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Possible effects of climatic change on estimated crop yields in Canada

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Possible effects of climatic change on estimated crop yields in Canada

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ABSTRACT

This bulletin describes the effects of selected scenarios of climatic change on estimated dry matter yields for cereal, oilseed, potato, forage (first cut only), and corn crops in Canada. Yields are estimated for each scenario using a generalized crop growth model and modifying the temperature and precipitation input data in relation to the 1941-70 normals period.

Modification of the climatic data reflects the effects of warmer/cooler and drier/wetter climatic conditions for 2 situations: 1) a growing season length similar to the 1941-70 period, and 2) a growing season length deviating from the normals period (i.e. longer or shorter). Analyses of changes in yield resulting from anticipated changes in climate are presented for various agricultural regions in Canada.

RÉSUMÉ

Le présent bulletin décrit l'effet des fluctuations climatiques, selon certains scénarios, sur le rendement en matière sèche estimé pour les céréales, les oléagineux, la pomme de terre, les fourrages (première coupe uniquement) et le mais au Canada. Pour chacun des scénarios, les auteurs ont évalué les rendements à l'aide d'un modèle général de culture où ils ont introduit des températures et des taux de précipitation modifiés par rapport à ceux de la période de 1941 à 1970, considérés comme données normales.

La modification des données climatiques avait pour but de simuler l'effet des variations temps plus chaud - temps plus froid et temps plus sec - temps plus humide, dans deux cas: 1) avec une période de végétation semblable à la normale de 1941-1970 et 2) une période de végétation différente de la normale (c'est-à -dire, plus longue ou plus courte). Les auteurs ont analysé les variations de rendement qui résulteraient de fluctuations des conditions climatiques dans diverses régions agricoles au Canada.

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TABLE OF CONTENTS

	Page
ABSTRACT	iii
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	vi
LIST OF TABLES	vi
1. INTRODUCTION	1
2. METHODOLOGY	2
2.1 Dry matter yield estimation	2
2.2 Input data	2
2.3 Modification of input data to simulate climatic change	4
3. RESULTS AND DISCUSSION	6
3.1 FIXED growing season length	11
3.1.1 Estimated yields	11
3.1.2 Summary	16
3.2 VARIABLE growing season length	20
3.2.1 Cereal and oilseed yields	20
3.2.2 Potato yields	21
3.2.3 Forage yields	21
3.2.4 Corn yields	21
3.2.5 Summary	22
4. CONCLUSIONS	22
4.1 Effect of a warming trend	22
4.2 Effect of a cooling trend	24
4.3 Effect of changing precipitation	24
REFERENCES	25

LIST OF FIGURES

Figure		Page
1.	Example of two types of temperature change scenarios used: (a) FIXED GSL; (b) VARIABLE GSL.	5
2.	Locations used in the study.	8
3.	Changes in estimated dry matter yields from normal for cereals and oilseeds for FIXED and VARIABLE GSL.	13
4.	Changes in estimated dry matter yields from normal for potatoes for FIXED and VARIABLE GSL.	14
5.	Changes in estimated dry matter yields from normal for forages for FIXED and VARIABLE GSL.	15
6.	Changes in estimated dry matter yields from normal for corn for FIXED and VARIABLE GSL.	17

LIST OF TABLES

Table		Page
1.	Values of crop characteristics used in yield calculations.	3
2.	Climatic scenarios.	7
3.	Climate normals (1941-70) for locations used in the study.	9
4.	Estimated dry matter yields for normal (1941-70) climate.	10
5.	Growing season start, end, length and corn heat units for each temperature change scenario using VARIABLE GSL.	12
6.	Corn Heat Units for each temperature scenario using FIXED GSL.	18
7.	Changes in estimated dry matter yield for ±1°C change in temperature and ±20% change in precipitation using FIXED GSL.	19
8.	Changes in estimated dry matter yield for ±1°C change in temperature and ±20% change in precipitation using VARIABLE GSL.	23

1. INTRODUCTION

Agricultural productivity and crop yields are strongly linked to the physical environment in which crops are grown. Variability in climate between years cause crop yields to fluctuate depending on the event, its severity, and abnormality. These year to year variations may be considered as random and generally unpredictable. However, longer term climatic changes which produce distinctly different climatic regimes from the normal may have a significant influence on crop yields and the geographic zones in which crops can be grown. Such a change might result from the increase in carbon dioxide (CO_2) concentration in the atmosphere which is occurring at a fairly rapid rate (Keeling et al., 1976a, 1976b).

The general consensus from the literature is that the most probable effect of an increased CO_2 concentration is an increase in temperature, although the projected magnitude of this change varies depending on the prediction model used (Schneider, 1975; Plass, 1956; Manabe and Wetherald, 1975, 1980; Sellers, 1973). In any event, a temperature rise of around 1°C early in the next century is probably not unrealistic, and this could have major repercussions for agricultural regions in Canada. If rising CO_2 is accompanied by an increase in temperature, the growing season length in various agricultural zones may well be expanded. In fact, it has already been estimated in the United States that a 1°C temperature increase would shift the corn belt 175 km further northeast (Newman, 1980).

In this study, a crop growth model has been used to simulate possible effects on yield of climatic scenarios which represent how the climate may change. The model, developed by F.A.O. (1978) and modified by Stewart (1981) for land evaluation studies in Canada, was used to estimate potential net biomass and dry matter yields. Using this methodology various constraints are applied against the potential values to estimate the agroclimatically attainable or expected net biomass and dry matter yields on a continental scale. Model results are currently available for spring wheat, corn, soybean, phaseolus bean and potato (Dumanski and Stewart, 1981).

This report documents the application of a modified form of the Stewart model for estimating dry matter yields for corn, forage, potato, cereal and oilseed crops for selected climatic scenarios aside from the "normal" case. Normal is defined as the average climate for the 1941-70 period. A climatic scenario is defined as a positive or negative variation in temperature and/or precipitation from normal. The dry matter production data calculated for the 1941-70 normal period are used as a reference for establishing the change in production from either an increase or decrease in temperature or precipitation. Model results can be interpreted, especially those simulating increased temperatures, as possible effects of increasing atmospheric CO_2 concentration.

2. METHODOLOGY

2.1 Dry Matter Yield Estimation

The model applied in this study to compute dry matter biomass production is outlined in detail by Stewart (1981), and hence, only a brief description is given here.

Constraint-free net biomass production, (B_N) or dry matter yield, of the harvestable portion of a crop that can be produced under given climatic conditions in the absence of all yield reducing factors were estimated from the procedure developed by de Wit (1965) as

$$B_N = 0.36\ b_{GM}/(1/N - 0.25\ C_T), \qquad (1)$$

where: b_{GM} is the gross biomass production, N is the number of days required to mature a crop, and C_T is a maintenance respiration coefficient. Crop dry matter yield B_y was then derived as

$$B_y = B_N \times H_I, \qquad (2)$$

where: H_I is the harvest index defined as that fraction of the net biomass production that is economically useful.

Values of B_y computed by eqn. (2) are constraint-free or genetic potential yields. These values, however, do not consider the effect of yield reducing factors such as moisture stress; weeds, pests and diseases; climatic effects on yield components, yield formation, quality of produce; and field workability. These factors should be considered if agronomically attainable yields are to be calculated. For the purposes of this study, values of B_y were corrected by a moisture stress yield reducing factor (MSF) to give values of estimated dry matter yield (B_{ye}):

$$B_{ye} = B_y \times MSF. \qquad (3)$$

The remaining yield reducing factors were considered negligible and ignored. Details of the calculation procedures for C_T, b_{GM}, and MSF are outlined in detail by Stewart (1981) in his eqns. (3, 4 and 16a), respectively. Values of crop characteristics used in this study to derive B_{ye} are listed in Table 1.

2.2 Input Data

The procedures for estimating net biomass and dry matter yields are designed to evaluate the long-term crop production capability on a continental basis using basic climatic information.

Input data required by the model include long-term monthly averages of temperature, precipitation, incoming solar irradiance, windspeed and vapour pressure. These data were either obtained from observation networks

TABLE 1: Values of crop characteristics used in yield calculations.

	Cereals	Potato	Corn	Forage	Oilseeds
GSL	75-110	75-140	90-130	0-75*	75-120
LAI	3.1-5.0	2.5-5.0	3.0-4.0	1.0-5.0	2.3-3.5
H_I	0.11-0.40	0.45-0.60	0.15-0.35	0.80	0.29-0.34
DMMP	0.85	0.325	0.85	1.00	0.85
K_y	1.15	1.10	1.25	1.00	1.25

GSL = growing season length (days)
LAI = leaf area index (dimensionless)
H_I = harvest index (dimensionless)
DMMP = dry matter in the main product (percent)
K_y = crop yield response to moisture stress (dimensionless) (see eqn. 16a, Stewart, 1981).

*First cut only

(Atmospheric Environment Service, Environment Canada) or derived using simple empirical equations.

Normals data representing the 30-year average for the years 1941-70 from climatic stations were converted by computer interpolation to a 1290 equal area grid square system, each grid representing an area 100 km by 100 km. Climatic data for each grid square included precipitation, mean, maximum, and minimum air temperature (reduced to sea level), vapour pressure, windspeed, and incoming solar irradiance. Climatic data for each of 755 soil map units contained in the Soils Map of Canada (Clayton et al., 1977) were then derived from the grid square data. This was accomplished by superimposing the grid square framework onto the 1:5 M Soils of Canada Map and estimating the area of each soil unit contained in each grid square. From this, the basic climatic data for each soil unit was obtained using a simple weighting procedure (Stewart, 1981).

In certain instances the grid square data were considered inadequate for describing the climate of various soil units (ie. mountainous area of British Columbia). In these cases, data for several stations contained in the soil unit were averaged. For soil units containing no climate stations, the grid square data were used. In certain instances, interpolation from station data to the 100 km grid is a limitation in that some microclimates may be averaged out (ie. Annapolis Valley).

2.3 Modification of input data to simulate climatic change

In this study climatic change is simulated by varying temperature and precipitation in two ways. The first, is a climate represented by warmer-cooler/drier-wetter conditions based on the assumption that the growing season length (GSL) is similar to the present climate (ie. the 1941-70 normals) and will not change. This form of climatic change, referred to as "FIXED GSL", is illustrated in Fig. 1 (a) in relation to the 1941-70 normals. To simulate this effect the 1941-70 normals temperature data were modified using the expression:

$$T_I = Tn_I + (Tmax - Tn_I) \sin (3.1416 \times I/GSL), \qquad (4)$$

where: T_I is the modified temperature on day I based on a mean temperature change of T for the growing season; Tn_I is the 1941-70 normal temperature calculated for day I, Tmax is the maximum temperature during the growing season estimated as (Tmaxn + 1.571 ΔT) where Tmaxn is the maximum growing season temperature for the 1941-70 normals period.

The second form of climatic change was simulated by adjusting all monthly temperature data by ΔT, as illustrated in Fig. 1b. This type of change results in a change in growing season length and is referred to as "VARIABLE GSL".

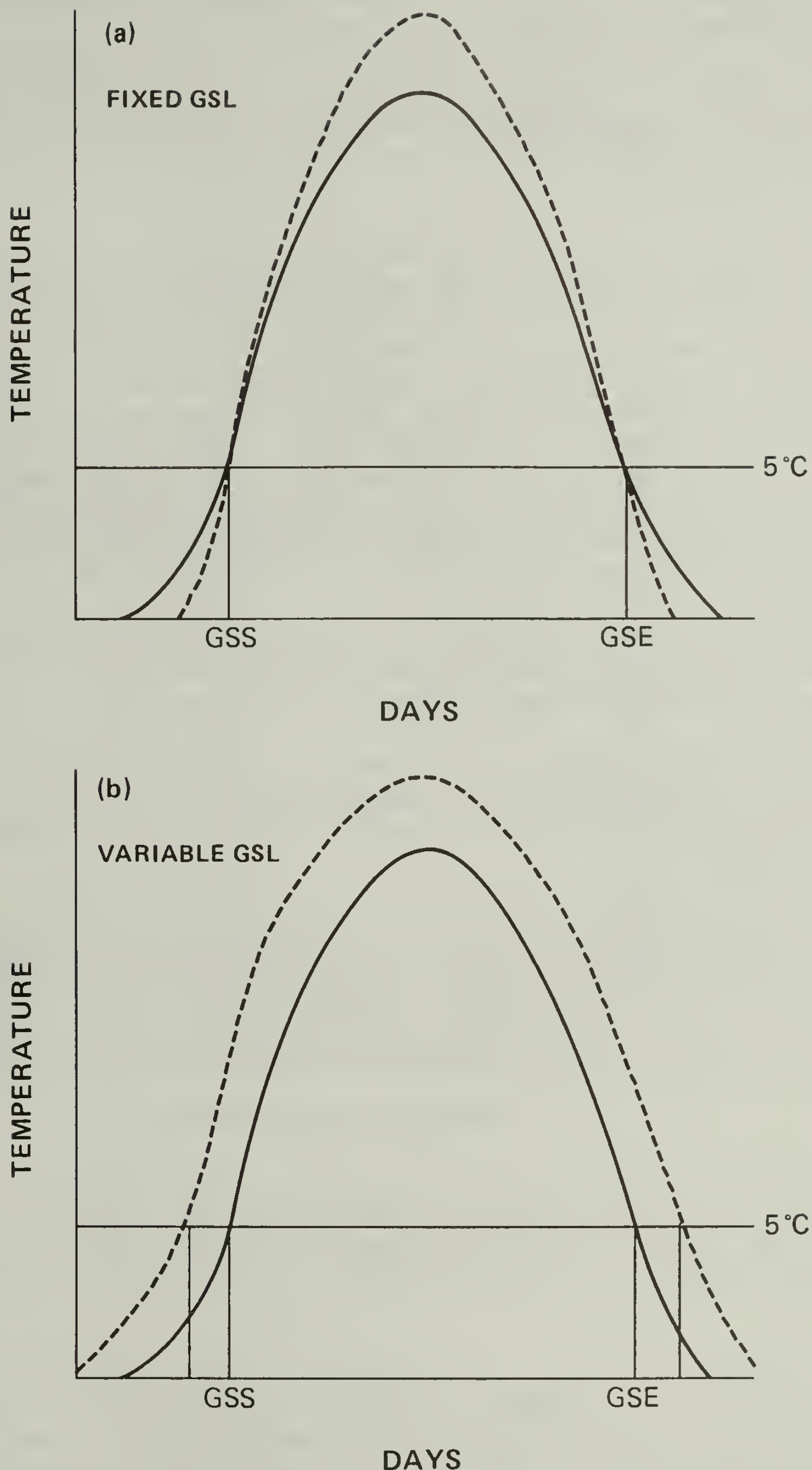

Figure 1. Examples of two types of temperature change scenarios used: (a) FIXED GSL; (b) VARIABLE GSL. (——) denotes normal temperature curve, (---) denotes temperature deviation from normal.

Changes in precipitation were handled identically for both types of climatic change by adjusting the monthly normals. This assumes that no major shifts in precipitation pattern within the growing season occurs and that the change is equally distributed throughtout the growing season. Precipitation is handled in this manner for simplicity since at the present time there is no way of knowing how the precipitation pattern might change within the growing season.

The 1941-70 monthly normals were used as base data. In VARIABLE GSL these data were adjusted to reflect the desired change in temperature and precipitation while all other climate input data were held constant at the normals level. Daily values of all climatic variables except precipitation were generated using the Brooks (1943) sine curve interpolation technique. Monthly precipitation values were converted to weekly values and input on a weekly basis. Mean growing season values were then derived by summing the data between the growing season start (GSS), and end (GSE), and dividing by GSL. The dates for the start and end of the growing season were set by the date the mean minimum air temperature first exceeded 5°C in the the spring and fell below 5°C in the fall.

In FIXED GSL, the monthly and daily data for the 1941-70 normals period were used to derive GSS and GSE for each soil unit. Temperature data between these dates were adjusted using eqn. (4).

For both types of climatic change, anticipated yields are estimated for 22 combinations of temperature (+3°C to -3°C from normal) and precipitation (60% to 140% of normal). The various climatic scenarios are listed in Table 2.

Model computations must be interpreted with the realization that long term climatic normals rather than actual daily information are used. In addition, growing season averages, and bulk crop phenological characteristics are employed, while various crop growth stages and management variations (eg. fertilizer and pesticide use) are omitted.

3. RESULTS AND DISCUSSION

For the purpose of this analysis, seven locations (Fig. 2) across Canada were chosen to determine the effects of different climatic change scenarios on B_{ye} in various climatic regions. Climatic data averaged over the period May 1 to September 30 for each location are listed in Table 3.

Changes in B_{ye} in relation to the 1941-70 normals for the selected scenarios are shown in Fig. 3-6 for cereals, oilseeds, potatoes, forages and corn, for both FIXED and VARIABLE GSL. Absolute values for B_{ye} can be determined by adding or subtracting the change in yield shown on the graphs from the B_{ye} values determined for normal climatic conditions listed in Table 4. Yield trend curves for the different

TABLE 2: Climatic scenarios.

Scenario Number	Temperature Change °C from Normal	Precipitation Change % of Normal
1	0	100
2	+3	60
3	+3	80
4	+3	100
5	+3	120
6	+3	140
7	+2	80
8	+2	100
9	+2	120
10	+1	80
11	+1	100
12	+1	120
13	-1	80
14	-1	100
15	-1	120
16	-2	80
17	-2	100
18	-2	120
19	-3	60
20	-3	80
21	-3	100
22	-3	120
23	-3	140

Figure 2. Locations used in the study.

TABLE 3: Climatic normals (1941-70) for locations used in the study.

Area Number	Location	Climate Normals (May-September)			
		T	P	K	PE
1.	Southern Saskatchewan	13.9	227	20.6	600
2.	Okanagan Valley	15.8	151	20.6	542
3.	Prairie fringe (Prince Albert, Saskatchewan)	13.6	249	18.7	520
4.	Southern Ontario	17.0	371	19.2	517
5.	Peace River region Alberta	12.6	250	18.0	456
6.	Annapolis Valley Nova Scotia	14.4	448	18.5	444
7.	Northern Ontario clay belt	13.3	428	17.7	425

T = mean air temperature (°C)
P = total precipitation (mm)
K = incoming solar irradiance ($MJ\ m^{-2}\ day^{-1}$)
PE = total potential evapotranspiration (mm)

TABLE 4: Estimated dry matter yields (t/ha) for normal (1941-70) climate[1].

Location	Cereals	Oilseeds	Potatoes	Forage[2]	Corn[3]
Southern Saskatchewan	1.7	1.6	2.9	4.4	0.0
Okanagan Valley	2.2	1.7	3.8	4.0	3.0
Prairie fringe	2.5	2.5	4.2	4.9	0.0
Southern Ontario	3.6	3.2	6.8	5.2	5.4
Peace River	2.8	3.1	4.8	5.4	0.0
Annapolis Valley	4.1	3.8	7.8	5.3	0.0
Northern Ontario clay belt	3.8	3.7	6.0	6.1	0.0

[1]Dry matter yields are estimated for a maximum growing season length of n days, where n = 110, 120, 140, 75 and 130 days for cereals, oilseeds, potatoes, forage and corn respectively (see Table 5 for GSL values).

[2]Forage yields are applicable to first cut only (GSL = 75 days).

[3]Areas with less than 2500 CHU are indicated as having 0.0 grain corn yields because of inadequate maturity.

locations are reduced to one curve where yield values are within ±0.5 t/ha of the mean value (eg. Fig. 3b).

3.1 FIXED GSL

For FIXED GSL, the values of GSS, GSE and GSL for a given location are not affected by changes in temperature. These parameters are fixed by the computations for the 1941-70 normals period and are listed in Table 5 for VARIABLE GSL with no temperature change applied ($\Delta T = 0°C$). If the GSL exceeded maximum limits set for each crop in Table 1, then the maximum GSL value listed was used in the yield calculations.

3.1.1 Estimated yields. Results for cereals and oilseeds are often combined since the response to climate change is similar for both crops (Fig. 3). The trend is one of declining yield with increasing temperature. Yields in the drier areas (eg. S. Sask. (1), Okanagan V. (2)) are more sensitive to temperature changes than those of more moist areas (eg. Annapolis V. (6), and N. Ont. clay belt (7)) due to increased moisture stress resulting from higher temperatures. Values of B_{ye} for the N. Ont. clay belt (7) are least affected by temperature changes.

For +3°C, yields of cereals and oilseeds are reduced in all areas to the point where a 40% increase in precipitation will not offset the effects of increased moisture stress (Fig. 3D). At -3°C, yield increases range between 1 and 2 t/ha above normal in the drier regions at above normal precipitation levels (Fig. 3E). In the more moist areas, yields are unaffected over the range of precipitation levels investigated.

Yield trends for potatoes (Fig. 4) were very similar to those of cereals and oilseeds. Figure 4 (A, B, and C) indicates a decline in B_{ye} in all areas as temperatures increase above normal values for levels of precipitation from 80% to 120% of normal. Yields in the N. Ont. clay belt (7) are least affected by increased temperature. In S. Sask. (1), Okanagan V. (2), Prairie fringe (3), and S. Ont. (4), yields increased as temperatures dropped below normal. Below normal temperatures had little or no effect on yields in the Peace R. (5), Annapolis V. (6) or the N. Ont. clay belt (7).

Results for forages (Fig. 5) apply to the first cut only (maximum GSL = 75 days). Yield trends for FIXED GSL are similar to those obtained for cereals and oilseeds. For the below normal temperature scenarios, values of B_{ye} were generally within 0.5 t/ha of the normal scenario yields except for S. Sask. (1) and the Okanagan V. (2) where yields increased by about 1 t/ha at -3°C for precipitation amounts 100% of normal or higher. At -3°C, yields were virtually unaffected by changes in precipitation in S. Ont. (4), Annapolis V. (6) and the N. Ont. clay belt (7) (Fig. 5E). In most of the other regions, yields increased gradually from less than 1 t/ha below the no change scenario at 60% of normal precipitation to 0.5 to 1.0 t/ha above normal at 140% of normal precipitation.

TABLE 5: Growing season start (GSS), end (GSE), length (GSL) in days and Corn Heat Units (CHU) for each temperature change scenario using VARIABLE GSL.

		Temperature Change Scenario ΔT (°C)						
Location	Parameter	-3	-2	-1	0	+1	+2	+3
S. Sask.	GSS	20 Jun	13 Jun	6 Jun	29 May	23 May	18 May	13 May
	GSE	22 Aug	28 Aug	1 Sep	6 Sep	12 Sep	17 Sep	22 Sep
	GSL	64	77	88	101	113	123	133
	CHU	1017	1294	1559	1865	2175	2470	2775
Okanagan Valley	GSS	7 Jun	29 May	22 May	14 May	7 May	29 Apr	22 Apr
	GSE	4 Sep	11 Sep	18 Sep	25 Sep	2 Oct	9 Oct	15 Oct
	GSL	90	106	120	135	149	164	177
	CHU	1493	1845	2192	2568	2945	3348	3739
Prairie fringe	GSS	20 Jun	13 Jun	6 Jun	29 May	23 May	18 May	13 May
	GSE	22 Aug	28 Aug	2 Sep	7 Sep	12 Sep	17 Sep	23 Sep
	GSL	64	77	89	102	113	123	134
	CHU	987	1262	1541	1849	2148	2444	2764
S. Ont.	GSS	25 May	19 May	15 May	9 May	4 May	26 Apr	20 Apr
	GSE	27 Sep	3 Oct	8 Oct	13 Oct	19 Oct	24 Oct	2 Nov
	GSL	126	138	147	158	169	182	197
	CHU	2232	2569	2886	3237	3597	3994	4422
Peace R.	GSS	28 Jun	17 Jun	9 Jun	30 May	23 May	17 May	12 May
	GSE	14 Aug	22 Aug	29 Aug	4 Sep	11 Sep	17 Sep	23 Sep
	GSL	47	67	82	98	112	124	135
	CHU	625	958	1260	1596	1931	2257	2583
Annapolis Valley	GSS	13 Jun	6 Jun	30 May	24 May	18 May	12 May	6 May
	GSE	17 Sep	23 Sep	30 Sep	7 Oct	13 Oct	20 Oct	2 Nov
	GSL	97	110	124	137	149	162	181
	CHU	1443	1751	2088	2434	2786	3162	3607
N. Ont. clay belt	GSS	19 Jun	12 Jun	6 Jun	31 May	27 May	22 May	17 May
	GSE	25 Aug	1 Sep	8 Sep	15 Sep	21 Sep	1 Oct	7 Oct
	GSL	68	82	95	108	118	133	144
	CHU	990	1279	1573	1883	2172	2528	2861

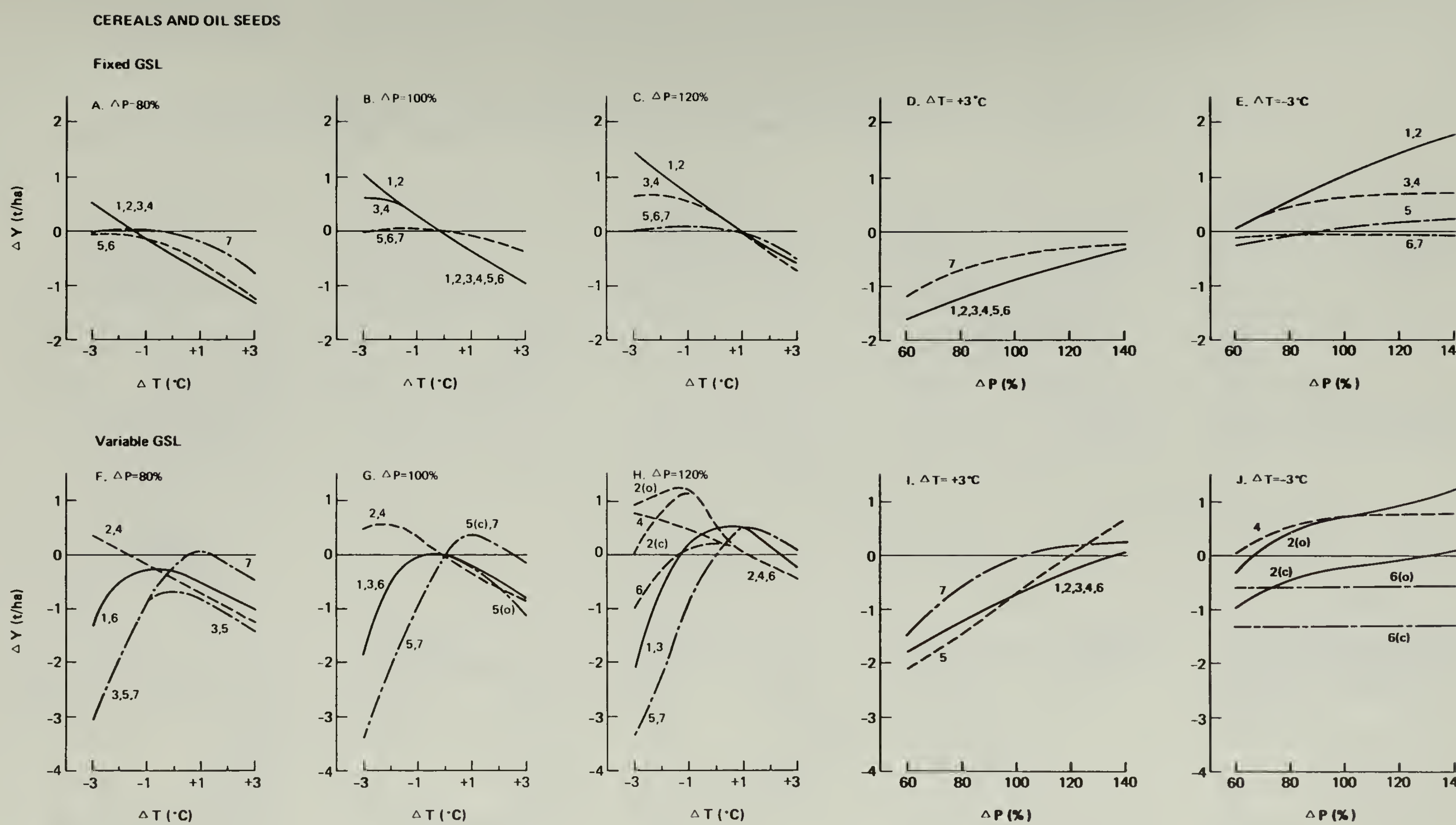

Figure 3. Changes in estimated dry matter yields from normal (ΔY) for cereals (c) and oilseeds (o) for FIXED and VARIABLE GSL. ΔT: change in temperature (°C) from normal; ΔP: percentage of normal precipitation. Locations are (I) S. Sask, (2) Okanagan V., (3) Prairie fringe, (4) S. Ont., (5) Peace R., (6) Annapolis V., (7) N. Ont. clay belt.

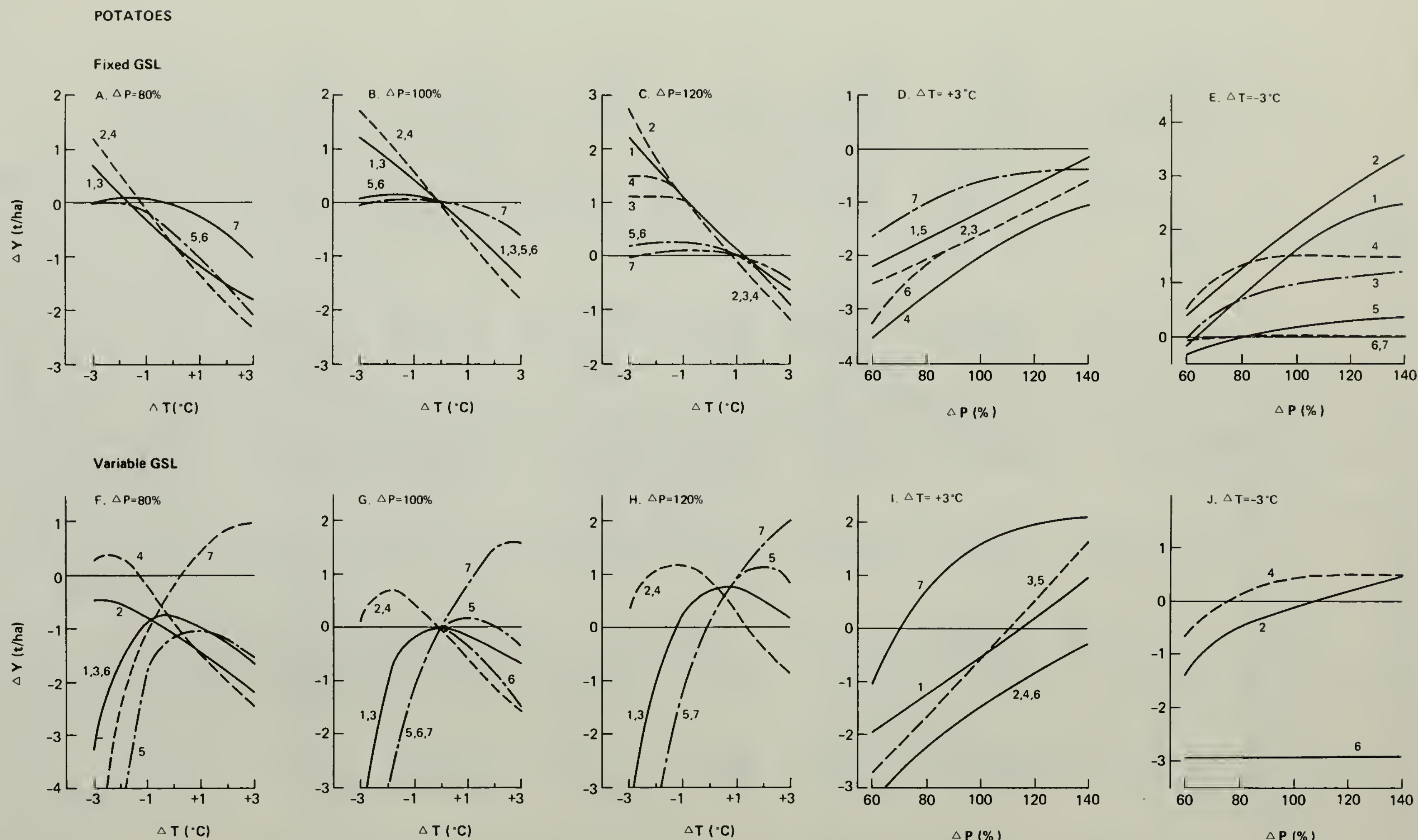

Figure 4. Changes in estimated dry matter yields from normal (ΔY) for potatoes for FIXED and VARIABLE GSL. Locations are as in Figure 3.

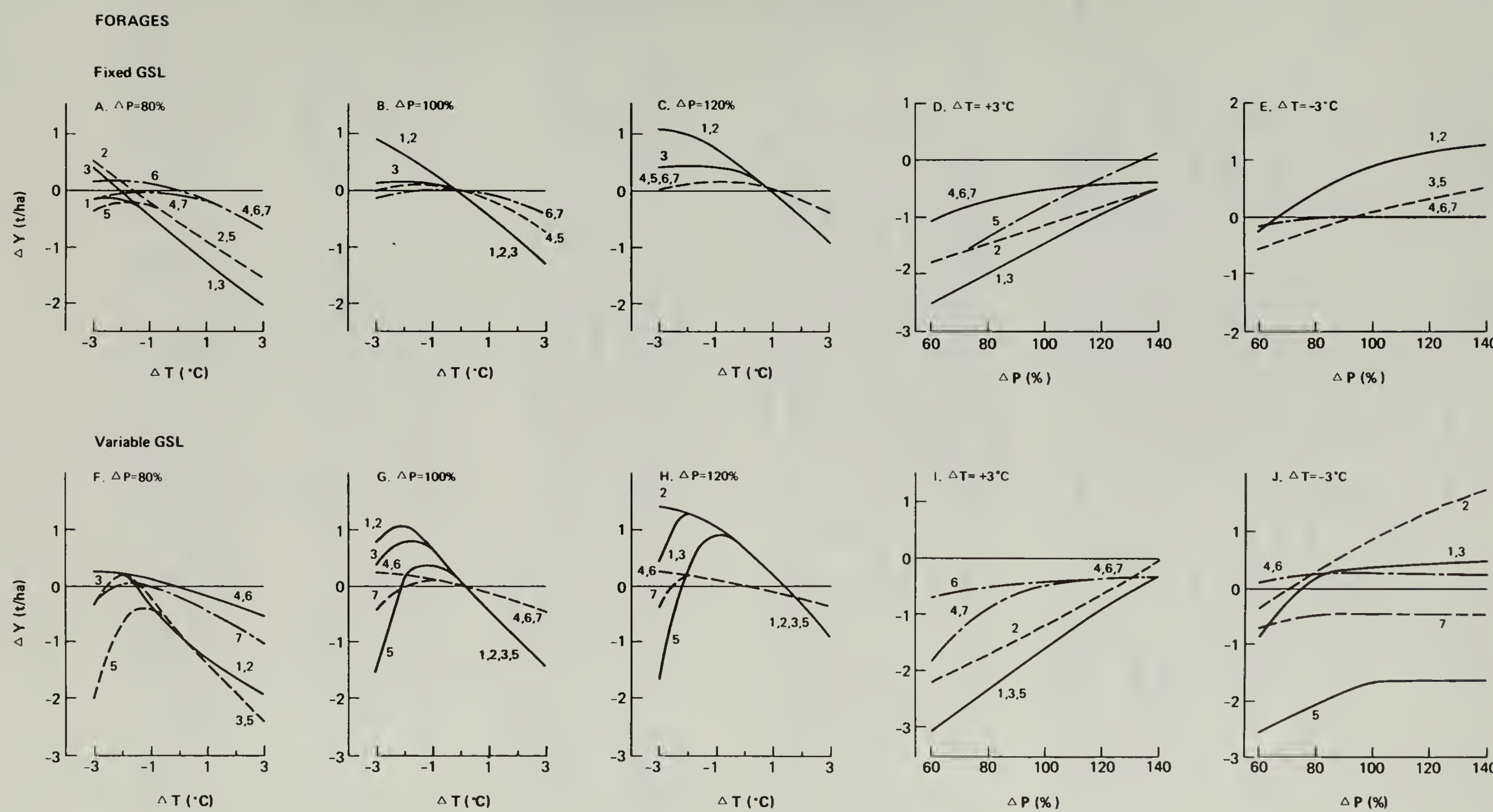

Figure 5. Changes in estimated dry matter yields from normal (ΔY) for forage for FIXED and VARIABLE GSL. Locations are as in Figure 3.

Results for corn (Fig. 6) are only shown for areas where grain corn could reach maturity given the constraint of 2500 Corn Heat Units (CHU) for normal climate (ie. S. Ont. (4) and the Okanagan V. (2)) as shown in Table 4. The available CHU's for each temperature change using FIXED GSL are listed in Table 6. The change in available CHU'S for a 1°C change in temperature from normal ranges from 139 to 243. Below normal temperatures affect the available CHU's more than above normal temperatures. Furthermore, in the short growing season areas (S. Sask, (1), Prairie fringe (3), and Peace R. (5)) CHU's were less sensitive to changes in temperature than in the areas with longer growing season (ie. Okanagan V. (2), S. Ont. (4), and the Annapolis V. (6)). Under the no change scenario estimated yields for the Annapolis V. (6) were zero because CHU's were under-estimated by the climatic interpolation procedure. For all positive temperature changes, the only additional region showing capability is the Annapolis V. (6). For below normal temperatures, S. Ont. (4) is the only region with capability for grain corn production. However, this region's capability ceases at temperatures exceeding -3°C from normal.

The yield trend in corn using FIXED GSL is for lower yields as temperatures rise above normal values, with precipitation levels of 80 and 100% of normal. At precipitation levels 100% and 120% of normal, corn yields in S. Ont. (4) tend to peak at 1941-70 temperature levels. Yields were slightly reduced at both higher and lower temperatures, although the changes are not large (less than 0.25 t/ha per °C temperature change). The greatest decline in corn yields occur when increased temperatures are accompanied by lower precipitation (Fig. 6A). The maximum decline in yield (2.5 t/ha) occurs in the scenario with a +3°C temperature change and precipitation at 60% of normal.

3.1.2 Summary. Of all the climatic scenarios investigated, the ±1°C change in temperature and ±20% change in precipitation are probably the most likely scenarios for climatic change over the next few decades. Changes in estimated yield for these scenarios were summarized (Table 7). Yield changes for 80% and 120% of normal precipitation with no change in temperature were estimated by linear interpolation at temperatures of ±1°C since yields were not computed for these scenarios.

A -1°C change in temperature generally increased yields by less than 0.5 t/ha. Almost no yield changes occurred in the cooler and /or wetter areas (Peace R. (5), Annapolis V. (6), N. Ont. clay belt (7)). Yield increases were greatest for potatoes and least for forages. The large negative change in yield for corn in the Okanagan V. (2) results from the total CHU's falling below the 2500 CHU threshold, eliminating production (Table 7).

A temperature increase of +1°C resulted in a decrease in yields mostly in the range of 0.3 to 0.6 t/ha. The N. Ont. clay belt (7) was the only area where +1°C had no effect on yield. The large increase in grain corn yield in the Annapolis V. (6) was due to the 2500 CHU threshold being met.

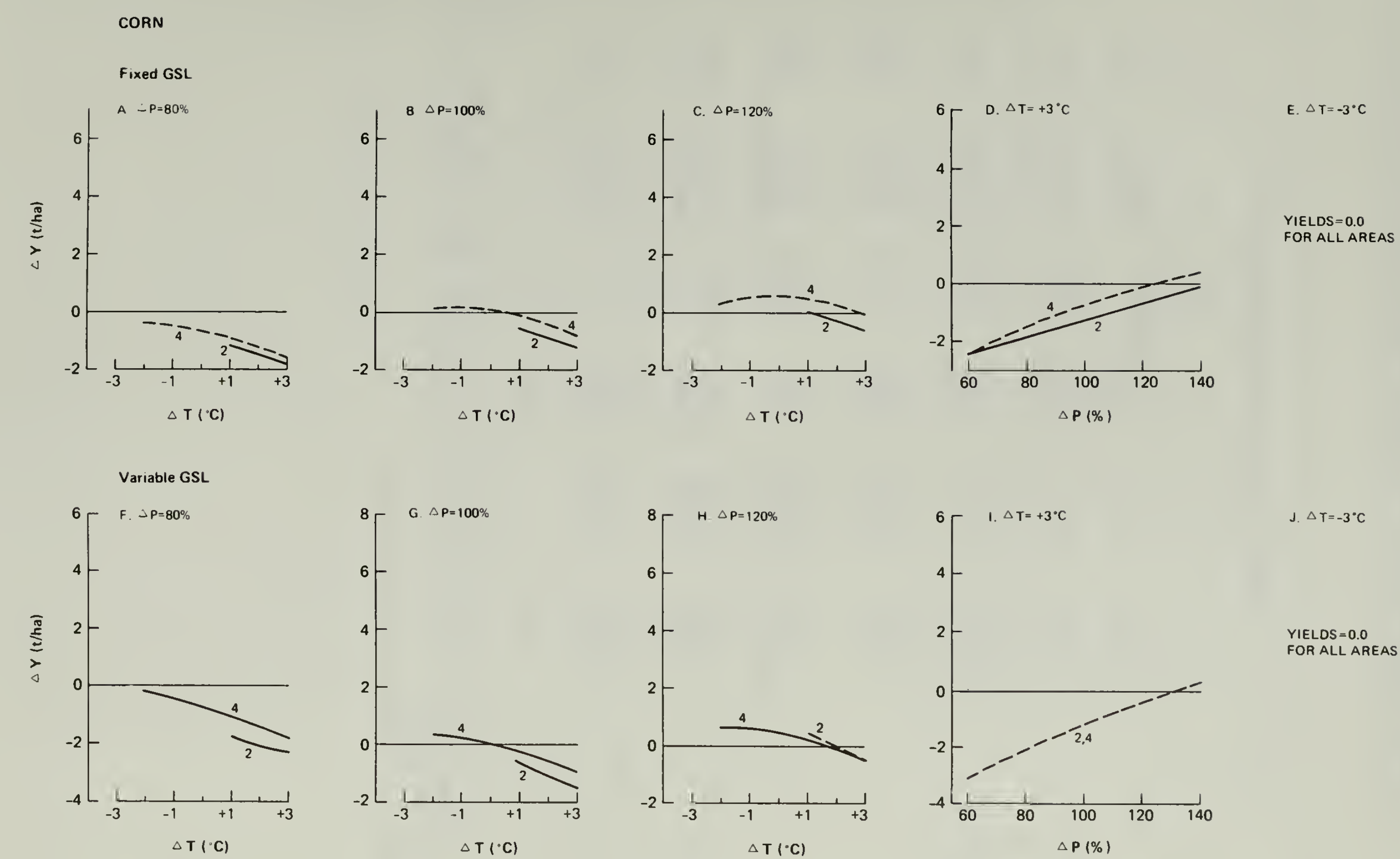

Figure 6. Changes in dry matter yield from normal (ΔY) for corn for FIXED and VARIABLE GSL. Locations are as in Figure 3.

TABLE 6: Corn Heat Units (CHU) for each temperature change scenario using FIXED GSL*.

	Temperature Change Scenario ΔT (°C)						
Location	-3	-2	-1	0	+1	+2	+3
S. Sask.	1395 (-470)	1560 (-305)	1717 (-148)	1865	2004 (+139)	2135 (+270)	2258 (+393)
Okanagan V.	1952 (-616)	2169 (-399)	2374 (-194)	2568	2750 (+182)	2921 (+353)	3081 (+513)
Prairie fringe	1358 (-491)	1530 (-319)	1694 (-155)	1849	1996 (+147)	2134 (+285)	2263 (+414)
S. Ont.	2468 (-768)	2737 (-499)	2993 (-243)	3236	3466 (+230)	3682 (+446)	3885 (+649)
Peace R.	1084 (-512)	1263 (-333)	1434 (-162)	1596	1750 (+154)	1896 (+300)	2034 (+438)
Annapolis V.	1701 (-732)	1956 (-477)	2201 (-232)	2433	2655 (+222)	2864 (+431)	3062 (+629)
N. Ont. clay belt	1332 (-551)	1525 (-358)	1708 (-175)	1883	2048 (+165)	2204 (+321)	2351 (+468)

*Growing season start, end and length for FIXED GSL are identical to the zero temperature change scenario of VARIABLE GSL (Table 4) for all temperature changes.
(   ) denotes difference from normal.

TABLE 7: Changes in estimated dry matter yield (ΔB_{ye}) for +1°C change in temperature and ±20% change in precipitation using FIXED GSL*.

Location	ΔYield (t/ha)					ΔYield (t/ha)				
	Ce	O	P	F	Cn	Ce	O	P	F	Cn
	A. ΔT=-1°C P=100%					B. ΔT=+1°C P=100%				
S. Sask.	0.2	0.3	0.4	0.2	-	-0.3	-0.3	-0.4	-0.7	-
Okan. V.	0.2	0.2	0.5	0.2	-3.0	-0.3	-0.4	-0.7	-0.5	-0.6
Prairie f.	0.2	0.3	0.4	0.1	-	-0.4	-0.4	-0.6	-0.5	-
S. Ont.	0.3	0.4	0.7	0.2	0.2	-0.3	-0.3	-0.7	-0.1	-0.2
Peace R.	0.1	0.1	0.1	0.0	-	-0.3	-0.3	-0.5	-0.2	-
Annap. V.	0.1	0.1	0.1	0.0	-	-0.3	-0.3	-0.5	-0.1	5.6
N. Ont. clay belt	0.0	0.0	0.1	0.0	-	0.0	0.0	0.0	0.0	-
	C. P=80% ΔT=0					D. P=120% ΔT=0				
S. Sask.	-0.4	-0.5	-0.6	-0.9	-	0.4	0.4	0.6	0.3	-
Okan. V.	-0.5	-0.5	-0.7	-0.5	-	0.3	0.3	0.5	0.3	-
Prairie f.	-0.5	-0.6	-0.8	-0.8	-	0.3	0.4	0.5	0.2	-
S. Ont	-0.3	-0.4	-0.7	0.0	-0.7	0.2	0.3	0.5	0.0	0.5
Peace R.	-0.4	-0.5	-0.7	-0.5	-	0.1	0.2	0.2	0.3	-
Annap. V.	-0.2	-0.3	-0.5	-0.1	-	0.0	0.0	0.0	0.0	-
N. Ont. clay belt	-0.1	-0.1	-0.1	-0.1	-	0.0	0.0	0.0	0.0	-

*Change in yields for precipitation changes at ΔT = 0 were estimated by interpolation from ΔY at ±1°C.

Ce = cereals, O = oilseeds, P = potatoes, F = forage, Cn = corn

A precipitation decrease of 20% reduced yields by 0.3 to 0.8 t/ha for most crops and areas. However, in the N. Ont. clay belt (7) estimated yields were reduced by only 0.1 t/ha.

A precipitation increase of 20% resulted in no significant yield changes in the Annapolis V. (6), and the N. Ont. clay belt (7), but slight increases in yield of 0.6 t/ha or less for all other areas. Potatoes had the largest yield increases.

3.2 VARIABLE GSL

The effects of the temperature change scenarios on GSS, GSE and GSL using VARIABLE GSL are shown in Table 5 for each region selected. On average, the GSS is delayed and the GSE is advanced by about 6-7 days for each 1°C decrease in air temperature, although there are differences for some areas and some temperature scenarios. For example, in the Peace R. (5) area the difference between GSS for the +3°C and +2°C temperature scenarios is 5 days compared to 11 days for the -2°C and -3°C temperature scenarios. The GSL changes 12-15 days on average with a 1°C change in temperature, although it varies from 9 to 20 days for the range of scenarios selected. Temperature changes had the greatest effect on GSL for the Okanagan V. (2) and the Peace R. (5) (averaging 14.5 days/°C) and the least effect for S. Sask. (1), S. Ont. (4) and the Prairie fringe (3) areas (averaging approximately 11.7 days/°C).

The changes in growing season length resulting from changes in temperature have a significant effect on estimates of dry matter yield, particularly in those areas which already have marginal growing seasons (eg. the Peace R. (5) and the N. Ont. clay belt (7)).

It should be noted that the parameters GSS, GSE and GSL in Table 5 are based on the climatic data for each location. When calculating yields, a maximum limit was set to the GSL for each crop as shown in Table 1. The climatic GSL was used in the yield model unless the GSL exceeded these limits.

3.2.1 Cereal and oilseed yields. Decreased air temperature resulted in a sharp decline in yields of cereals and oilseeds in S. Sask. (1), Prairie fringe (3), Peace R. (5) and the N. Ont. clay belt (7) (Fig. 3F, G and H). The sharp decline in B_{ye} can partly be attributed to a significant shortening in GSL. In the warmer climates of S. Ont. (4) and the Okanagan V. (2), B_{ye} values tend to increase above normal values as temperatures fall below normal. In these areas the positive impact on estimated yield can be attributed to reduced moisture stress at cooler temperatures given no change in precipitation.

For above normal temperatures and no change in precipitation, yields decline below normal in all areas except the N. Ont. clay belt (7). Results indicate that increased moisture stress at higher temperatures has a greater negative influence on estimated yield that the positive effect of a longer growing season. In the shorter growing season areas (eg. Prairie fringe (3), Peace R. (5), N. Ont. clay belt (7)), yields peak near the 0 to +1°C temperature change at precipitation amounts ranging from 80% to 120% of normal. In the longer growing season areas (eg. Okanagan V. (2), S. Ont. (4)) the peak estimated yields were generally reached at negative temperature changes of -1 or -2°C (Fig. 3G and H) or not at all (Fig. 3F).

The negative effect of a +3°C temperature change on yield is entirely offset by precipitation increases of 40% above normal (Fig. 3I). For the -3°C temperature change scenario, no yields are indicated for S. Sask. (1), Prairie fringe (3), Peace R. (5), and the N. Ont. clay belt (7).

3.2.2 Potato yields. VARIABLE GSL predicts a sharp drop in B_{ye} of potatoes as temperatures decrease below normal values (Fig. 4) for all areas except the warmest regions (Okanagan V. (2) and S. Ont. (4)). Trends were very similar to those for cereals and oilseeds although the magnitude of the changes in yield were considerably greater. The sharp decline in yield is primarily attributed to the change in growing season length. Peak yields occurred between the 0 to +1°C temperature change except for the N. Ont. clay belt (7) where B_{ye} continued to increase as temperatures were increased by up to +3°C.

At temperature changes of -3°C, only the Okanagan V. (2), S. Ont. (4), and the Annapolis V. (6) indicated some yield potential (Fig. 4J), and only the warmest regions (Okanagan V. (2) and S. Ont. (4)) responded to changes in precipitation.

3.2.3 Forage yields. Changes in B_{ye} for forage tend to peak in most regions at temperatures of -2°C or more below normal (Fig. 5F, G and H), although changes in yields were considerably less than for cereals, oilseeds and potatoes. At below normal temperatures, yields tend to remain above normal for precipitation amounts 100% and 120% of normal. The reduced effect of low temperatures on forage yields in comparison to other crops is likely due to the relatively short growing season requirements (maximum 75 days) for the first cut of forages.

The response of yield to increasing precipitation (Fig. 5I and J) was similar to other crops. Yield responses to precipitation changes for S. Sask. (1), Prairie fringe (3), S. Ont. (4), Peace R. (5) and N. Ont. clay belt (7) were greater at high temperatures (+3°C) than low temperatures (-3°C). Yields were virtually unaffected by changes in precipitation at a temperature change of -3°C in the wettest areas (S. Ont. (4), Annapolis V. (6), N. Ont. clay belt (7)). The Okanagan V. (2) was the only region where yields continued to increase as precipitation amounts increased to 140% of normal at -3°C.

3.2.4 Corn yields. Table 5 indicates the available CHU for each temperature change scenario. On average, a 1°C temperature change results in a change of about 300-365 CHU's. Changes in CHU's tend to be somewhat greater for above normal temperatures and warmer areas than for below normal temperatures and cooler areas. With the assumption that grain corn can only mature in areas with an average of 2500 or more available CHU's, then a 1°C decrease in mean temperature would eliminate the potential for growing grain corn from all areas except S. Ont. (4) as shown in Table 6. Conversely, an increase in mean temperature of 1°C would expand grain corn production capability to the Annapolis V. (6); 2°C to N. Ont. clay belt (7); 3°C to the remaining areas (S. Sask. (1), Prairie fringe (3), Peace R. (5)). As mentioned earlier, the Annapolis V. (6) is indicated as having no potential for grain corn under normal climate conditions since the available CHU's in that area are slightly underestimated by the 100 km grid square data base.

Yield trends for corn are shown in Fig. 6. Yield trends are very similar to FIXED GSL. The negative effect of a +3°C increase in temperature on yield was not offset until precipitation increased to greater than 120% of normal. Corn yields decrease as temperatures increase due to higher moisture stress. This drop in yield occurs because GSL is set at a constant maximum of 130 days. If GSL was allowed to increase with warming to simulate longer growing season varieties, yields would likely increase.

3.2.5 Summary. A change in temperature of -1°C decreased yields for most crops (except forages) in the cool, short growing season areas (Table 8). Cereal and potato yields in these areas (Peace R. (5), N. Ont. clay belt (7)) were reduced by 1 t/ha or more. In warmer areas, (ie. Okanagan V. (2)) yields increased by up to 0.5 t/ha.

A +1°C temperature increase caused yields to be reduced generally by 0.5 t/ha or less. In the coolest areas (Peace R. (5), N. Ont. clay belt (7)) yields increased for some crops (cereals, potatoes) although rarely more than 0.5 t/ha.

A 20% decrease in precipitation caused yields to be reduced by more than 1 t/ha in some cases (eg. potatoes in the Okanagan V. (2), Prairie fringe (3), and the Peace R. (5)).

A precipitation increase of 20% resulted in greater yields in the drier/warmer areas (S. Sask. (1), Okanagan V. (2), Prairie fringe (3), N. Ont. clay belt (7)) but had a negative or no significant effect on yield in most cases for the Peace R. (5), Annapolis V. (6), and the N. Ont. clay belt (7).

4. CONCLUSIONS

4.1 Effect of a warming trend

Results from this study suggest that a rise in temperature with no change in precipitation would lower crop yields in most areas of Canada for the crops studied. Reduced yields are due to increased moisture stress at

TABLE 8: Changes in estimated dry matter yield (ΔB_{ye}) for ±1°C change in temperature and ±20% change in precipitation using VARIABLE GSL*.

Location	ΔYield (t/ha)					ΔYield (t/ha)				
	Ce	O	P	F	Cn	Ce	O	P	F	Cn
	A. ΔT=-1°C P=100%					B. ΔT=+1°C P=100%				
S. Sask.	-0.3	0.3	-0.1	0.7	-	0.1	-0.2	-0.1	-0.5	-
Okan. V.	0.5	0.5	0.3	0.5	-3.0	-0.4	-0.4	-0.5	-0.5	-0.6
Prairie f.	-0.4	0.2	-0.2	0.6	-	0.1	-0.3	-0.2	-0.5	-
S. Ont.	0.3	0.3	0.2	0.1	0.3	-0.3	-0.3	-0.6	-0.1	-0.3
Peace R.	-1.3	-0.5	-1.5	0.4	-	0.4	-0.2	0.2	-0.4	-
Annap. V.	0.1	0.1	-0.8	0.1	-	-0.2	-0.2	-0.2	-0.1	5.4
N. Ont. clay belt	-1.0	-0.4	-1.0	0.0	-	0.5	0.3	0.7	-0.2	-
	C. P=80% ΔT=0					D. P=120% ΔT=0				
S. Sask.	-0.5	-0.6	-0.8	-0.8	-	0.4	0.5	0.6	0.8	-
Okan. V.	-0.6	-0.6	-1.1	-0.8	-	0.7	0.8	0.9	0.7	-
Prairie f.	-0.8	-0.2	-1.1	-0.8	-	0.3	0.4	0.5	0.6	-
S. Ont.	-0.4	-0.4	-0.8	-0.1	-0.7	0.2	0.3	0.5	0.1	0.5
Peace R.	-1.0	-1.0	-1.4	-0.8	-	-0.1	0.0	-0.1	0.5	-
Annap. V.	-0.2	-0.2	-0.8	0.0	-	0.0	0.0	-0.3	0.0	-
N. Ont. clay belt	-0.4	-0.2	-0.4	-0.3	-	-0.3	-0.1	-0.2	-0.1	-

*Change in yields for precipitation changes at ΔT =0 were estimated by interpolation from ΔY at ±1°C.

Ce = cereals, O = oilseeds, P = potatoes, F = forage, Cn = corn higher temperatures. The negative effect of warming temperatures on yield is enhanced if accompanied by a decrease in precipitation and reduced if precipitation increases to above normal values.

A few exceptions to the above yield trends were noted. For example, potato yields in the N. Ont. clay belt (7) increased with longer GSL caused by an increase in temperature (Table 5, Fig. 4). For corn, land areas suitable for production could expand northward in Ontario by 60 to 100 km for each 1°C rise in temperature, subject to soil limitations. Similarly, the land areas suitable for grain corn production would expand in other humid regions of Canada which presently have insufficient heat units for present-day hybrids to reach maturity.

4.2 Effect of a cooling trend

Results show varying effects on estimated yield due to cooling. If GSL does not change, estimated yields of all crops (except corn) increase in the drier/warmer areas at normal precipitation levels. This effect is likely due to a reduction in moisture stress. Conversely, in the cooler/wetter areas there is little or no effect on estimated yield.

A reduced GSL results in large reductions of the estimated yield for all crops except the first cut of forages, and in all areas except those with long GSL's (ie. Okanagan V. (2) and S. Ont. (4)).

Assuming a minimum requirement of 2500 CHU's, a 1°C decrease in temperature accompanied by a shorter GSL would eliminate grain corn in all areas except in S. Ont. (4). A 3°C decrease in temperature would eliminate the potential for grain corn from all areas of Canada.

4.3 Effect of changing precipitation

Yields tend to increase as precipitation increases. Yields typically change by 0.5 to 0.8 t/ha for a 20% change in precipitation at normal temperatures. At 3°C below normal, yields are significantly affected by precipitation changes only in drier areas(ie. S. Sask. (1), Okanagan V. (2)). At temperatures above normal, yield is significantly influenced by precipitation in all areas although the effect is greatest in the driest regions.

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