Quantification of Spatial and Temporal Changes in Wheat Yields

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1. Introduction

Crop yield and crop yield variability are two of the five important criteria for sustainable land management (Smyth and Dumanski 1993). While average crop yields are often used to assess yield performance, this is not particularly useful for evaluating sustainable farming systems. This is because average yields represent a long-term normal, without providing information on performance changes over time. Sustainability requires information on yield trends, to assess whether yields are stable or increasing thereby contributing to sustainability, or whether they are negative and thereby signaling probable failure sometime in the future. Information is also required on trends in yield variability to assess whether the risk of crop production is stable, increasing or decreasing.

Trends in yield and variability (risk) do not change synchronously. The best situation occurs when yields are increasing and variability is decreasing; this is a strong signal that crop production technologies are contributing towards sustainability. Conversely, if yields are decreasing and variability is increasing, then obviously the system will fail, probably in the not too distant future.

Over the past forty to fifty years, dramatic increases in yields of most crops have been observed in Canada. These increases can be attributed to improved plant breeding techniques, resulting in better varieties, and improved soil and crop management practices such as increased fertilizer application, better weed and pest control, etc. However, 'recent' yield declines have been observed in some corn yield trends (Dumanski et al. 1986) for Southern Ontario and yields first increasing and then leveling off as observed for spring wheat trends in Western Canada (Stewart and Dwyer 1990b). These constant yields or yield decreases with time may well be an indication of soil degradation problems. Yield trends with time could be an important indicator of soil health and whether technology and management improvements are reaching a limit.

Because weather can induce such large year to year variations in yield, particularly in Western Canada, it often obscures the yield trends caused by other factors. Much of this weather variation can be removed using mathematical models and by plotting residuals (differences between measured yields and model calculations) against time. This has been done with linear regression (Dumanski et al. 1996) and deterministic models (Stewart and Dwyer 1990b).

The objectives of this study were (i) calculate and map changes in spring wheat yield and yield variability and (ii) separate the effects of long-term weather from management practices using the large area spring wheat model of Stewart and Dwyer (1990a).

2. Methodology

2.1 Agroecological Resource Areas (ARA's)

The agricultural portion of the Canadian prairies is divided into ARA's to provide a natural, ecologically based framework for regional agricultural land evaluation (Shields et al. 1991). ARA's are distinguished by dominant (or consistent combinations of) characteristics of agroclimate, surface form, soil texture and soil development. Thus the agricultural potential, land use and management can be considered fairly similar throughout an ARA. Data files associated with the ARA's include compiled data on soil, landuse, landform, regional climate and farm economics (Kirkwood et al. 1993).

2.2 Crop Insurance Yield Data

Records maintained by the Manitoba Crop Insurance Corporation (MCIC) were accessed to evaluate trends in yield and yield variability. The records include comprehensive data on yield, farm management practices and bio-physical data on a legal subdivision basis for each subscriber since 1960. The records were overlaid onto an ARA map using the ARC/Info geographic information system, to geo-reference them correctly.

Records were selected from the data base according to the following criteria:

- Spring wheat (Triticum aestivum L.) was chosen as the test crop.
- Management practices were standardized such that:
  - yields from stubble seeded and summer fallow seeded fields were kept separate
  - the level of nitrogen fertilizer application was 45 to 110 kg N ha^{-1}.
- Only years with 10 or more observations meeting the above criteria were included.

Average annual yields and their coefficient of variation (CV) were calculated for each ARA. Trends were calculated by linear regression of yield and CV against time with the trend being the slope of the regression line. The results were mapped at the ARA level at a scale of 1:2 million, using the ARC/Info geographic information system.

2.3 Modeling

The observed trends in Crop Insurance yield data with time were further analyzed in four selected ARAs representing a wide range of growing and farm management conditions in Manitoba (Table 1). Representative soil types and their physical profile characteristics (bulk density, soil water content at field capacity and at the wilting point) were obtained by using a cross tabulation file which links the ARA polygon map to the Soil Names and Soil Layer Files of the Canadian National Soil Data Base. Daily weather data, including maximum and minimum air temperatures and precipitation were derived for each ARA using the Thiessen polygon weighting technique (Williams and Hayhoe 1982). The technique was applied to a network of stations with the weighting coefficients checked by local experts and, when necessary, adjusted based on non-representative station elevations.

Table 1. General characteristics of the four selected Agroecological Resource Areas (ARAs).

	ARA 10	ARA 12	ARA 34	ARA 35
Centroid location (lat/long)	49°43'/99° 33'	50°12'/100°19'	49°45'/97°51'	49°45'/97°25'
Area (km^2)	3429	8303	2590	9198
Growing season precipitation deficit (mm)	263	245	272	254
Growing season length (days)	180	173	184	184
Wheat as a % of cropland	13	31	27	26
Dominant soil type	Stockton	Newdale	Gnadenthal	Red River
Texture	Sandy loam	Loam	Clay loam	Clay
Drainage	Well	Moderately well	Imperfectly	Poorly

The wheat growth model of Stewart and Dwyer (1990a) was used to calculate above ground dry matter accumulation(G) on a day-to-day basis:

$$\frac{dG}{dt} = \Delta G = a_1 F_S F_W L_A - R$$

where a_1 is an ARA specific empirical calibration coefficient, F_S is the daily solar radiation, F_W is a water stress function, L_A is the leaf area index and R is a respiration function based on the mean daily air temperature (see Stewart 1981). Daily solar radiation was estimated from daily maximum and minimum air temperatures and precipitation using the equations derived by De Jong and Stewart (1993).

The water stress function was the ratio of actual to potential transpiration, AT/PT. Potential evapotranspiration (PET) was calculated from Baier and Robertson (1965) and Baier (1971), using only maximum and minimum air temperatures and daily solar radiation at the top of the atmosphere (Robertson and Russelo 1968) as input. PET was divided into potential transpiration and potential soil evaporation by a leaf area index function (Ritchie and Burnett 1971). Actual transpiration (AT) was calculated from a complex soil-plant-atmosphere resistance analog model and a three layer soil water budget described in detail by Stewart and Dwyer (1986) and Stewart and Dwyer (1990a). Downward water transfer between soil layers occurred mainly by simple overflow. Daily values of precipitation were added to the top layer and if its water content exceeded field capacity the excess flowed into the second layer. Similarly, water could flow from the second into the third layer and beyond the root zone, the latter becoming unavailable for the crop. Water was also allowed to diffuse between layers using the hydrological functions of Clapp and Hornberger (1978) and a finite difference form of the diffusion equation in which a sink term accounted for crop water uptake, i.e. actual transpiration. A soil-crop resistance analogue was then used to calculate leaf water potential and actual transpiration (Stewart et al. 1985a and b).

Leaf area expansion was a function of leaf water potential which was calculated in the model four times a day using an air temperature function. In previous work, the temperature function was an Arrhenius type from Rickman et al (1975), but in this study the rate of leaf expansion was set at zero at temperatures $<5^0$C, after which it increased linearly at a rate of 0.18 cm^2 $^0C^{-1}$ under optimum soil water conditions. This promoted more leaf growth at lower temperatures than the Arrhenius equation and significantly improved estimates of yield.

Eq. 1 was solved by simple trapezoidal integration using a daily time step. The model ran over each growing season generating leaf area and biomass. Routines to calculate initial spring (May 1) soil moisture values and seeding dates, as a function of surface soil water contents (Stewart and Dwyer 1990a) were incorporated into the model. Phenological development was determined from air temperatures using a biometeorological time scale (Robertson 1968). Total above ground biomass on day n was calculated as:

$$G_n = \sum_{j=1}^{n} \Delta G_j \Delta t$$

where Δt is a time step of one day. After heading, dry matter was translocated to the ears and ear dry weight was calculated as:

$$D_i = 0.33 G_h + a_2 \sum_{j=1}^{m} \Delta G_j$$

where G_h is the above ground biomass at heading, m is the number of days from heading to soft dough and a_2 is an empirical coefficient.
The unique aspect of this approach was our ability to fit the complex deterministic model to MCIC yield data to determine a small number of coefficients using least squares. This was made possible by using numerical differentiation and Marquardt's algorithm (Marquardt 1963). The complete model can be represented by:

$$Y = M(a_1, a_2, a_3)$$

where Y is the estimated modelled yield, M is the deterministic portion of the model and coefficients a_1, a_2 and a_3 are associated with biomass formation, translocation and harvest losses respectively.

3. Results and Discussion

3.1 Average Yields and Trends

Because Manitoba has a humid-continental climate, not many fields are left in summer fallow. Consequently, the province wide analysis of average yields and trends will be restricted to stubble seeded spring wheat. Moreover, many ARAs were not reporting spring wheat yields during the 1960s and consequently the long-term averages (Fig. 1) and trends (Figs. 2 and 3) refer to the 1970-1989 period.

The average yields ranged from 1650 kg ha^{-1} in ARA 1 to nearly 2400 kg ha^{-1} in ARA 36. Generally, the lowest yields were reported on the sandier soils in the driest, southwestern part of the province (approximate average growing season precipitation deficit is 290 mm), while the higher yields were reported on finer textured soils with less drought stress (e.g. average growing season precipitation deficit in ARA 35 is 254 mm).

Spring wheat yield trends (Fig. 2) were generally stable or increasing at an average rate of 15.9 kg ha^{-1} in 18 out of 25 ARAs. Decreasing yield trends were observed in ARAs with average yields less than 2000 kg ha^{-1}, with significant decreases (slope < -20 kg ha^{-1}) in ARAs 1 and 11. There was a statistical significant relationship (r = 0.64 with n = 25) between average yield and trend in yield. Yield variability was low, varying from 20 to 32% (data not shown). The low yield variability was probably due to the fact that nutrient and moisture stresses affecting yield were, at least partly, eliminated, because the records were from stubble seeded fields which received 45-100 kg fertilizer nitrogen per hectare. Trends in variability (Fig. 3) were fairly stable throughout the province, except in the southwestern corner, where the variability increased by approximately 0.9% yr^{-1}. A significant negative correlation (r = -0.75 with n = 25) was found between trends in wheat yield and wheat yield variability.

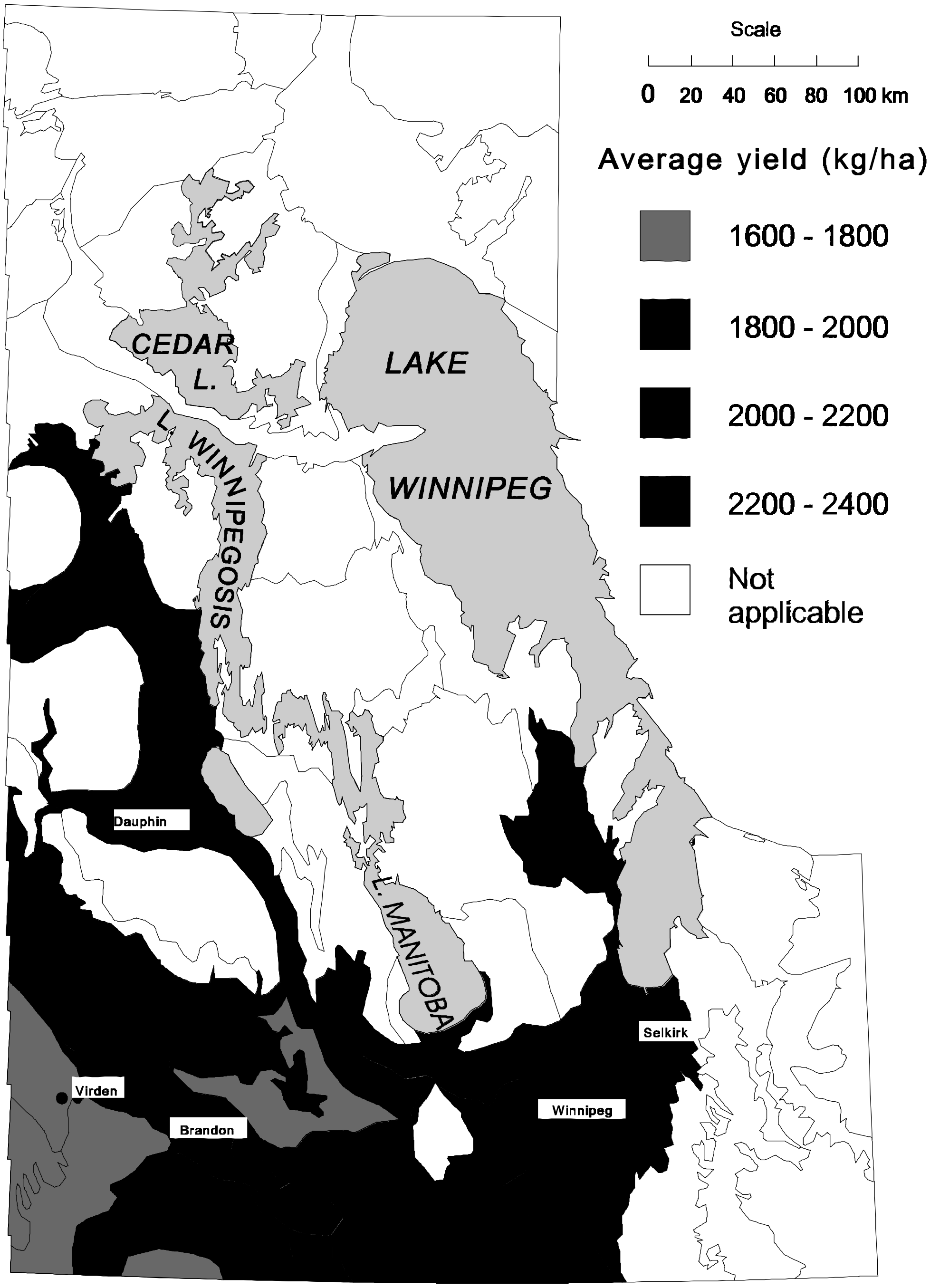

Figure 1. Long-term average wheat yields, 1970 – 1989.

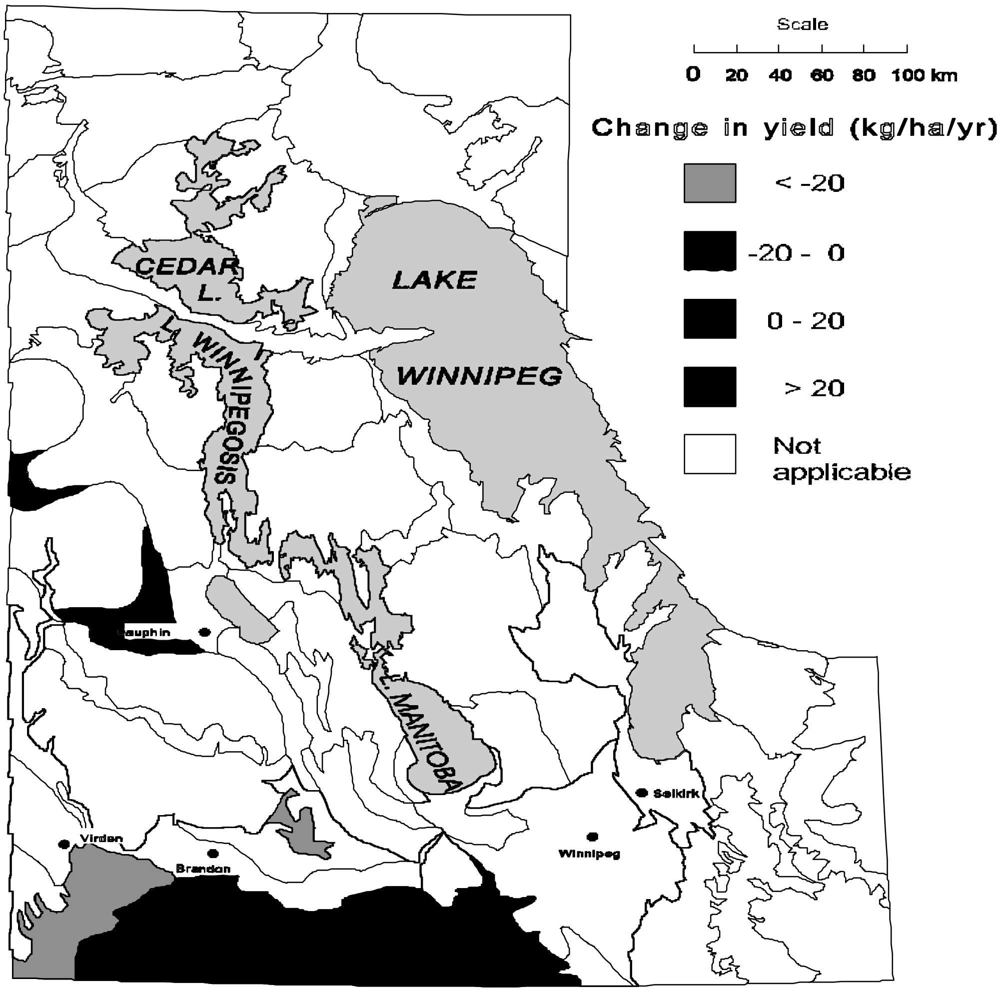

Figure 2. Annual change in yield, 1970 – 1989.

3.2 Modeled yields in ARAs 10, 12, 34 and 35

The model fitted the MCIC yield data in the four selected ARAs reasonably well with correlation coefficients varying from 0.55 to 0.82 (Table 2). Small underpredictions of yield occurred in ARAs 10 and 12 (relative error approximately -4%), and overpredictions were made for ARAs 34 and 35. The latter ARAs are characterized by imperfectly drained, clayey soils on level to very gently sloping topography (Table 1), and consequently abnormally low yields occur during years with excessive precipitation. Because the model does not account for moisture excess or flooding during periods of the growing season, it would overpredict yields in wet years.

One of the implicit model assumptions is that soil and crop management practices remain the same during the simulation period. Also, no soil degradation nor soil improvements take place. Hence, any trend in modelled yields must be attributed to trends in weather conditions. The modelled wheat yields did not change significantly ($P<0.01$) with time indicating that the weather conditions in the four ARAs neither deteriorated nor improved for grain growing conditions during 1964 to 1989. The observed yields in ARA 10 and 12 also remained stable, which raises the question of whether potential yield increases from technological advancements, like increased fertilizer use improved varieties, better weed and pest control, etc., is being offset by soil degradation problems. In ARAs 34 and 35 the modelled yields tended to decrease, but not significantly, and the observed yields increased during the period of investigation. Hence, the slightly worsening weather conditions, and possible deteriorating soil conditions, were offset by positive technological advances.

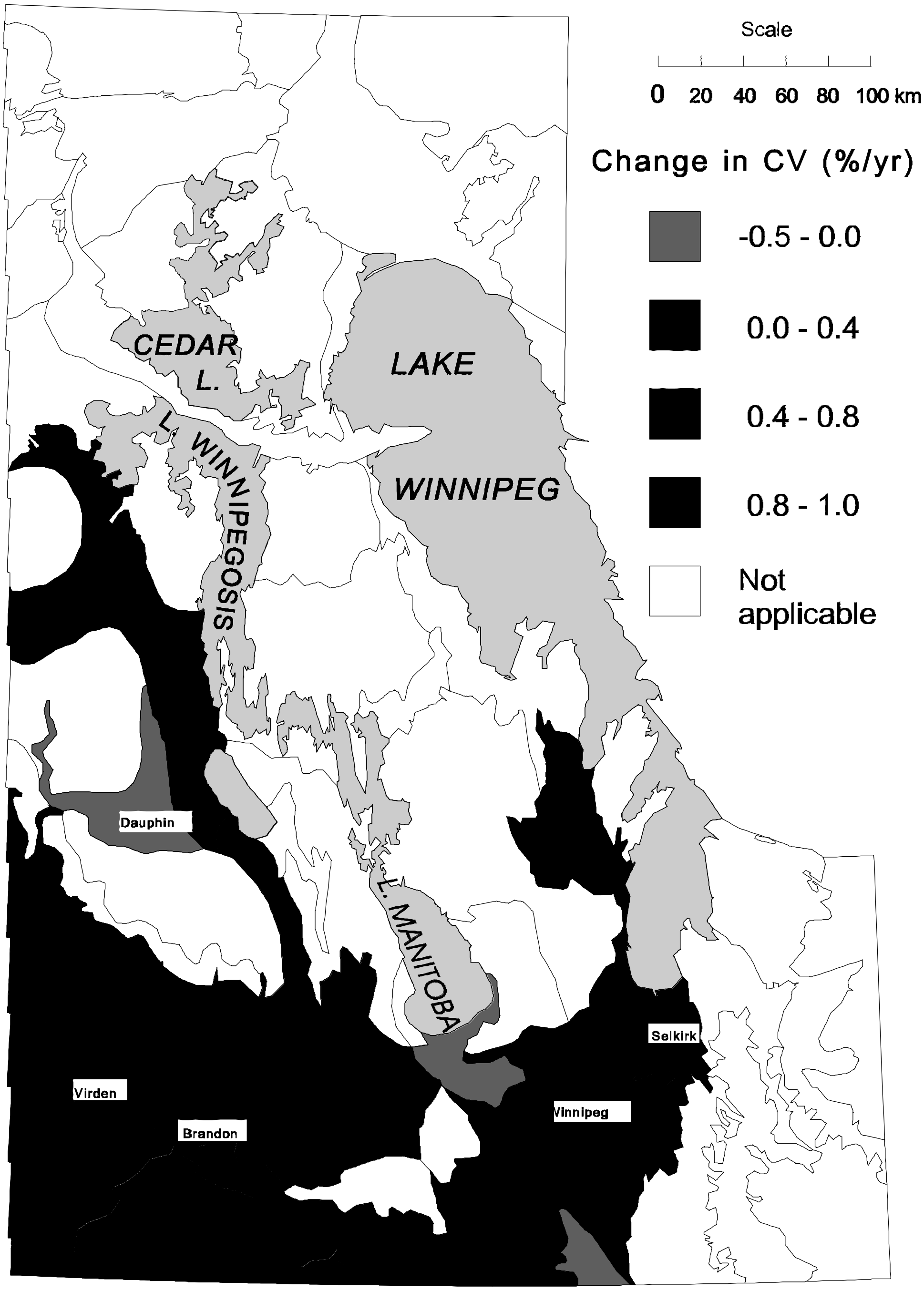

Figure 3.Change in CV (%/yr) of wheat yields, 1970 – 1989.

Table 2 A statistical comparison of modelled yields and Crop Insurance observed yields.

ARA	Number of years	Correlation coefficient	Root mean square error (kg ha^{-1})	Relative error (%)
10	22	0.82	233.3	-4.2
12	24	0.77	229.3	-3.6
34	26	0.73	425.4	10.5
35	24	0.55	650.3	21.7

Further investigations are required to elucidate the effects of technological changes and soil degradation upon wheat yield trends. It is envisioned that more comprehensive 'all inclusive' models, like for example EPIC (Williams 1995), CERES (Ritchie and Otter 1985) and CropSyst (Stockle et al. 1994) which integrate all the major processes in the soil-crop-atmosphere-management system, can be used. However, while these models tend to do well in simulating one particular aspect of the system, none of them accurately mimics the complexity of the real world (see e.g. Pfeil et al. 1992; Moulin and Beckie 1993; Diekkruger et al. 1995) and local testing and calibrating will be required prior to using these models.

4. Conclusions

In most of Manitoba spring wheat yields are stable or increasing and yield variability trends are stable, signifying that sustainable land management practices are in place. However, a less rosy picture emerges in the drier areas of the province and in ARAs with sandy soils. Here, the impact of land management upon sustainability should be monitored closely. Weather conditions have not affected the long term trends in spring wheat yields. The effect of technological advances and soil degradation on yield trends remain to be investigated.

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6. References

Baier, W. 1971. Evaluation of latent evaporation estimates and their conversion to potential evaporation. Can. J. Plant Sci. 51:255-266.

Baier, W. and G.W. Robertson. 1965. Estimates of latent evaporation from simple weather observations. Can. J. Plant Sci. 45:276-284.

Clapp, R.B. and G.M. Hornberger. 1978. Empirical equations for some soil hydraulic properties. Water Resour. Res. 14:601-604.

De Jong, R. and D.W. Stewart. 1993. Estimating global solar radiation from common meteorological observations in western Canada. Can. J. Plant Sci. 73:509-518.

Diekkruger, B., D. Sondgerath, K.C. Kersebaum and C.W. McVoy. 1995. Validity of agroecosystem models: a comparison of results of different models applied to the same data set. Ecol. Modelling 81: 3-29.

Dumanski, J., A. Bootsma and V. Kirkwood. 1986. A geographic analysis of grain corn yield trends in Ontario using a computerized land information base. Can. J. Soil Sci. 66: 481-497.

Dumanski, J., R. De Jong, A. Bootsma and M. Brklacich. 1996. Crop production risk as a factor in sustainable land management. In: Data Reliability and Risk Assessment in Soil Interpretations. SSSA Special Publication Number 47, Soil Sc. Soc. of Amer. Inc., Madison, Wisconsin, USA.

Kirkwood, V., A. Bootsma, R. De Jong, J. Dumanski, J.C. Hiley, E.C. Huffman, A. Moore, C. Onofrei, W.W. Pettapiece and B. Vigier. 1993. Agroecological resource area databases for the prairies: user's manual. Tech. Bull. 1993-13E, Research Branch, Agric. Canada, Ottawa, On. 21pp.

Marquardt, D.W. 1963**.** An algorithm for least squares estimation of non-linear parameters. J. Soc. Ind. App. Math. 11:431-441.

Moulin, A.P. and H.J. Beckie. 1993**.** Evaluation of the CERES and EPIC models for predicting spring wheat grain yield over time. Can. J. Plant Sci. **73**: 713-719.

Pfeil, E. v., W. Hundertmark, F.D. Thies and P. Widmoser. 1992. Calibration of the simulation model "Ceres Wheat" under conditions of soils with shallow watertable and temperate climate. Part 1: Limitations in the applicability of the original model and necessary modifications. Z. Pflanzenernahr. Bodenk. **155**: 323-326.

Rickman, R.W., R.M. Ramig, and R.R. Allmaras. 1975. Modeling dry matter accumulation in dry land wheat. Agron. J. 67:283-289.

Ritchie, J.T. and E. Burnett. 1971. Dryland evaporative flux in a subhumid climate plant influence. Agron. J. 63:56-62.

Ritchie, J.T. and S. Otter. 1985**.** Description and performance of CERES-Wheat: a user-oriented wheat yield model. USDA-ARS, ARS **38**: 159-175.

Robertson, G.W. 1968**.** A biometeorological time scale for a cereal crop involving day and night temperatures and photoperiod. Int. J. Biometeor. 12:191-223.

Robertson, G.W. and D.A. Russelo. 1968**.** Astrometeorological estimator for estimating time when sun is at any elevation, elapsed time between the same elevations in the morning and afternoon, and hourly and daily values of solar energy, Q_o. Ag. Met. Tech. Bull. 14. Agrometeorology Section, Plant Res. Inst., Can. Dept. Of Agric., Ottawa.

Shields, J.A., C. Tarnocoi, K.W.G. Valentine and K.B. MacDonald. 1991**.** Soil landscapes of Canada: Procedures manual and user's handbook. Agric. Canada Publ. 1868/E. Communications Branch, Agric. Canada, Ottawa.

Smyth, A.J. and J. Dumanski. 1993. FESLM: An International Framework for Evaluating Sustainable Land Management. A Discussion Paper. World Soil Resources Report 73. Food and Agriculture Organization, Rome. 74pp.

Stewart, D.M., L.M. Dwyer and R.L. Desjardins. 1985(a). A mathematical model of transpiration using non-linear least squares analysis. Can. Agric. Eng. 27:1-6.

Stewart, D.M., L.M. Dwyer and R.L. Desjardins. 1985(b). The effect of available soil water and root density on actual and potential transpiration relationships. Can. Agric. Eng. 27:7-11.

Stewart, D.W. and L.M. Dwyer. 1986. Development of a growth model for maize. Can. J. Plant Sci. 66:267-280.

Stewart, D.W. and L.M. Dwyer. 1990(a). A model of spring wheat (Triticum aestivum) for large area yield estimations on the Canadian prairies. Can. J. plant Sci. 70:19-32.

Stewart, D. W. and L.M. Dwyer. 1990(b). Yields and protein trends of spring wheat (Triticum aestivum) on the Canadian prairies, 1961-1982. Can J. Plant Sci. 70:33-44.

Stewart, R.B. 1981**.** Modeling methodology for assessing crop production potentials in Canada. Tech. Bull. 96, Research Branch, Agriculture Canada, Ottawa. Ont. 29pp.

Stockle, C.O., S.A. Martin and G.S. Campbell. 1994. CropSyst, a cropping systems simulation model: water/nitrogen budgets and crop yield. Agric. Systems **46**: 335-359.

Williams, J.R. 1995. The EPIC model. In: V.P. Singh (ed.) Computer Models of Watershed Hydrology. Water Resources Public., Littleton, Colorado.

Williams, G.D.V. and H.N. Hayhoe. 1982. Computing and mapping Thiessen weighting factors from digitized boundaries and climatological station latitudes and longitudes. J. Appl. Meteorol. 21: 1563-1566.