisture distribution and root distribution. Validation of SIMFOY is accomplished by comparison of soil moisture and yield estimates with measured values for different soils over a number of years. Results indicate that the model simulated seasonal dry matter production of alfalfa with reasonable accuracy.

INTRODUCTION

The estimation of plant growth and development using climatic factors has received considerable interest in recent years (De Wit, 1958; Hanks, 1974; Holt et al., 1975). Relationships developed have ranged from simple regression techniques to process models of the soil—plant—environment system. In practice, the type of model developed depends upon its intended use or objectives and also on the availability of meteorological variables to be used as inputs. The objective of this study was to develop a simulator of seasonal forage dry matter production as related to daily soil moisture status for a 'dry weather-forage crop' insurance plan in Ontario, Canada. The plan provides an alternative to the present method of estimating hay and pasture yields from "hay-mow" measurements for crop insurance in drought years. Actual measurements of hay and pasture yield are difficult if not impossible to make. The many ways of harvesting hay (dry hay, haylage, grass silage, etc.) make it impossible to record an accurate actual yield. Likewise, there is no practical way to measure pasture yields. Thus, a simple model that uses readily available daily climatic data to estimate soil moisture and predict forage growth and development on a daily basis was chosen. SIMFOY, name given to the *sim*ulator of *fo*rage *y*ield, is more empirical than models such as SIMED (Holt et al., 1975) which are process-based and require many meteorological variables at frequent intervals. However, SIMFOY is more functional and practical for predicting seasonal yields.

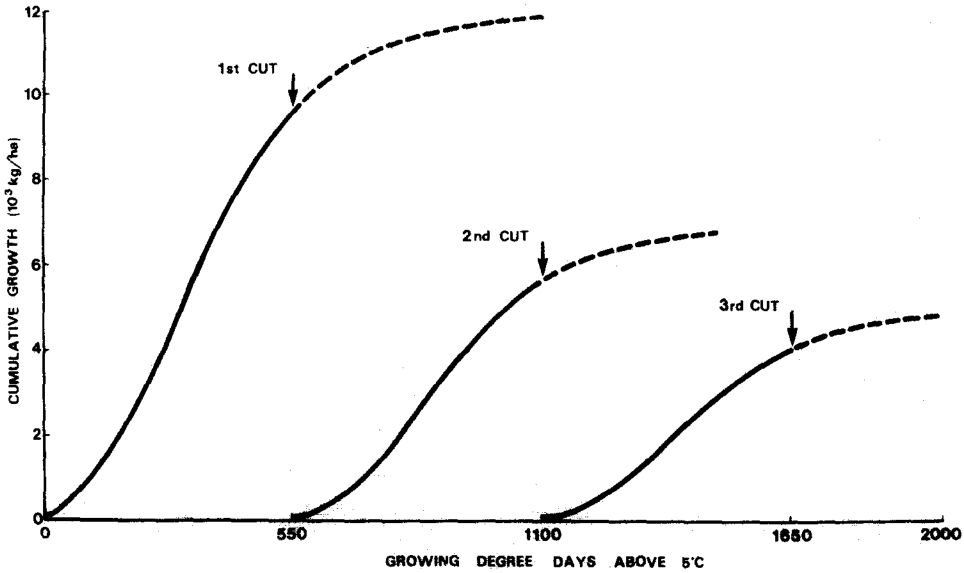

Fig.1. Idealized growth curves used in program SIMFOY.

MODEL DESCRIPTION

Dry matter production

An idealized growth curve was assumed for optimum soil moisture conditions and crop development time (Fig.1). The sigmoidal curve is based on the observed relationship between growth and time typical of many plants including forage crops. The curve is defined by the following equation:

$$Y_p = Y_m/(1 + \exp(a + bD^c)) \qquad (1)$$

where Y_p is cumulative potential growth at crop development time D, Y_m is maximum cumulative growth (12,000, 7,000 and 5,000 kg/ha used herein for the 1st, 2nd, and 3rd growth cycles, respectively). The values of the constants a, b and c are respectively 5.3, − 6.7 and 0.5 when crop development time is normalized so as to make D equal 1.0 at harvest time. The crop development time was assumed to be a function of temperature and was linearly related to growing degree days above 5°C. On this scale of cumulative degree days, alfalfa flowers appear at approximately 550 (harvest time, Fig.1).

The potential daily growth increment, G_p, is calculated by taking the difference in the cumulative potential growth, Y_p, between day i and day $i-1$, hence:

$$G_p(i) = Y_p(i) - Y_p(i-1) \tag{2}$$

Any departure from this potential daily growth is assumed to depend directly on soil moisture. Temperature influences growth indirectly as it is used to estimate crop development time. Solar or net radiation and precipitation are used to estimate evaporation and soil moisture, but for SIMFOY it was assumed that these environmental factors do not affect growth directly.

Daily simulated growth, G, is related to daily available soil moisture, S, and available soil moisture capacity, A, as follows:

$$\left.\begin{array}{ll} G = (G_p/d)(S/A) & \text{if } S/A < d \\ G = G_p & \text{if } S/A \geq d \end{array}\right| \tag{3}$$

where d is some fraction less than one (0.8 used herein). S/A is weighted according to the assumed root distribution of the crop in each of the several soil zones as a fraction of the total roots (Table I).

Eq. 3 is similar to that used by Hanks (1974) except that he related dry matter yield to transpiration and potential transpiration instead of S/A. The similarity is apparent when transpiration is estimated as a function of available moisture (S/A), and when water loss through evaporation is negligible compared to water loss through transpiration. The latter situation is true for crops that nearly cover the ground surface like most forage crops. The validity of eq. 3 and similar equations found in the literature (De Wit, 1958; Hanks, 1974) is not firmly established but these equations seem to give reasonable results (Arkley, 1963; De Wit, 1958; Hanks, 1974; Hanks et al., 1969).

The assumed root distribution in each of the several soil zones (Table I) was based on the distribution with depth of the observed changes in soil moisture between rain-free periods in 1966, 1967 and 1968 from several sites and various soil types (Selirio et al., 1978). This method of estimating rooting depth and distribution was found to be reasonably accurate for forage species (Bennett and Doss, 1960). Only one set of values were used since no significant differences were found among soil types.

The harvestable dry matter at the end of each growth cycle was obtained by summing the daily growth, G, over the crop's growth period, i.e. from start of growth (or since previous cut) to harvest time (550 degree days above 5°C to first flower used herein). Growth in spring was assumed to commence following a period after March 15 when daily mean temperature exceeded 5°C for 5 days. Date of actual start-of-growth can be assigned to override this estimated date. Aftermath growth commenced following each cut.

TABLE I

Assumed fraction of effective roots in each soil zone for specified time intervals of the growing season, defined in terms of degree-days $>5^{\circ}C$, used to calculate daily growth, G, from S/A (eq. 3)

Soil moisture zone	Soil depth (cm)	Cumulative degree-days $> 5^{\circ}C$ to:							
		$0 < 55$	$55 < 110$	$110 < 165$	$165 < 220$	$220 < 275$	≥ 275	$0 < 110$	≥ 110
		First cut harvest						*2nd and 3rd cut harvests*	
1	0–7.5	0.40	0.35	0.30	0.25	0.25	0.20	0.35	0.20
2	7.5–15	0.30	0.30	0.25	0.25	0.20	0.20	0.30	0.20
3	15–30	0.20	0.20	0.25	0.25	0.20	0.20	0.20	0.20
4	30–45	0.10	0.10	0.10	0.15	0.15	0.20	0.10	0.20
5	45–60	0	0.05	0.05	0.05	0.10	0.10	0.05	0.10
6	60–75	0	0	0.05	0.05	0.10	0.10	0	0.10

Soil moisture budgeting technique

Daily soil moisture was estimated using a technique similar to that of Selirio and Brown (1971). The basic ideas of the versatile budget (Baier and Robertson, 1966) are employed in this technique except that the water extraction pattern is allowed to vary with soil moisture distribution as well as root distribution. The soil was divided into six zones, each at depth interval of 15 cm except for the upper two zones which were 7.5 cm each, and each zone has known soil moisture values at field capacity and at permanent wilting point. The total depth of soil profile for purpose of SIMFOY is 75 cm.

Potential evapotranspiration, *Ep*, was estimated from net radiation (or an estimate of it from hours of bright sunshine; Selirio et al., 1971), using the relationship of Priestley and Taylor (1972) and where the slope of the saturation vapour pressure—temperature curve is evaluated from daytime mean temperature*[1]. *Ep* was then divided into 20 increments and assigned to each of several zones in the rooting depth profile (Table II) to estimate actual evapotranspiration, *Ea*. The increment technique allows moisture extraction from one zone at a time using one increment of *Ep* per zone and the relative evapotranspiration ratio (*Ea/Ep*, Fig.2) for that zone. Also the *Ea/Ep* ratio is adjusted continuously as water is removed from a zone.

Daily soil moisture extraction proceeds from zone 1 through zone 6 and repeats the procedure until the 20 increments were used up, according to the normal extraction pattern (Table II). However, if moisture is replenished in the upper zones by precipitation and such that the percent of available moisture in zone j is greater than in the adjacent zone $(j + 1)$, the extraction proceeds from the upper zones to zone j only. The extraction may proceed through zone $(j + 1)$ when the percent available moisture is less in zone j than in zone $(j + 1)$, or when the number of increments allowed in the upper zones to zone j is reached. The total number of increments that can be credited to any one zone in one day cannot exceed the maximum limit shown in Table II. The iterative procedure is repeated until 20 increments are used up.

It is assumed that evapotranspiration on day i took place first and precipitation occurred later in day i as precipitation day ends at 08h00 on day $(i + 1)$. Daily precipitation is assumed effective and used to recharge the soil to field capacity in the top zone first, then the next zone using the remaining water, and so forth until the precipitation amount was used up or all zones were brought to field capacity. Any unaccounted precipitation was assumed lost as percolation and/or runoff and did not enter into the budgeting process.

The soil moisture budgeting technique started each year following a period after March 1 when there had been accumulated a total of 10 days at which the maximum temperature was greater than 5°C. All soil zones are assumed

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*[1] Daytime mean temperature = 3/4 (maximum temperature) + 1/4 (minimum temperature).

TABLE II

Normal and maximum number of increments of potential evapotranspiration ($Ep/20$) for each soil zone for specified time intervals of the growing season, defined in terms of degree-days $> 5^\circ C$, used to estimate daily soil moisture

Soil moisture zone	Soil depth (cm)	Cumulative degree-days $> 5^\circ C$ to: $0 < 55$		$55 < 110$		$110 < 165$		$165 < 220$		$220 < 275$		≥ 275		$0 < 110$		≥ 110	
		nor.	max.	nor.	max.	nor.	max.	nor.	max.	nor.	max.	nor.	max.	nor.	max.	nor.	max.
		First cut harvest												*2nd and 3rd cut harvests*			
1	0–7.5	8	11	7	10	6	9	5	8	5	7	4	6	7	10	4	6
2	7.5–15	6	7	6	7	5	7	5	7	4	7	4	6	6	7	4	6
3	15–30	4	4	4	4	5	5	5	5	4	4	4	4	4	4	4	4
4	30–45	2	2	2	2	2	2	3	3	3	4	4	4	2	2	4	4
5	45–60	0	0	1	1	1	1	1	2	2	2	2	3	1	1	2	3
6	60–75	0	0	0	0	1	1	1	1	2	2	2	2	0	0	2	2

to be at field capacity when moisture budgeting commenced, a fair assumption under Southern Ontario conditions.

Soil moisture and actual evapotranspiration

Relationships between the *Ea/Ep* ratio and available soil moisture are often used to estimate *Ea* for a given *Ep*. These relationships are summarized by Baier and Robertson (1966). The *Ea/Ep* ratio is also dependent upon the evaporative demand. Denmead and Shaw (1962) demonstrated that under low evaporative demand the *Ea/Ep* ratio proceeds at unity over a larger range of available soil moisture whereas under relatively high evaporative demand it begins to decrease at a relatively high soil moisture because plants cannot supply water fast enough to meet the evaporative demand. The relationship used in the present work assumed the following: (1) the *Ea/Ep* ratio decreases linearly with available soil moisture to wilting percentage; (2) the *Ea/Ep* ratio decreases below unity starting at a percent available moisture equivalent to the relative degree of evaporative demand to a maximum *Ep* of 7.0 mm; and (3) the *Ea/Ep* ratio cannot exceed unity nor drop below 0.05. An example is shown in Fig.2 for three daily *Ep* values of 7.0, 3.5, and 1.0 mm of water.

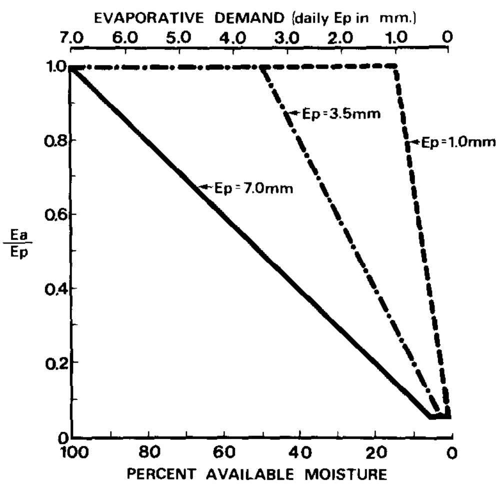

Fig.2. Ratio of actual evapotranspiration (*Ea*) and potential evapotranspiration (*Ep*) at different levels of soil moisture and three evaporative demand conditions.

Computational procedures

The computational procedures for SIMFOY were programmed in FORTRAN IV language. The computation proceeds as follows. (1) Program SIMFOY initializes the soil zone depth intervals, soil moisture values at field capacity and wilting point, assumed root distribution assigned to each of the zones (Table I), and maximum and usual number of increments of Ep assigned to each of the six zones (Table II). Also, it initializes the growth, development, and other variables. (2) SIMFOY reads the daily climatic data. (3) It then calculates daily growing degree days above 5°C and crop development time (D, eq. 1). (4) It computes daily Ep and defines the curve relating Ea/Ep ratio to available moisture (e.g. Fig.2). (5) Program SIMFOY simulates changes in daily soil moisture in each of the soil zones, and estimates the available moisture (S/A, eq. 3). (6) It computes cumulative potential growth (Y_p, eq. 1), maximum daily growth increment (G_p, eq. 2), relative growth rate, daily growth (G, eq. 3), and accumulated growth. (7) At the end of each day, SIMFOY adds precipitation, if any, to the soil. (8) Program SIMFOY checks if it is time to cut. If it is not, SIMFOY reads the next day's climatic data. If it is time to cut, SIMFOY stores the estimated yield for that growth cycle and initializes the necessary variables. (9) SIMFOY exits the step-by-step procedures at the end of the season and prints the dry matter production for each growth cycle, and phenological dates such as start-of-growth date and harvest dates. (10) The step-by-step computations through program SIMFOY are then repeated for another year and/or location using a different set of daily climatic data and soils.

MODEL VALIDATION

SIMFOY was developed for a specific purpose using information already available. No experiments were conducted to test the hypotheses used in the model. Some 'growth curve', soil moisture, and climatological data were available for a preliminary validation of the model.

Data used

Crop data. Alfalfa yields, from a 'growth curve' experiment (Fulkerson et al., 1967), collected at weekly intervals in 1961, 1962 and 1963 at Guelph, Ontario were compared with simulated values. Alfalfa yields*[1] for a six year period (1961—66) at Guelph and for 3 years (1966—68) at Ridgetown, Ontario were also compared with simulated dry matter production from each of the three growth cycles.

Soil moisture data. Records of soil moisture from various sites in Southwestern Ontario were used to compare with simulated values (Selirio et al., 1978). Soil moisture values were obtained by gravimetric measurements in the surface layer (0—15 cm) and by the neutron scattering technique by

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*[1] Forage crop investigations, Ontario, 1966, 1967, and 1968. Reports on field trials of varieties and mixtures. Dept. of Crop Science, University of Guelph.

placing a probe*[1] to depths of 23, 38, 53, 76, 107 and 137 cm. Soil moisture observations were recorded at approximately two-week intervals from the middle of April to the middle of October. Soil constants for each observation site, including bulk density, moisture percentage at 1/3-bar and 15-bar tensions and textural class, were obtained by sampling the soil profile. Soil moisture values observed in early spring were used as the field capacity value, because the 1/3-bar moisture value was found to be too low. The 15-bar moisture value was used as the permanent wilting point value.

Climatological data. The basic climatological inputs for SIMFOY were daily maximum and minimum temperatures, precipitation, and hours of bright sunshine. Either net radiation or global solar radiation was used in lieu of hours of sunshine whenever available. Copies of these records were obtained from the Atmospheric Environment Service of the Department of Environment, Canada. Daily solar radiation at the top of the atmosphere and daylength were obtained from the Smithsonian Meteorological Tables (List, 1966).

Forage yield estimates

Comparisons of simulated growth with actual alfalfa yields from a 'growth curve' experiment (Fulkerson et al., 1967) are shown in Fig.3 for two alfalfa varieties and for two years that had markedly different spring seasons. Predicted yield was close to actual at the hay cut stage (cut time), although the simulated curve underestimated growth during the first month in 1961 and after the hay cut stage in 1962. The vertical bars in Fig.3 depict the standard deviation from a mean of six replications.

Simulated and observed alfalfa dry matter yields for a 3-cut system of harvest management for a number of years at two sites in Ontario are summarized in Table III. Fig.4 depicts the relative accuracy of the simulated yields (Sim1) compared to observed (Obs.) for the same data in Table III, except 1965 and 1966 at Guelph are omitted. The vertical bars in Fig.4 represent a standard deviation from a mean of two (1961—63, Guelph), five (1966—67, Ridgetown) and twelve (1968, Ridgetown) varieties and six replications*[2]. Standard deviations were not available for 1964 nor were the yields for the second cut harvest. These comparisons indicate that SIMFOY overpredicts first-cut yields by 12% and underpredicts second-cut yields when soil moisture is in short supply, e.g. *6* in Fig.4 (also see Fig.5a, Ridgetown, 1966 for the soil moisture regime from late June through July). Simulated yields using the actual date of cutting (Sim2, Table III) are closer to observed yields (Obs.) than the simulated yields using simulated date of cutting (Sim1, Table III) because SIMFOY predicts the date of cut-

*[1] Nuclear — Chicago Corp., Chicago, Ill.

*[2] Personal communications, 1977, from R. S. Fulkerson, University of Guelph and A. D. McLaren, Ridgetown College of Agricultural Technology.

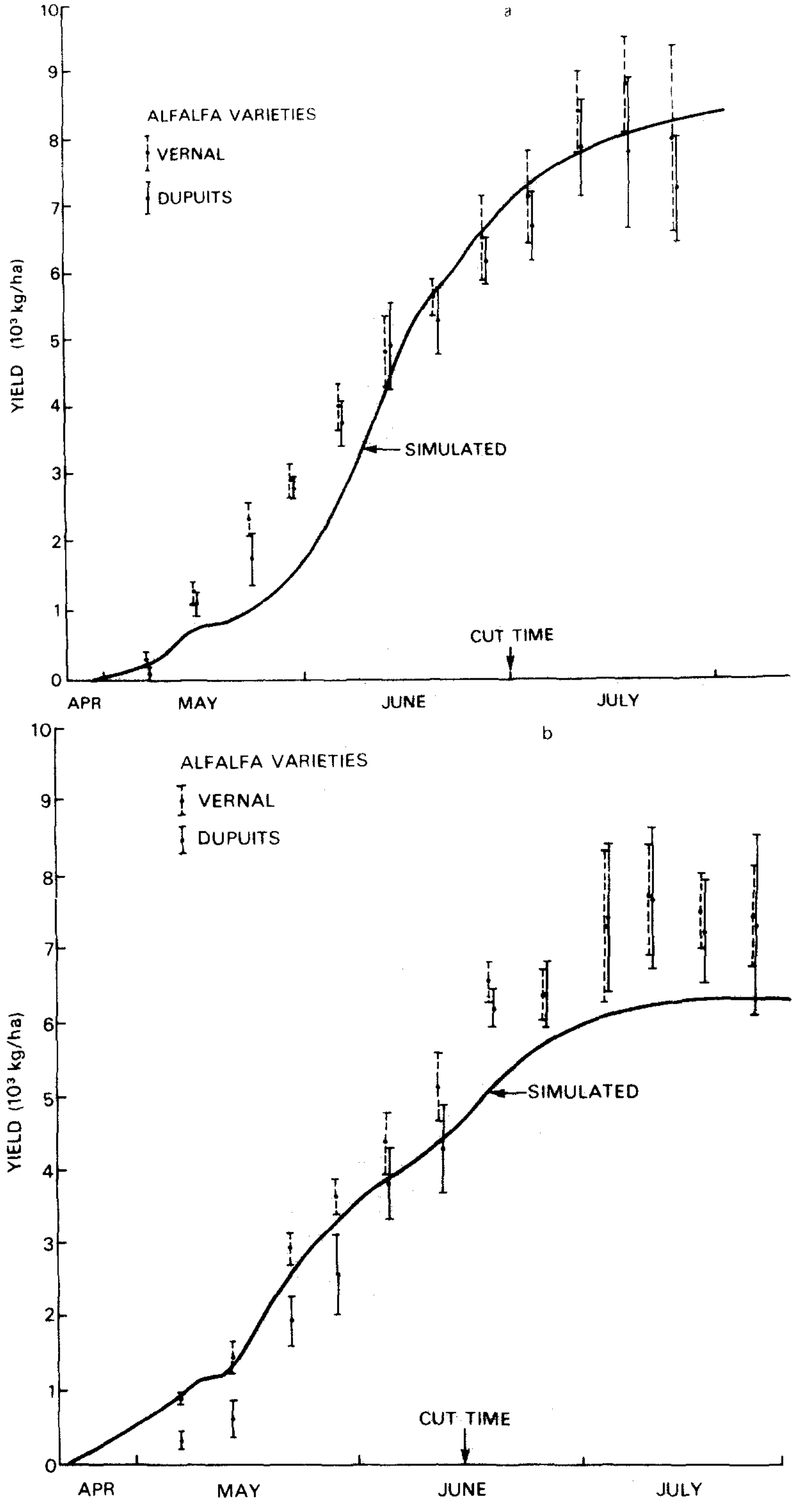


Fig.3. Comparison of simulated and observed growth of alfalfa for: (a) 1961; and (b) 1962 at Guelph, Ontario. The vertical bars depict the standard deviation from mean

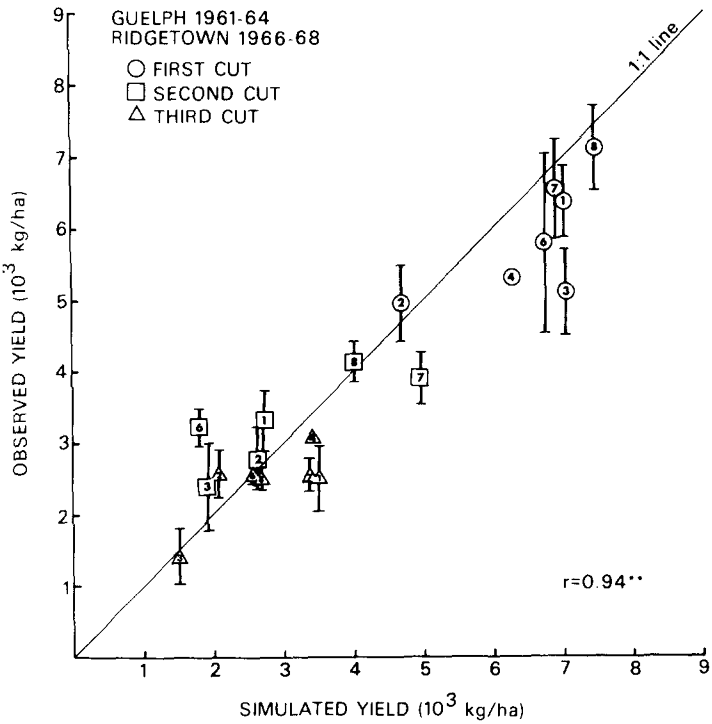


Fig.4. Comparison of observed and simulated yields of alfalfa hay at two sites in Ontario. Numbers inside symbol refer to year and vertical bars depict the standard deviation from mean yields.

ting later than actual in the majority of cases (Table IV), possibly because the actual cutting time was earlier than the time of first flower. Estimated total seasonal yields were within 15% of the observed (Obs.) in 7 out of the 8 years for Sim2 and in only 4 out of the 8 for Sim1, 1965 and 1966 at Guelph included (Table III).

Sensitivity tests, where available soil moisture capacity (A) was adjusted, showed that SIMFOY yield estimates were sensitive to changes in the A parameter especially during years with extended drought periods, e.g. late June through July, 1966 at Ridgetown (see Fig.5a).

Soil moisture estimates

Results indicate that the simulated soil moisture values compare reasonably with measured values for the six soil types used in the validation (Table V). The average differences between observed and simulated values were within 9% of each other, although there were individual cases that had larger differences and some of these may have been errors in measurement. The observed readings at 23, 38, 53, and 76 cm were compared to

TABLE III

Comparison of simulated (Sim1 and Sim2)*[1] and observed (Obs.) alfalfa dry matter yields (kg/ha) for a 3-cut system of harvest management at two sites in Ontario

Site and year	First cut harvest			Second cut harvest			Third cut harvest		
	Sim1 (kg/ha)	Sim2	Obs.	Sim1 (kg/ha)	Sim2	Obs.	Sim1 (kg/ha)	Sim2	Obs.
Guelph:									
1961	7003	6512	6372	2723	2728	3319	3495	3748	2500
1962	4690	4396	4958	2640	2568	2796	2074	2252	2573
1963	7031	6874	5114	1921	1715	2396	1517	1668	1420
1964	6275	5749	5333	3978	2133	Missing	3423	2952	3087
1965	4917	3800	3380*[2]	2477	2059	2233*[2]	1249	1320	1252*[2]
1966	5741	3784	3427*[2]	1084	1632	1593*[2]	1466	1376	1075*[2]
Ridgetown:									
1966	6733	6374	5794	1805	2301	3226	2561	2100	2563
1967	6877	7391	6548	4962	5226	3910	3378	3010	2551
1968	7428	7869	7119	4014	4117	4143	2700	2737	2509

*[1] Sim1 = simulated dry matter yield at simulated date of cutting; Sim2 = simulated dry matter yield at actual cutting date.
*[2] Harvested at bud stage.

simulated values for the 3rd, 4th, 5th, and 6th zones, respectively. Measurements at 0—15 cm depth were used to compare with the simulated values at both the 1st and 2nd zones. The 1st, 2nd and 6th observed depths do not correspond precisely with depth intervals used in the simulation, and should be kept in mind when comparing the results. Fig.5 shows comparisons of daily values at Ridgetown for a relatively dry year (1966) and wet year (1967). The vertical bars in Fig.5 depict the standard deviation from a mean of three measurements. Large deviations in the 5th zone in Fig.5a were due to consistent low readings in one of the three tubes.

One of the shortcomings of the soil moisture budgeting technique is that it does not account for the moisture retained by the soil in excess of field capacity (see Fig.5). This is a problem early in spring especially with a large amount of rainfall. Also, it appears from the results that the field capacity and wilting point values need to be known accurately for each soil type and zone depth since the simulated values are sensitive to these parameters. Despite these shortcomings, the soil moisture budgeting technique estimates daily values of soil moisture fairly well.

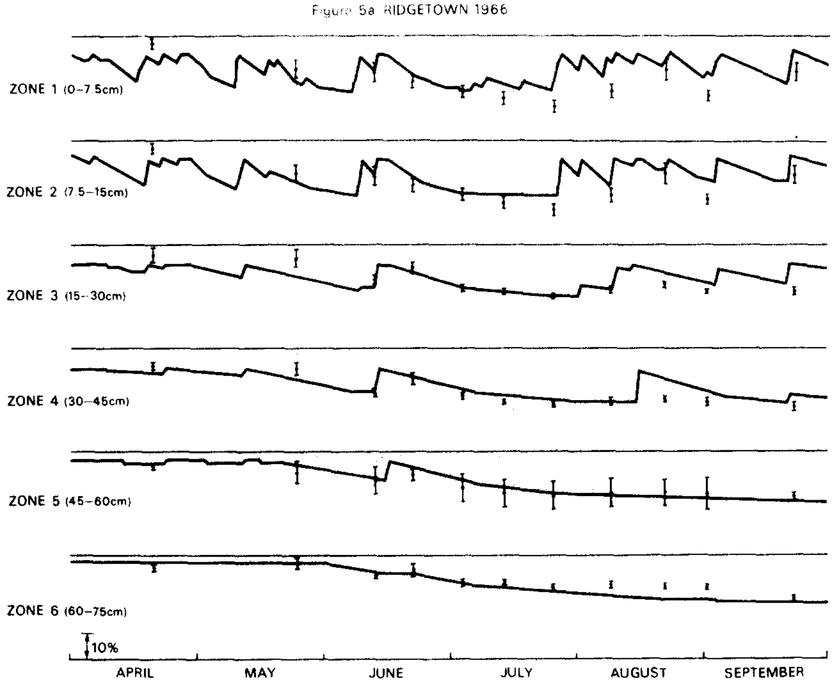
CONCLUSIONS

A simulation model for predicting forage yield as related to soil moisture on a daily basis has been developed. Results indicate that the model simulated seasonal dry matter production of alfalfa with reasonable accuracy.

TABLE IV

Simulated and actual dates of cutting for a 3-cut system of harvest management at two sites in Ontario

Site and year	First cut harvest		Second cut harvest		Third cut harvest	
	simul.	actual	simul.	actual	simul.	actual
Guelph:						
1961	June 30	June 26	Aug. 7	July 31	Sept. 13	Sept. 11
1962	June 14	June 11	July 26	July 16	Sept. 7	Sept. 12
1963	June 27	June 24	Aug. 3	July 30	Sept. 15	Sept. 9
1964	June 23	June 16	July 28	July 10	Sept. 15	Aug. 25
1965	June 26	June 7	Aug. 7	July 16	Sept. 15	Aug. 20
1966	June 29	June 15	Aug. 4	July 21	Sept. 15	Aug. 26
Ridgetown:						
1966	June 23	June 21	July 26	Aug. 5	Sept. 1	Sept. 2
1967	June 18	June 23	July 25	July 31	Sept. 3	Sept. 6
1968	June 13	June 20	July 21	July 29	Aug. 24	Sept. 4



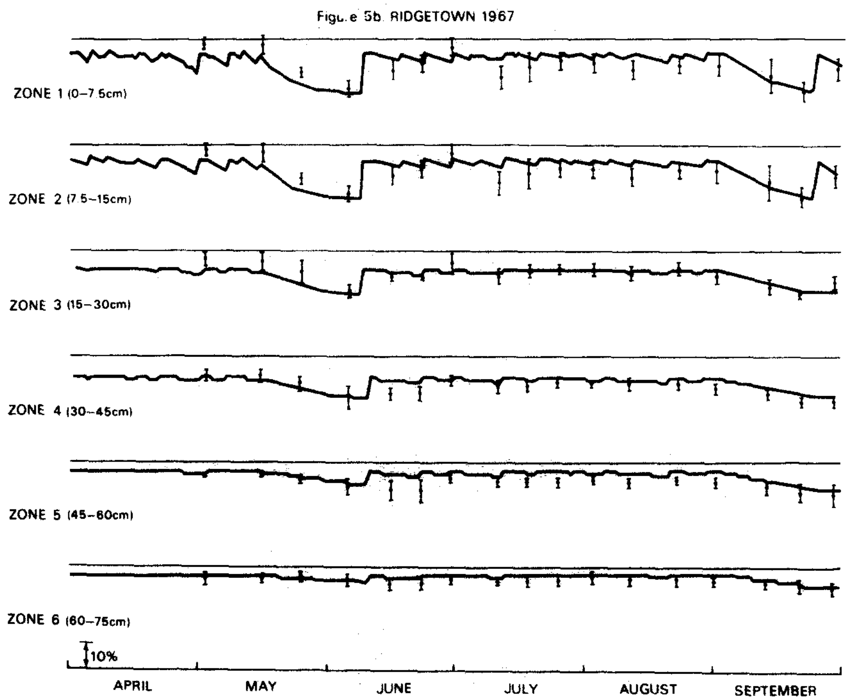


Fig.5. Comparison of daily simulated and observed soil moisture for (a) 1966, a relatively dry year, and (b) 1967, a relatively wet year at Ridgetown, Ontario. The vertical bars depict the standard deviation from mean observed moisture values.

TABLE V

Correlation coefficients between daily simulated and observed soil moisture per zone depth at six sites in Ontario.

Site and soil type	No. obs.	Soil zone depth (cm): 0—7.5	7.5—15	15—30	30—45	45—60	60—75
Brownsville, Perth silt loam	17	0.80**	0.77**	0.71**	0.90**	0.96**	0.97**
Cainsville, Brantford loam	46	0.67**	0.60**	0.51**	0.62**	0.71**	0.81**
Courtland, Fox loamy sand	16	0.88**	0.90**	0.88**	0.91**	0.87**	0.61*
Edy's Mills, Brookston silty clay	46	0.63**	0.64**	0.67**	0.82**	0.91**	0.92**
Kohler, Haldimand clay	15	0.50*	0.58*	0.65**	0.69**	0.78**	0.96**
Ridgetown, Brookston loam	49	0.59**	0.56**	0.60**	0.77**	0.86**	0.95**

* Significant at 5% level
** Significant at 1% level

Estimates of soil moisture also compared well with measured values for the six soil types used in the validation. It was decided, based on these results, that SIMFOY could be used for the 'dry weather-forage crop' insurance plan in Ontario, Canada.

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