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Modelling methodology for estimating forage yield potential in Canada

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Méthode de modélisation relative à l'estimation des potentiels de rendement des plantes fourragères au Canada

Cover illustration
The dots on the map represent Agriculture Canada research establishments.

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FOREWORD

This modelling effort came about as a result of the need for forage yield information for broad scale land evaluation studies in Canada. Forages constitute a major portion of the total agricultural production system in almost all regions of the country and no evaluation of land capability and crop suitability would be complete without its consideration. Previous work has been done to estimate crop production potentials of five annual crops grown in Canada using a crop growth model. However, a suitable model for forages was not available until now.

The modelling work was undertaken as part of a land evaluation study led by Dr. J. Dumanski in the Land Resource Research Centre. Throughout the course of this work progress was reviewed by the project team and on-going plans were formulated as required. The objective was to develop a model which would estimate forage yields for all areas of Canada using the climatic normals data available in the Land Potential Data Base, and for Agroecological Resource Areas in the prairie region using climatic normals data prepared under the Prairie Land Evaluation Project.

SUMMARY

This bulletin describes the modelling methodology that was developed to estimate average potential (constraint-free) and anticipated (rainfed) forage yields in Canada. A revised general crop growth model previously used to estimate production potentials of annual crops in Canada was selected as a basis for the forage model (FORYLD). Subroutines were developed and validated with field data to simulate normal growth periods and cutting schedules for alfalfa and for grasses (timothy, bromegrass, wheatgrass). Each growth period was then treated as a full season for annual crops in the FAO model. Several significant modifications in addition to cutting schedules were incorporated into FORYLD. These included the following: i) the manner in which leaf area index was estimated; ii) the relationship between maximum leaf photosynthesis and temperature; and iii) the proceduree used to determine the moisture stress factor for computing anticipated yields from potential yields. Comparisons of model yield estimates with yields observed in field trials at various locations across Canada were made for calibration and validation. Results indicate that the model estimates potential and anticipated yields with an accuracy of about ± 1 t/ha.

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1. INTRODUCTION

The concept of using computer models of crop growth and yield to estimate potential crop production from information on climatic and soil resources is not new. In 1978, the Food and Agricultural Organization of the United Nations (FAO) published procedures for assessing the production potential of eleven crops in developing countries (FAO, 1978). The FAO procedures involved estimating constraint-free yield potentials from the temperature and radiation regimes and then evaluating anticipated yield potential under rainfed conditions by taking moisture stress and other yield-reducing factors into consideration. The procedures used to quantify the effects of water stress on yield were documented by Doorenbos and Kassam (1979). The FAO procedures were subsequently adapted for estimating the production potential of five annual crops in Canada (Dumanski and Stewart, 1983; Stewart, 1983). Estimates of crop yields and production potential were made for 755 soil areas outlined on the Soils Map of Canada (Clayton et al., 1977) using representative climatic and soil information for each map unit. Information on soils, climate and potential crop yields, either used as input for or generated by these studies, have since become part of a computerized information base called the Land Potential Data Base (Kirkwood et al., 1989).

Up to now, studies on the production potential of Canada's land resources have focused primarily on annual crops. There is a need, however, to develop procedures for evaluating production potentials of perennial forage crops since forages are a very significant part of the agricultural production systems in Canada. Such evaluations are needed for a variety of on-going activities, such as land use planning, crop management decisions, agricultural policy development, crop insurance programs, agricultural research planning and evaluation, and so forth.

The purpose of this bulletin is to describe the modelling procedures developed for estimating forage yield potentials in Canada from climatic and soils information. The basic framework of the modelling procedures has been previously documented (Stewart, 1983) and thus will only be briefly summarized. Emphasis is placed on describing the modifications made to existing methodologies for forages.

Numerous species and varieties of forages are grown in Canada. To keep the modelling effort within available resources, the work concentrated on simulating yields of several of the most common legume and grass species grown, namely alfalfa, timothy (for moist regions) and crested and intermediate wheatgrass (for the drier prairie regions). These species generally also had the most data available from field trials at a sufficient number of locations for model calibration and validation. Emphasis was placed on estimating long term yield potential only using climatic normals data and not on predicting yields on an annual basis.

Forage yields are frequently affected by factors such as persistence of the crop and overwintering damage, particularly for alfalfa. However, lack of available data and resources prevented incorporation of these factors into the model at this stage. Consequently, efforts were concentrated towards estimating average forage yield potentials in the first few years after establishment, assuming no yield reductions due to winterkill. Considerable additional research and experimental data will be necessary if these factors are to be incorporated into the model.

2. MODEL DEVELOPMENT

2.1. Selection of Model

In developing a forage model for estimating average yield potentials in Canada, we choose to modify the existing FAO model adapted for Canadian conditions by Stewart (1983) (hereafter referred to simply as the FAO model). Reasons for this choice include the following: 1) computer software for the existing model was readily available; 2) climatic and soils information required as input to the model were also readily available from the Land Potential Data Base (Kirkwood et al., 1989); 3) other workers have had some success in adapting the FAO model for estimating annual yields of forages (McBride and Brown, 1984); 4) the model is capable of estimating both potential constraint-free yield with no moisture stress and anticipated yields under rainfed conditions.

The FAO model estimates the constraint-free net biomass production (B_N) using the equation:

$$B_N = 0.36\ b_{gm} / (1/N + 0.25\ C_t) \qquad (1)$$

where b_{gm} is the maximum rate of biomass production ($Kg.ha^{-1}.day^{-1}$) under full cover (leaf area index $\geq$ 5).

N is the growing season length (days).
C_t is a maintenance respiration function which is dependent on mean air temperature.

b_{gm} is determined by a method of DeWit (1965), using estimates of the maximum rate of biomass production on clear and overcast days. The seasonal mean fraction of daytime when the sky is overcast is estimated from incoming global solar radiation. b_{gm} is also dependent on the maximum rate of leaf photosynthesis which is a function of crop species and temperature. Equation (1) assumes that the cumulative potential growth follows an idealized sigmoidal growth curve under unconstrained conditions. An adjustment is made to the constraint-free net biomass production if maximum leaf area index (LAI) of the crop is < 5.0.

The potential net dry mattter yield (B_y) is determined by taking the harvest index (H_i) into account, i.e.

$$B_y = B_N \times H_i \qquad (2)$$

where H_i is the fraction of the net biomass production that is economically useful. B_y is therefore the potential yield that can be harvested under conditions where water, nutrients, weeds, pests and diseases do not limit crop growth.

Anticipated yield (B_{ya}) is the harvestable yield after reductions due to workability (harvest losses) and moisture stress are taken into consideration. This is determined in the FAO model as follows:

$$B_{ya} = B_y \times MSF \times WF \qquad (3)$$

where MSF is the moisture stress factor and WF is the workability factor.

In the FAO model, the moisture stress factor is computed from the ratio of actual (AE) to potential (PE) evapotranspiration, using an empirically-derived yield response factor (K_y) taken from Doorenbos and Kassam (1979), i.e.

$$MSF = 1 - K_y (1 - AE/PE) \qquad (4)$$

AE and PE are seasonal averages determined using a soil moisture budgeting procedure. The workability parameter was estimated from fall workday probabilities. Subsequent discussion will focus on the modification made to the FAO model for forages. For convenience, the modified forage model will be referred to as FORYLD.

2.2. Simulating Growth Periods and Cutting Schedules

The FAO model for Canada was designed to estimate average potential yields for annual crops for an average growing season whose length was determined by temperature. In the case of forages, several growth periods and harvests are usually possible during a growing season. Therefore, subroutines were developed to simulate average growth periods and harvest dates from climatic normals data for legumes (alfalfa) and for grasses (timothy, wheatgrass). Each growth period was then treated as a complete growing season in FORYLD.

2.2.1. Criteria for estimating date of first cut

Average dates of first cut for both legumes and grasses were estimated using accumulated photothermal units (PTU's). PTU's were defined as accumulated growing-degree days above a 5°C base (GDD) modified by a daylength factor. Previous studies have shown that accumulated GDD can be used to estimate maturity dates in specific geographic regions (Bootsma, 1984; Harcourt, 1984). However, on a Canada-wide basis, significant differences in daylength can occur which may affect the rate of development to maturity of some forage species. A review of the literature indicated that the effects of daylength on the rate of development can vary considerably among different forage species and varieties. However, for many of the most common grass and legume species (e.g. timothy, bromegrass, alfalfa, clover) longer daylengths induce earlier heading or flowering, while short daylengths delay flowering and may even inhibit it completely (Evans and Allard, 1934; Allard and Evans, 1941; Evans and Wilsie, 1946; Ludwig et al., 1953; DeRuiter and Taylor, 1979). Based on this evidence, an empirical approach was adopted for including daylength effects in FORYLD, using the concept of a relative development rate (RDR). The relationship assumed between RDR and daylength or photoperiod (P) is shown in Fig. 1 and can be mathematically approximated by

$$RDR = -0.37+0.1626(P) - 0.005942(P^2) + 0.000062217(P^3) \quad (5)$$

Daily PTU's were computed from GDD multiplied by RDR as follows:

$$\text{Daily PTU} = (T_{MN} - 5.0) \times RDR \quad (6)$$

where T_{MN} is the 30-year normal daily mean temperature (1951-80 period).

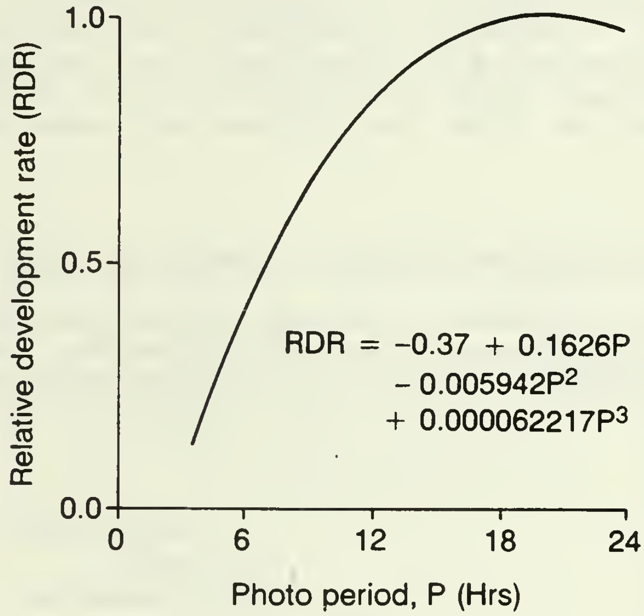

Figure 1. Relative development rate (RDR) as a function of photoperiod or daylength (P).

The PTU's required for first cut were evaluated by accumulating average daily PTU's (using 1951-80 temperature normals) from the time $T_{MN} \geq 5°C$ in spring to the average date of first cut of alfalfa at 26 locations across Canada. Average cutting dates were determined from reports on forage variety trials conducted by various co-operators in western Canada, Ontario and the Atlantic provinces (e.g. Ontario Forage Crops Committee, 1968; Atlantic Committee on Crops, 1982; Expert Committee on Forage Crops, 1983). Observed average cutting dates were based on the data from these regional reports; available data ranged from as little as two years to more than ten years. Using this procedure, it was determined that alfalfa requires approximately 480 PTU's to reach maturity for first cut. It was assumed that regional trials were harvested around the time when early to medium maturing varieties of alfalfa reach early bloom stage. Some cultivars could require more or less than 480 PTU's for first cut, but these variations were not taken into consideration in FORYLD. Since alfalfa is often grown with timothy or bromegrass, it was assumed that the same PTU accumulation applied to grass species.

A variety of RDR functions, similar to that of Fig. 1, which assumed either a greater or lesser effect of photoperiod on RDR, were also tried (including a constant RDR of 1.0, in which case PTU's equal GDD's). The results indicated, reasonable estimates could be made with various functions including GDD's and that, therefore, selection was not critical. However, the function shown in Fig. 1 was chosen since it resulted in the lowest standard deviation (3-4 days) of the difference between average estimated and observed cutting dates at the 26 locations.

Latitudes of locations used in these cutting date tests ranged from as far south as Ridgetown, Ontario (42°N) to as far north as Fort Vermilion, Alberta (58°N). This provided considerable range in daylengths (15 versus 18 hours, respectively, on June 25). The influence of time of year on daylength is also taken into consideration using the PTU concept. Locations with late springs due to cool temperatures will generally experience longer daylengths during the first growth period than other locations at the same latitude which warm up earlier in the spring.

2.2.2. Criteria for estimating dates of additional cuts

Criteria for scheduling additional cuts were developed from available data on cutting dates from regional variety trials of alfalfa, timothy and bromegrass. For alfalfa, cutting dates depend primarily on

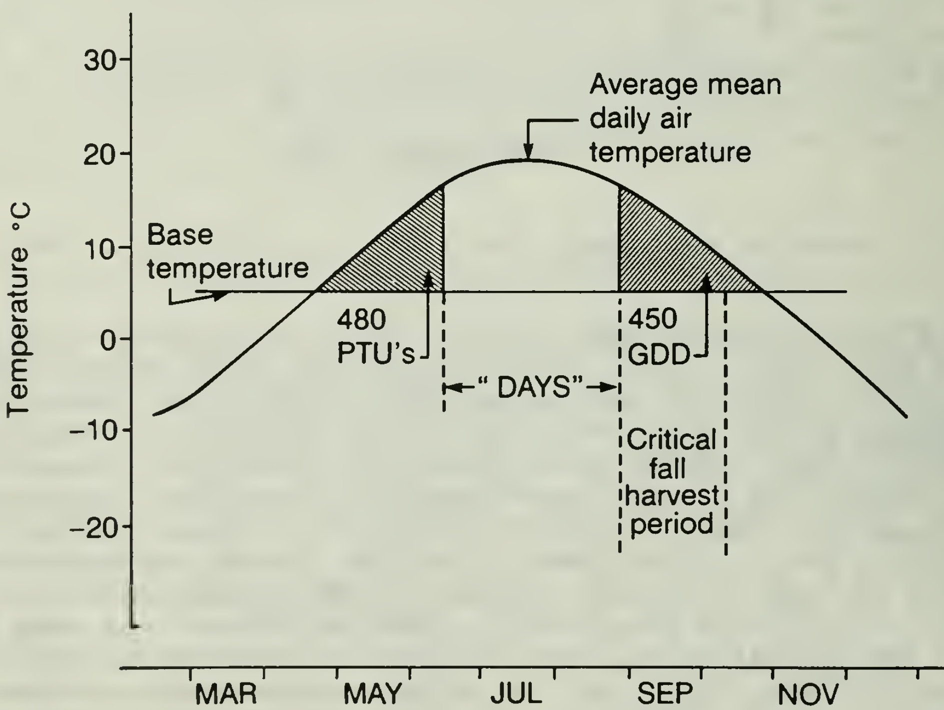

Figure 2. Relationship between the average mean daily air temperature and the variable DAYS used in selection of cutting date criteria for alfalfa.

Table 1. Criteria for estimating average cutting dates for Alfalfa - Option 1.

DAYS †	Number of cuts	Cutting date criteria: 1st cut	2nd cut	3rd cut	4th cut
<0	0-1	480 PTU (No cut if date is 42 days before GSE ††).	-	-	-
0-21	1-2	480 PTU	Optional at GSE	-	-
22-43	2	480 PTU	Earliest of: a) 15 days after D_{450} b) 44 days after 1st cut		
44-55	2-3	480 PTU	44 days after 1st cut	Optional at GSE	-
56-59	3	480 PTU	44 days after 1st cut	GSE	
60-79	3	480 PTU	Latest of: a) DAYS/2 after 1st cut b) 32 days after 1st cut	Latest of: a) DAYS/2 after 2nd cut b) 32 days after 2nd cut	
$\geq$80	3-4	480 PTU	$\frac{\text{DAYS}-10}{2}$ after 1st cut	$\frac{\text{DAYS}-10}{2}$ after 2nd cut	Optional at GSE

† Number of days from date when 480 PTU have accumulated in spring to D_{450}.

†† GSE is growing season end, defined by the date when average mean daily air temperature first drops to 5°C or lower in autumn. The model assumes that the maximum number of days for growth is 60 days for a cut taken at the GSE, i.e. no additional dry matter accumulates after 60 days even if harvest is delayed to the GSE.

the number of days (DAYS) between the first cut and the start of the critical fall harvest period (D_{450}) as shown in Fig. 2. Normally alfalfa should not be harvested during the critical 4-6 weeks period before killing frost, so that sufficient food reserves can be accumulated in the roots to decrease the chance of winter injury (Woolley and Wilsie, 1961; Fulkerson, 1970). The start of the critical fall period was estimated from the time when an average of 450 GDD still remained in the fall (Bootsma and Suzuki, 1985).

The need to avoid harvesting during the critical period is still somewhat controversial. Cutting during this period may be relatively safe if winterkill is not usually a problem or if harvesting frequency is not too intense. Experimental data at Kamloops, B.C. (Stout, 1986) suggest that allowing sufficient time between cuts is more crucial for maintaining a healthy stand than avoiding harvest during the traditional critical period for that region.

Since different cutting strategies can often be employed for alfalfa with similar success, two sets of cutting date criteria (Option 1 and Option 2) were developed (Tables 1 and 2). Option 1 contains the main criteria used in FORYLD. However, for selected values of the variables DAYS, a second cutting option is also applied (Table 2). If the last

Table 2. Criteria for estimating average cutting dates for alfalfa - Option 2 (only if different from Option 1).

DAYS	No. of cuts	Cutting date criteria		
		1st cut	2nd cut	3rd cut
22-29	2	480 PTU	GSE	-
35-43	2-3	480 PTU	D_{450}	Optional at GSE
60-79	3	480 PTU	55 days after 1st cut	GSE
≥80	3	480 PTU	$\frac{DAYS+5}{2}$ days after 1st cut	$\frac{DAYS+5}{2}$ days after 2nd cut

cut is optional, it implies that this cut can be safely harvested only if winter injury is not a significant problem. If winter injury is a concern, improved survival may be achieved by leaving the fall growth to help catch snow for additional protection.

Cutting date criteria for grasses (Table 3) are based on the number of days (GDAYS) between first cut and the time when 400 GDD remain in the fall (D_{400}). Since grasses are more winterhardy than alfalfa, there is less concern about avoiding harvest during a critical fall rest period.

Table 3. Criteria for estimating average cutting dates for grasses.

GDAYS†	No. of cuts	Cutting date criteria		
		1st cut	2nd cut	3rd cut
<25	0-2	480 PTU*	Optional 55 days after 1st cut*	-
≥25	2-3	480 PTU	55 days after 1st cut	Optional 55 days after 2nd cut*

† No. of days from date when 480 PTU have accumulated in spring to D_{400}.
* Cut is not possible if date is <30 days before GSE.

2.2.3. Validation of cutting date criteria

Cutting date criteria for alfalfa and grasses (timothy, bromegrass and wheatgrass) were validated by comparing estimated average dates based on criteria in Table 1 and 3 with observed average cutting dates at various locations (Appendix 1). Observed data were obtained from three sources: a) variety performance trials conducted across Canada (e.g. Ontario Forage Crops Committee, 1968; Atlantic Committee on Crops, 1982; Expert Committee on Forage Crops, 1983); b) Agriculture Canada, LRRC CANSIS performance management file (Dr. K.B. MacDonald, personal commun.); c) various scientific papers in the literature. Much of the data from regional performance trials were also used in developing the criteria, and thus, this validation is not strictly independent.

Estimated and observed average cutting dates were highly correlated ($r \geq 0.83$) for each of three cuts of alfalfa and the first cut of grass (Table 4). Lower correlation for the second cut of grass was expected

Table 4. Correlation coefficient (r) between cases of estimated and observed average cutting dates for alfalfa and grasses.

Crop	Cut number	Number of cases	r
Alfalfa	1	44	0.92
Alfalfa	2	28	0.95
Alfalfa	3	8	0.98
Alfalfa	1-4	81	0.99
Grasses	1	16	0.83
Grasses	2	10	0.41
Grasses	1-2	26	0.96

since the critical fall harvest period is not normally important for winter-hardy grasses, thus allowing for more flexibility in harvest management. Correlation coefficients for all cuts combined were very high ($r \geq 0.96$) since cutting dates are also correlated with time.

The linear relationships between estimated and observed average cutting dates are shown graphically in Fig. 3. These tests indicate that cutting date criteria in Tables 1 and 3 are generally suitable for

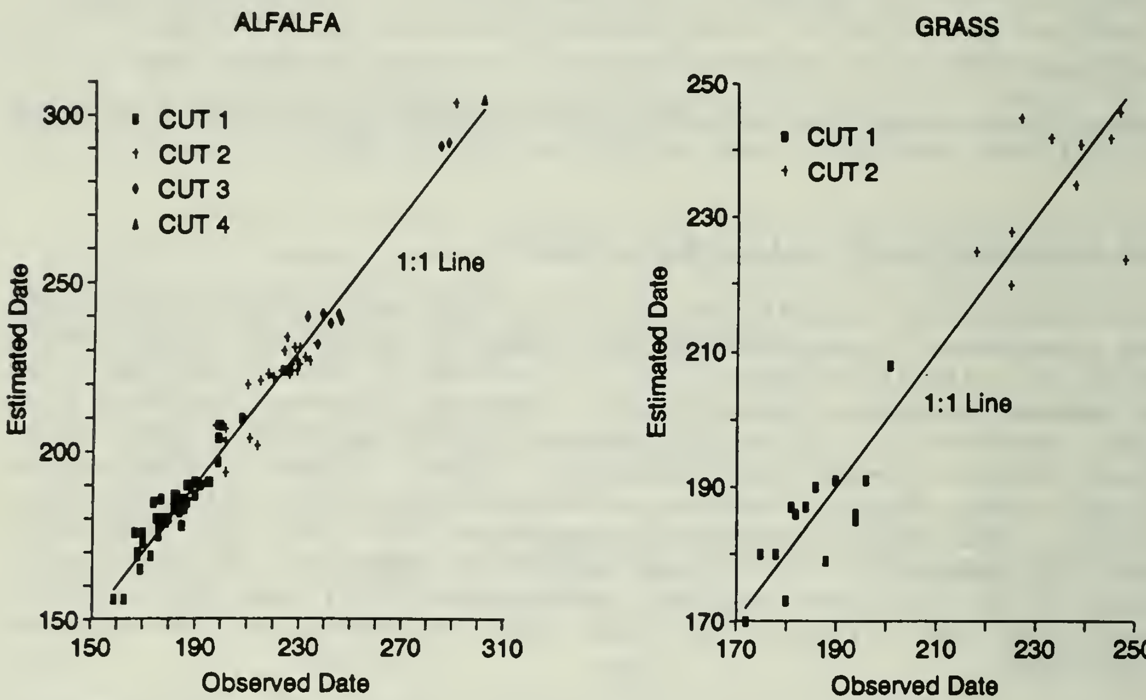

Figure 3. Comparison between average estimated and observed cutting dates (Calender day) for up to four cuts of alfalfa and two cuts for grasses.

alfalfa and grasses. However, this is not a rigorous validation since: a) some observed average cutting dates are based on relatively few years of data; b) stage of maturity at cutting was often not recorded and could vary and c) climatic stations used may not always represent the test location adequately.

Insufficient data were available to statistically validate Option 2 (Table 2). However, enough cases suggested this option to be a valid alternative cutting strategy under some conditions.

2.3. Additional Modifications to the FAO Model for Application for Forages

2.3.1. Workability factor

Adequate information was not available to estimate harvest losses for forages for inclusion in FORYLD. The workability factor in the FAO model (Stewart, 1983) was based on soil moisture during the fall harvest period. However, harvest losses in forages depend more on above ground conditions (precipitation and evaporation) than on moisture in the soil. Thus, this factor was set equal to 1.0.

2.3.2. Respiration losses

The maintenance respiration function C_t in equation (1) is computed in the FAO model by the expression

$$C_t = C_{30} \ (0.044 + 0.0019T + 0.0010T^2) \qquad (7)$$

where C_{30} is the maintenance respiration coefficient at 30°C and T is the mean air temperature over the growing season. FORYLD assumed values of 0.0283 and 0.0108 for C_{30} for alfalfa and grasses, respectively (i.e. the values used for legume and non-legume crops in the FAO model).

2.3.3. Leaf area index (LAI)

The maximum crop growth rate in the FAO model was adjusted when maximum LAI was < 5.0 (Stewart, 1983). This directly affected the constraint-free net biomass production (B_N) in equation 1. LAI was also used to split total evaporation between bare soil evaporation and plant transpiration. In the FAO model, daily LAI values were simulated from the progression in growing season length from LAI curves for annual crops. However, these curves were found to underestimate the typical LAI for perennial forages reported in the literature (Hunt et al., 1970; Carter and Sheaffer, 1983). The procedures used to estimate LAI in FORYLD for alfalfa were based on typical LAI curves reported in the literature. Maximum LAI was assumed to be 6.5 for the first cut and 6.0 for the second and third cut. If the last cut occured at the end of the growing season, a maximum LAI of 4.5 was assumed. Maximum LAI is only reached after a growth period of $\geq$ 45 days. For growing periods (GSL) of < 45 days, the LAI is estimated by the formula

$$\text{LAI} = \text{Maximum LAI} \times \frac{\text{GSL}}{\text{Maximum GSL}} \qquad (8)$$

where the maximum LAI is as noted above and the maximum GSL is 45 days.

For grasses, maximum LAI was assumed to be 6.0 for the first cut and 4.0 for any additional cuts. Maximum GSL was set at 55 days.

2.3.4. Start of growing season

The FAO model assumed the start of the growing season for annual crops as the day on which the average daily minimum air temperature exceeded 5°C (Stewart, 1983). The growing season for perennial forages is longer; in FORYLD it was assumed to coincide with the period when the average daily mean air temperature (T_{MN}) exceeded 5°C (Chapman and Brown, 1966). The first growth period began at the start of the growing season and ended when the first cut was taken. Growth periods for later cuts began the first day following the previous cut and ended on the cutting date.

2.3.5. Soil moisture budgeting

In FORYLD soil water budgeting was initiated in spring (known as the Moisture Growing Season Start, or MGSS) (Stewart, 1983) when the average daily potential evapotranspiration (PE) first exceeded average daily precipitation (P) or on the first date when T_{MN} exceeded 5.0°C, whichever occured last. The latter date corresponded closely to the time when average snow depth was less than 2.5 cm for seven consecutive days as reported in the Hydrological Atlas of Canada (Fisheries and Environment Canada, 1978). Thus, it was assumed that the soil surface had thawed, and evaporation proceeded normally after this date.

2.3.6. Harvest index

A harvest index (H_i) of 0.95 was assumed for FORYLD, meaning that almost all of the net biomass production was available for harvest. A small portion (5%) was assumed as unharvested stubble and wastage.

2.4. Simulation of Potential Net Dry Matter Yield

2.4.1. Assumptions for maximum crop growth rate

Constraint-free net biomass production (B_N) is a function of b_{gm}, the maximum rate of gross biomass production (eq. (1)). b_{gm} is in turn affected by the rate of biomass production on clear and overcast days and the fraction of the day that the sky is overcast (Stewart, 1983). b_{gm} is further adjusted depending on the maximum leaf photosynthesis rate (P_m), which is a function of the seasonal mean daytime temperature (T_{mdt}) and the crop species. McBride and Brown (1984) calibrated P_m versus T_{mdt} curves for six forage species (all C_3 crops) using yield data from forage variety trials in Ontario. Curves for medium maturing alfalfa and for timothy were selected from McBride and Brown (1984) for use in FORYLD as follows:

for alfalfa,

$$P_m = -57.6446 + 8.2645\ T_{mdt} - 0.2066\ (T_{mdt})^2 \qquad (9)$$

for grasses,

$$P_m = 3.0667\ T_{mdt} - 0.1022\ (T_{mdt})^2 \qquad (10)$$

These relationships are compared with the P_m versus T_{mdt} curve used for C_3 crops in the FAO model (Fig. 4).

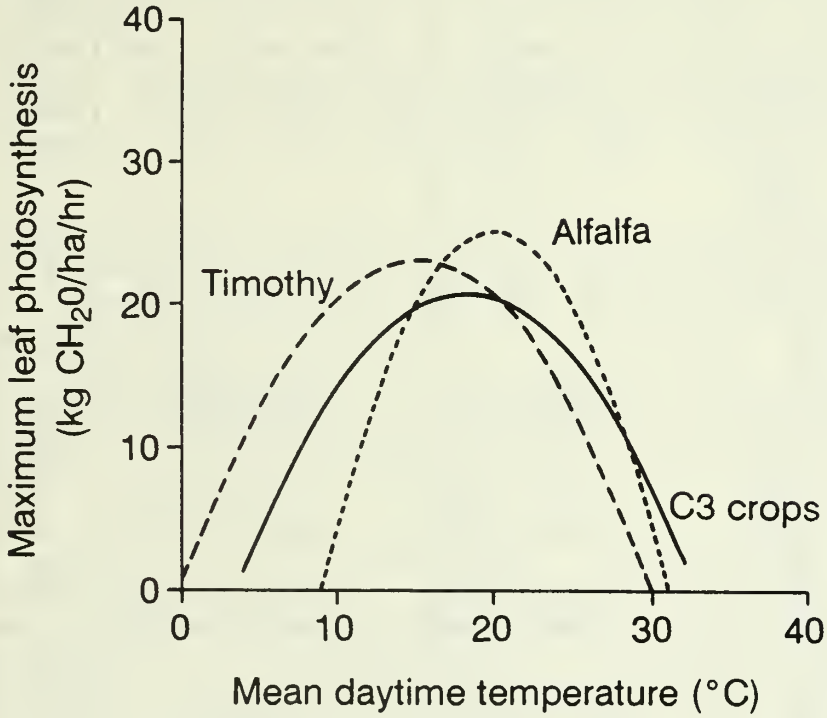

Figure 4. Relationship between maximum leaf photosynthetic rate (Pm) and mean daytime temperature (T_{mdt}).

2.4.2. Validation of potential (constraint-free) yield

Estimates of potential forage yields with no moisture stress (B_y, eq. (2)) were compared with observed yields from regional variety performance trials for selected locations in Canada (Table 5). Several years with the highest yields were selected, assuming that there would be little or no moisture stress in these years. However, since some stress due to moisture deficits may occur even in the best years, the observed yields are themselves only estimate of potential yield. Management factors such as fertilizer applications and harvest dates may also have influenced observed yields. In western Canada, observed yields were extracted from data on irrigated trials. A yield was determined for each trial-year by averaging data for selected standard varieties. Effects of age of stand on yields was minimized by using data only from the first three years after establishment.

Table 5. Comparison between estimated (EST) and observed (OBS) average potential dry matter yields of a) alfalfa and b) timothy.

Location	Dry matter yield (t/ha) & data use ratio										
	Cut 1			Cut 2			Cut 3			Total	
	EST	OBS	n/N†	EST	OBS	n/N	EST	OBS	n/N	EST	OBS
a) Alfalfa											
Kamloops, B.C.††	8.5	5.6	2/10	4.9	5.2	3/10	3.9	3.7	3/10	17.3	14.5
Swift Current, Sask.††	9.1	9.5	4/13	5.8	5.5	4/13	-	-	-	14.9	15.0
Ridgetown, Ont.	8.0	7.5	4/19	4.6	6.2	2/19	4.2	3.8	4/19	16.8	17.5
Ottawa, Ont.	8.0	6.8	3/12	4.4	3.7	2/12	4.0	3.6	1/12	16.4	14.1
Charlottetown, P.E.I.	8.3	7.7	2/8	5.2	5.0	1/8	-	-	-	13.5	12.7
Average:	8.4	7.4		5.0	5.1		4.0	3.7		15.8	14.8
b) Timothy											
Ridgetown, Ont.	8.9	8.3	2/11	4.7	4.2	2/10	-	-	-	13.6	12.5
Ottawa, Ont.	8.6	7.8	3/19	5.0	5.0	2/15	-	-	-	13.6	12.8
Kapuskasing, Ont.	9.3	6.8	2/16	5.7	4.9	2/16	-	-	-	15.0	11.7
Truro, N.S.	9.8	8.7	2/14	5.6	3.4	2/11	-	-	-	14.9	12.1
Charlottetown, P.E.I.	9.4	8.9	3/17	5.5	4.2	3/16	-	-	-	14.5	12.4
Average:	9.2	8.1		5.3	4.3		-	-	-	14.5	12.4

† n is the number of years data with high yields used to compute OBS; N is the total number of years for which yield observations were available.

†† Yield data is based on irrigated variety trials at these locations.

Potential dry matter yields estimated by FORYLD were, on average, about 1 t/ha higher than observed yields (Table 5). At several individual locations, the estimated yields were almost 3 t/ha above observed values (e.g. alfalfa cut 1 at Kamloops; timothy cut 1 at Kapuskasing). Low observed yields at these locations are most likely due to below optimum management levels or due to moisture stress. In several instances model estimates were lower than observed yields (e.g. alfalfa cut 2 at Ridgetown). This could be due to differences in length of growing period used in the model in comparison to the field trial or because of better than average temperature and/or solar radiation during a growth period. However, since model estimates were based on long term normals, reasons for yield differences could not be positively identified.

Estimated potential dry matter yields were compared with observed values for a number of additional locations not shown in Table 5. In most cases, observed yields were lower than estimated values. Largest differences were experienced for the first cut of alfalfa, where observed potential yields were typically 2 to 3 t/ha lower. It is likely that even in the best years, forages grown in regional performance trials do not always reach the maximum potential yield due to below optimum management levels (i.e. fertility), moisture stress and/or winter injury.

Overall, the model seems to provide reasonable estimates of the potential constraint-free yield of forages. The comparative tests are only a general indicator and not a rigorous validation of the model. Differences in estimated potential yields between locations for individual cuts (Table 5) are relatively small. This may be expected, since potential yields are only affected by temperature, solar radiation and length of growing period and not by moisture supply. The number of cuts that are feasible is the greatest factor affecting the potential yield of forages at a given location.

2.5. Simulation of Anticipated Dry Matter Yields

2.5.1. Model procedures and modifications

The modified FAO model estimates anticipated dry matter yields (B_{ya}) by reducing potential yields (B_y) by a moisture stress factor (MSF) computed from the AE/PE ratio (Section 2.1, eq. (3) and (4)). Estimated yields using the FAO procedure to compute the MSF were compared with average observed yields from regional variety performance trials at sixteen locations across Canada for the first two cuts of alfalfa and nine locations for two cuts of timothy. The yield response factory K_y was assumed to be 1.0 and 1.1 for alfalfa and timothy respectively. Soil available water-holding capacity (AWC) was estimated from soil particle size information obtained from trial reports or directly from co-operators. The relationship between particle size and AWC was taken from DeJong and Shields (1988) and is shown in Table 6.

Applying these relationships directly to the modified FAO model gave unsatisfactory results. On the average, forage yields were overestimated by about 70% and 26% respectively for the first two cuts of

Table 6. Relationship between available water-holding capacity and soil particle size group (from DeJong and Shield, 1988).

Available water-holding capacity (mm)	Soil particle size groups
50	Sand; loamy sand
100	Sandy loam
150	Very fine sandy loam; clay
200	Silt loam; sandy clay; clay loam
250	Silty clay loam; sandy clay; /silty clay; clay; heavy clay

alfalfa, and by about 40% and 70%, respectively, for the first two cuts in timothy. Estimates were relatively insensitive to changes in K_y and AWC, and thus, could not be readily improved by adjusting these parameters. For these reasons, a different procedure was used to compute the MSF.

The approach adopted was that of McBride and Brown (1984), in which the MSF is related to a parameter known as the soil moisture deficit-surplus (SMDS). The SMDS is computed as follows:

$$SMDS = P + \theta_i - PE \qquad (11)$$

where P is the total precipitation during the growth period.

θ_i is the plant-available soil water content at the start of the growth period.

and PE is the total potential evapotranspiration during the growth period.

McBride and Brown (1984) calibrated the relationship between MSF and SMDS using annual forage yield data from variety performance trials in Ontario. However, because of much drier conditions on the prairies, recalibration of the MSF versus SMDS curve was necessary and this was accomplished by plotting actual MSF versus SMDS for all available locations with alfalfa and timothy yield data. A hand-fitted curve was drawn through the higher MSF values (low MSF values were assumed to be due to below optimum management or poor stand persistence). Actual MSF values were determined by:

$$MSF = \frac{B_a}{B_y} \qquad (12)$$

where B_a is the average dry matter yield observed for all available years in regional variety performance trials.

B_y is the constraint-free (potential) net dry matter yield estimated by FORYLD.

The relationship between MSF and SMDS used in FORYLD is shown in Figure 5 and is presented by the following cubic polynomial equation:

$$MSF = 0.594 + 2.426\ SMDS - 1.423(SMDS)^2 - 7.905(SMDS)^3 \qquad (13)$$

where SMDS is in metres. This estimate of MSF was then used in the calculations of anticipated dry matter yield (B_{ya}).

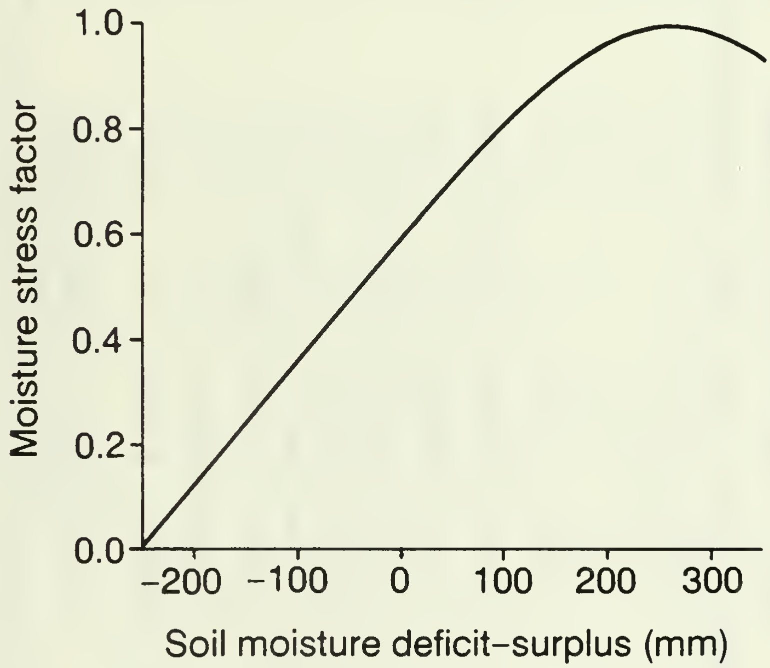

Figure 5. Relationship between the moisture stress factor (MSF) and the soil moisture deficit - surplus (SMDS).

As in the case of McBride and Brown (1984), this relationship was found to be equally valid for both alfalfa and timothy, and applicable for all cuts.

2.5.2. <u>Validation of anticipated dry matter yield (B_{ya})</u>

a) <u>Alfalfa and timothy yield validation</u>

Model estimates were compared with average observed yields at selected locations across Canada for up to three cuts of alfalfa (Table 7) and two cuts of timothy (Table 8), in order to validate as

Table 7. Comparison between observed and estimated average anticipated dry matter yield (B_{ya}) for alfalfa.

Location	Soil AWC	Observed average yield (t/ha)/ # of trial-years*				Estimated yield (t/ha)			
		Cut 1	Cut 2	Cut 3	Total	Cut 1	Cut 2	Cut 3	Total
Lacombe, Alb.	200	4.0/20	2.8/20	-	6.8	5.3	3.4	-	8.7
Indian Head, Sask.	250	3.0/26	2.4/7	-	5.4	4.9	2.9	-	7.8
Swift Current, Sask.	150	2.3/37	1.5/18	-	3.8	2.1	1.4	-	3.5
Brandon, Man.	200	3.9/22	2.3/22	-	6.2	4.8	2.8	-	7.0
Guelph, Ont.	130†	4.9/37	3.2/35	2.7/29	10.8	5.9	2.4	2.4	10.6
Kapuskasing, Ont.	50†	3.4/27	2.4/27	-	5.8	4.7	2.8	-	7.5
Kemptville, Ont.	100†	5.1/24	2.4/20	2.5/18	10.0	5.0	2.1	2.2	9.3
New Liskeard, Ont.	70†	4.7/22	2.9/20	-	7.6	4.5	2.8	-	7.2
Ottawa, Ont.	130†	4.9/26	2.8/26	2.3/25	10.0	5.5	2.5	2.4	10.3
Ridgetown, Ont.	200	6.0/47	3.9/47	3.0/25	12.9	6.8	3.1	2.7	12.7
Truro, N.S.	100	4.2/12	2.9/12	-	7.1	6.0	3.2	-	9.3
Charlottetown, P.E.I.	150	6.0/20	3.2/20	-	9.2	6.2	3.3	-	9.5
Mean		4.4	2.7	2.6	8.0	5.1	2.7	2.4	8.6

† AWC based on McBride and Brown (1984); all others are estimated using soil particle size groups in conjunction with Table 6.

* Data may include more than one trial in a given year at each location.

Table 8. Comparison between observed and estimated average anticipated dry matter yield (B_{ya}) for timothy.

Location	Soil AWC	Observed average yield (t/ha)/# of trial-years*			Estimated yield (t/ha)		
		Cut 1	Cut 2	Total	Cut 1	Cut 2	Total
Guelph, Ont.	130†	7.4/28	2.3/24	9.7	6.4	2.7	9.1
Kapuskasing, Ont.	50†	4.4/32	2.5/30	6.9	5.0	3.7	8.8
Kemptville, Ont.	100†	6.0/14	3.6/8	9.6	5.4	2.1	7.5
Ottawa,Ont.	130†	5.2/53	2.3/33	7.5	5.9	2.5	8.5
Ridgetown, Ont.	200	6.6/14	2.9/13	9.5	7.5	2.7	10.2
Fredericton, N.B.	100	5.2/53	2.3/33	7.5	6.2	2.9	9.1
Truro, N.S.	100	6.4/15	2.4/12	8.8	6.6	3.6	10.3
Charlottetown, P.E.I.	150	7.0/20	3.1/19	10.0	7.0	3.4	10.4
Mean		6.0	2.7	8.7	6.3	3.0	9.2

† AWC based on McBride and Brown (1984); all others are estimated using soil particle size in conjunction with Table 6.

* Data may include more than on trial in a given year at each location.

much as possible anticipated dry matter yield estimates produced by FORYLD. Observed average yields were calculated by averaging annual yields observed in forage variety trials conducted in the various regions of Canada (e.g. Ontario Forage Crops Committee, 1968; Atlantic Committee on Crops, 1982; Expert Committee on Forage Crops, 1983). Only yields based on data from the first and second year after the year of establishment were used to compute an average. Thus, effects of decline in stand persistence and of winter injury were minimized. In cases where significant winter injury was noted with trial results, the yields were omitted from the averaging procedure. The source of soil AWC information used in estimating B_{ya} is indicated in the tables. AWC's were either estimated from soil particle size information for the trial location used in conjunction with Table 6, or they were taken from estimates provided by McBride and Brown (1984). The number of trial-years of regional variety trial data from which observed average yields were computed are shown in the tables. Some years contain data from more than one trial at a location.

Mean estimated yields for alfalfa for all cuts combined were only 0.6 t/ha higher than the mean observed average for twelve locations (Table 7). There was a good correlation (r = 0.91) between estimated and observed alfalfa yields for all cuts combined at individual locations and the values followed closely to the 1:1 relationship (Fig. 6). For timothy, mean average estimated yield for all locations was within 0.3 t/ha of mean observed yields for both cuts 1 and 2 (Table 8). At some locations, estimated yields exceeded the observed by more than

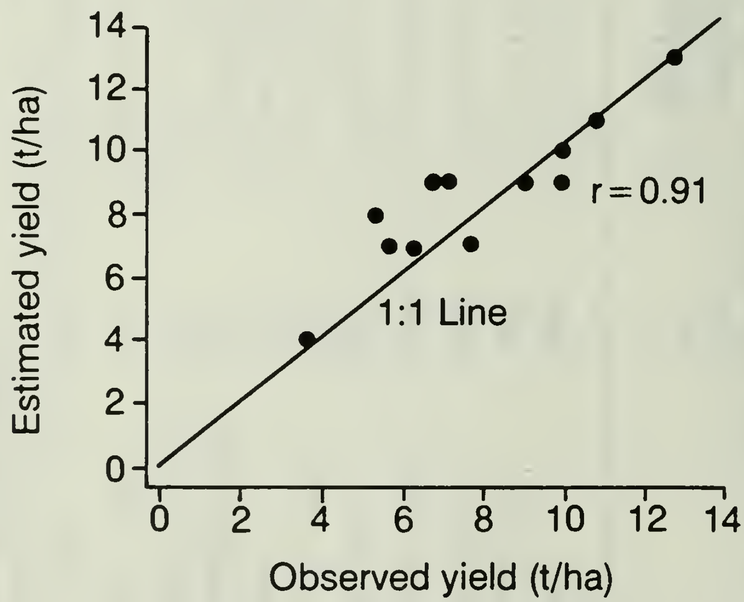

Figure 6. Comparison between average estimated and observed anticipated dry matter yield for all cuts of alfalfa combined (two-three cuts).

1 t/ha (e.g. first cut alfalfa at Indian Head, Kapuskasing and Truro; first cut timothy at Fredericton, second cut at Kapuskasing, Kemptville and Truro).

Some large differences between estimated and observed yields may be expected for several reasons: (i) soil AWC is only an approximate estimate; in many cases estimated yields would coincide with observed values if the AWC was adjusted by only one category (50 mm) or less; (ii) weather conditions during the trial years may have differed significantly from normal, particularly if relatively few years' data were available; and (iii) observed yields may have been influenced by management level, stand persistence, winter survival and varietal differences. While these tests do not provide a rigorous validation of the model, they do indicate that FORYLD provides reasonable estimates of both alfalfa and timothy yields under rainfed conditions. Although no specific comparisons were made with bromegrass yields, cutting schedules and yields are expected to be similar to timothy.

b) Wheatgrass yield validation

Observed yields on crested and intermediate wheatgrass were extracted and averaged from regional trial reports in western Canada (e.g. Expert Committee on Forage Crops, 1983). Data for the first three years only after the year of establishment were used. Comparisons between observed yields and those estimated for grasses by FORYLD are shown in Table 9 for crested and Table 10 for intermediate wheatgrass.

Estimated yields assume a soil AWC of 200 mm unless soil textural information was available, in which case, Table 6 was used to determine the AWC. Estimated mean yields averaged for all locations were within 0.1 t/ha of observed yields for both crested and intermediate wheatgrass. However, differences between observed and estimated yields for individual locations were frequently 0.5 t/ha or more. These differences may be expected since soil AWC values are very approximate and since observed yields are often based on only a few years' data. As was the case with alfalfa and timothy, yield estimates would coincide with observed values in most cases with an adjustment in AWC of only one category (50 mm) or less. Although these results do not constitute a rigorous test of the model, they indicate that the grass component of FORYLD provides reasonable estimates of anticipated dry matter yields of crested and intermediate wheatgrasses in western Canada.

3. SUMMARY AND CONCLUSIONS

The modified FAO model has been successfully used to estimate potential and anticipated dry matter yields of alfalfa and of several grass species grown in Canada. The model does not distinguish between grass species, i.e. the estimated yields represent those for the species best adapted to a particular region whether that be timothy, bromegrass or crested/intermediate wheatgrass. Subroutines which estimate growth periods and cutting schedules of alfalfa and grasses were developed since these are of crucial importance to the model; yields are often

Table 9. Comparison between observed and estimated average anticipated dry matter yield (B_{ya}) for crested wheatgrass.

Location	Soil AWC	Cut No.	No. years of data	Dry matter yield (t/ha) Observed††	Estimated
Lacombe, Alb.	200*	1	3	5.8	5.9
Indian Head, Sask.	200*	1	4	5.3	4.6
Melfort, Sask.	200	1	3	4.9	4.7
Melfort, Sask.	200	2	3	2.4	2.9
Saskatoon, Sask.	200	1	14	4.5	3.7
Swift Current, Sask.	250*	1	6	2.1	2.8
St. Claude, Man.†	200	1	3	6.1	5.9
St. Claude, Man.†	200	2	3	2.0	2.5
Mean				4.1	4.1

† Climatic data from Deerwood, Man., was used to estimate yield.
†† Average may include data from more than one trial in each year.
* Soil AWC's based on soil particle size information; all others are assumed values.

Table 10. Comparison between observed and estimated average anticipated dry matter yield (B_{ya}) for intermediate wheatgrasses.

Location	Soil AWC	Cut No.	No. years of data	Dry matter yield (t/ha) Observed††	Estimated
Beaverlodge, Alb.	200	1	8	5.1	6.0
Beaverlodge, Alb.	200	2	6	2.1	3.8
Lacombe, Alb.	200*	1	4	6.3	5.9
Lacombe, Alb.	200*	2	4	3.8	3.7
Lethbridge, Alb.	200	1	8	4.3	4.3
Lethbridge, Alb.	200	2	2	2.3	1.5
Indian Head, Sask.	200*	1	12	4.4	4.6
Melfort, Sask.	200	1	6	5.5	4.7
Saskatoon, Sask.	250*	1	9	4.2	3.7
Swift Current, Sask.	200*	1	11	2.4	2.8
Swift Current, Sask.	200*	2	4	0.5	1.2
Mean				3.7	3.8

†† Average may include data from more than one trial in each year.
* Soil AWC's based on soil particle size information; all others are assumed values.

heavily dependent on the number of cuts that can be taken. Other modifications of the FAO model included: (i) adjustment of the maximum photosynthetic rate versus temperature curve, (ii) change in the method used to calculate leaf area index and (iii) a change in the method used to determine the moisture stress factor which is used to derive anticipated yields from potential (constraint-free) yields.

Precise validation of a model such as FORYLD which computes average yields from climatic normals data is not possible due to the difficulty in obtaining suitable long-term observed yields from various locations. Nevertheless, results of validation presented here suggest that model estimates are generally within ± 1 t/ha of observed values, although individual locations may vary by as much as ± 2 t/ha. Larger yield differences between the model estimates and average yields observed in the field at some locations are likely due to management factor, stand persistence and/or overwintering damage. These factors could not be accounted for in the present model.

The yield estimates generated when FORYLD is applied to the appropriate climate data on a geographic basis should provide a useful source of information for studies in land evaluation. Estimated yields represent production levels that are attainable under irrigated (potential yield) and rainfed (anticipated yield) conditions the first few years after establishment under optimum management levels and with no winterkill.

In recent years, increased emphasis has been placed on determining crop production risk as it relates to variability in yields over time for land evaluation (Dumanski and Kirkwood, 1988). However, since FORYLD does not estimate yields on an annual basis, the risk factor in forage production cannot be assessed using this model. New modelling efforts are underway which will develop the capability of estimating forage yields on annual basis and thereby provide the required risk data. Meanwhile, estimates from FORYLD will provide a base of information which will help in assessing land suitability for forages and the potential effects of irrigation on yields. The model could also be a useful tool in evaluating the potential impact of climatic change scenarios on forage yields in Canada.

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5. APPENDIX

Appendix 1. Observed and estimated average cutting dates used in validation of cutting date criteria.

A. 1ST CUT - ALFALFA

Location	Cutting date Estimated	Cutting date Observed†	Years data	Data source††	Location	Cutting date Estimated	Cutting date Observed†	Years data	Data source††
B.C.					**SASK. (Cont'd)**				
Creston	Jun 18	Jun 17	3	a	Saskatoon	Jun 27	Jul 4[i]	2	a
Kamloops	Jun 5	Jun 12[i]	7	a	Saskatoon	Jun 27	Jun 26	2	a
Kamloops	Jun 5	Jun 8[i]	5	c1	Swift Current	Jun 29	Jun 26[i]	11	a
					Swift Current	Jun 29	Jun 24[i]	8	c3
ALBERTA					Swift Current	Jun 29	Jun 27	8	a
Beaverlodge	Jul 10	Jul 9	8	a					
Calgary	Jul 9	Jul 11[di]	3	b	**MANITOBA**				
Calgary-Turner Valley	Jul 16[q]	Jul 18[d]	9	b	Brandon	Jun 26	Jun 25	2	a
					Winnipeg	Jun 25	Jun 19	2	a
Calgary-Gleichen	Jul 5[q]	Jul 2[d]	4	b					
Claresholm	Jul 2	Jul 2[d]	8	b	**ONTARIO**				
Edmonton	Jul 4	Jun 23	2	a	Elora	Jun 25	Jun 16[j]	3	a
Edmonton	Jul 4	Jul 6[h]	3	b	Guelph	Jun 22	Jun 19	7	a
					Kapuskasing	Jul 10	Jul 14	7	a
Edmonton-Rochester	Jul 5[q]	Jul 5[h]	4	b	Kemptville	Jun 19	Jun 17	7	a
Fort Vermilion	Jul 3	Jul 5	5	a	New Liskeard	Jul 2	Jul 1	5	a
Lacombe	Jul 6	Jul 5	8	a	Ottawa	Jun 18	Jun 22	6	a
Lethbridge[i]	Jun 28	Jun 28	4	a					
Lethbridge	Jun 28	Jun 26[h]	4	b	Ridgetown	Jun 14	Jun 18	10	a
Olds	Jul 10	Jul 14	14	b	Thunder Bay	Jul 9	Jul 6	4	a
Pekisko - Turner Valley	Jul 21	Jul 27			**QUEBEC**				
Pincher Creek	Jul 10	Jul 15[e]	3	c2	Lennoxville	Jun 24	Jun 25	2	c4
Turner Valley	Jul 23	Jul 18[d]	9	b					
Vulcan[i]	Jul 3	Jul 4[d]	5	b	**ATLANTIC PROV.**				
					Charlottetown	Jul 6	Jul 2	9	a
SASKATCHEWAN					Fredericton	Jun 29	Jun 27	6	a
Choiceland	Jul 2	Jul 3	2	a	Nappan	Jul 6	Jul 1[h]	7	a
Indian Head	Jun 29	Jun 29[f]	2	a	St. John's West	Jul 27	Jul 19	9	a
Melfort	Jul 1	Jul 1	4	a	Truro	Jul 5[p]	Jun 26	14	a

Appendix 1. (Cont'd).

B. 2ND CUT - ALFALFA

Location	Cutting date: Estimated	Cutting date: Observed†	Years data	Data source††
B.C.				
Creston	Jul 21	Aug 2	3	a
Kamloops	Jul 13	Jul 21[gi]	2	a
ALBERTA				
Edmonton	Aug 17	Aug 11	3	a
Fort Vermilion	Aug 12	Aug 15	5	a
Lethbridge	Aug 11	Aug 6[i]	10	a
Lethbridge	Aug 11	Aug 14[hi]	2	b
Vulcan	Aug 16	Aug 20[hi]	4	b
SASKATCHEWAN				
Choiceland	Aug 15	Aug 17	2	a
Indian Head	Aug 12	Aug 13	2	a
Melfort	Aug 14	Aug 15	4	a
Tisdale	Aug 14[k]	Aug 18	2	a
Saskatoon	Aug 10	Aug 8	4	a
Swift Current	Aug 12	Aug 14	11	a
Swift Current	Aug 12	Aug 12[i]	3	a
MANITOBA				
Brandon	Aug 9	Aug 3	2	a
Winnipeg	Aug 8	Jul 29	2	a
ONTARIO				
Elora	Jul 27[i]	Jul 17	3	a
Guelph	Jul 26	Jul 21	5	a
Kemptville	Jul 23	Jul 19	5	a
New Liskeard	Aug 15	Aug 22	3	a
Ottawa	Jul 23	Jul 30	6	a
Ridgetown	Jul 23	Jul 22	9	a
Thunder Bay	Aug 22	Aug 13	3	a
ATLANTIC PROV.				
Charlottetown	Aug 19	Aug 16[h]	9	a
Fredericton	Aug 12	Aug 17[h]	7	a
Nappan	Aug 19	Aug 18	9	a
St. John's West	Oct 31	Oct 18	4	a
Truro	Aug 18[p]	Aug 12[f]	12	a

C. 3RD CUT - ALFALFA

Location	Cutting date: Estimated	Cutting date: Observed†	Years data	Data source††
B.C.				
Kamloops	Aug 20	Aug 25[gi]	2	a
SASKATCHEWAN				
Swift Current	Oct 19	Oct 15[i]	4	a
MANITOBA				
Brandon	Oct 18	Oct 12	2	a
ONTARIO				
Elora	Aug 28[j]	Aug 22	3	a
Guelph	Aug 29	Aug 27	4	a
Kemptville	Aug 26	Aug 30	5	a
Ottawa	Aug 27	Sep 3	4	a
Ridgetown	Aug 29	Sep 2	9	a

D. 4TH CUT - ALFALFA

Location	Cutting date: Estimated	Cutting date: Observed†	Years data	Data source††
B.C.				
Kamloops	Nov 1	Oct 29[i]	2	a

Appendix 1 (Cont'd).

E. 1ST CUT - GRASS

Location	Cutting date: Estimated	Cutting date: Observed†	Years data	Data source††
ALBERTA				
Edmonton	Jul 4	Jul 13	5	b
Edmonton-Rochester	Jul 5[q]	Jul 12	5	b
Lethbridge	Jun 28	Jul 7[m]	4	b
Pincher Creek	Jul 10	Jul 15[em]	3	c2
Swift Current	Jun 29	Jun 24[dhm]	7	c5
ONTARIO				
Guelph	Jun 22	Jun 29	12	a
Kapuskasing	Jul 10	Jul 9	5	a
Kemptville	Jun 19	Jun 21	5	a
Ottawa	Jun 18	Jun 25	6	a
Ridgetown	Jun 14	Jun 21	3	a
Thunder Bay	Jul 9	Jul 5	4	a
ATLANTIC PROV.				
Charlottetown	Jul 6	Jul 3	10	a
Fredericton	Jun 29	Jun 27[h]	12	a
Nappan	Jul 6	Jun 30	9	a
St. John's West	Jul 27	Jul 20	4	a
Truro	Jul 5[p]	Jul 1[h]	9	a

F. 2ND CUT - GRASS

Location	Cutting date: Estimated	Cutting date: Observed†	Years data	Data source††
ONTARIO				
Guelph	Aug 16	Aug 13[m]	7	a
Kapuskasing	Sep 3	Sep 4[m]	5	a
Kemptville	Aug 13	Aug 6[m]	5	a
Ottawa	Aug 12	Sep 5	5	a
Ridgetown	Aug 8	Aug 13	1	a
Thunder Bay	Sep 2	Aug 15	2	a
ATLANTIC PROV.				
Charlottetown	Aug 30	Sep 2	12	a
Fredericton	Aug 23	Aug 26	15	a
Nappan	Aug 30	Aug 21	6	a
Truro	Aug 29[p]	Aug 27	10	a

† Observed average cutting dates may include more than one trial per year.

†† Data were obtained from one of three sources: a) regional variety performance trials, b) CANsis performance management file and c) scientific publications as follows: c1 Stout, 1986; c2 Lutwick and Smith, 1977; c3 Irvine and McElgunn, 1982; c4 Gasser and Lachance, 1969; c5 Kilcher and Heinrichs, 1974.

d Cutting date is based on trials with mixed stand.

e Observed date is an approximate estimate.

f Observed date is based on 2-cut system only; later dates may be observed for 1-cut systems, earlier dates for 3-cut system.

g Observed date is based on 4-cut system only; later dates are observed for 3-cut systems.

h Observed date was adjusted for maturity.

i Data based on irrigated trials.

j Climate normals data for Fergus Shand Dam, Ontario were used.

k Climate normals data for Melfort, Saskatchewan were used.

m,n Observed grass cutting dates are for bromegrass and wheatgrass respectively; all others are for timothy.

p Model estimate is adjusted about four days earlier to compensate for bias in temperature normals at the order hourly climate station at Truro, Nova Scotia.

q Estimated dates are based on average from two available climate stations closest to the trial location.

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