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Testing the Broom's Barn Sugar Beet Growth Model with Crops Grown in Sweden

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Introduction

Many factors are known to influence sugar yield. These factors can be broadly grouped into physical environment, biological factors and agronomic practices. The Broom's Barn sugar beet growth model accounts for the environmental effects of temperature, rainfall, solar radiation, evapotranspiration and soil available water holding capacity. It, however, does not account for any effect of the biological factors such diseases, pests, weeds and varieties. It can account for the effects of sowing and harvesting date and irrigation, but ignores the effects of other agronomic factors such as crop population, harvesting loss, nutrition and soil pH variation.

The Broom's Barn sugar beet growth model is process-based and weather driven whereby the total crop growth and sugar yield are integrated at daily time intervals, assuming a crop population density of ≥75,000 per hectare. In order to simulate the crop growth and yield, the required inputs include the date of sowing and harvesting, soil available water holding capacity and the daily values of temperature, solar radiation, rainfall and potential evapotranspiration.

Under the water stress free conditions which define the potential growth and yield, solar radiation and temperature become the two main variables to determine the dry matter increase and sugar yield. The model calculates the daily crop foliage cover, canopy intercepted radiation, net total dry matter production and its partitioning into sugar. The model uses a potential radiation use efficiency which is adjusted daily by the total dry matter as the crop canopy ages. The radiation use efficiency (RUE) is also adjusted daily to make an allowance for the average brightness of the sunlight. This is estimated as the fraction of diffuse light which is calculated knowing the daily global radiation receipt, the day number of the year and the latitude of the site (Spitters *et al.* 1986). To account for the effects of soil water stress, a simple soil water balance model for a free draining soil profile is coupled to the growth model, tracking the daily amount of soil available water within the actual rooting zone, assuming a maximum rooting depth of 150 cm. Therefore, the potential radiation use efficiency is further reduced in proportion to the ratio between actual and potential crop evapotranspiration.

The objectives of this exercise are: to use the Broom's Barn sugar beet crop simulation model to simulate growth, development and yield in 24 fields in southern Sweden and to compare the output with observations made in those fields; to tune the model, based on the simulations above and any other growth and weather data that may be available, so that it can be used to forecast sugar beet productivity in Sweden.

Materials and methods

Sugar yields from crops harvested in each of three designated fields at Uppåkra (Farm1), Vragerup (Farm3), Bramstorp (Farm11) and Groeholm (Farm13) in 1999 and 2000 are used to test the Broom's Barn sugar beet growth simulation model. The required daily records of temperature, solar radiation, rainfall and potential evapotranspiration were obtained from Ädelholm to represent the weather conditions experienced by crops at Farm1 and Farm3 and from Jordberga to represent the weather conditions at Farm11 and Farm13. The latitude is 55.61˚N at Ädelholm and 55.31°N at Jordberga.

Climate data

The monthly average maximum and minimum temperature and the monthly total solar radiation, rainfall and potential evapotranspiration are shown in Table 1 at Ädelholm and in Table 2 at Jordberga. There are noticeable differences in rainfall between years and between solar radiation receipts between sites.

Soil available water content (SAWC)

Soil water content has been measured in laboratory for soil layers of 15-20, 30-35, 45-50 and 85-90 cm at soil water tensions of 0.005, 0.1, 0.6, 5 and 15 bar for each field at every farm in 1999 and 2000. In the Broom's Barn sugar beet growth model, SAWC is defined as the difference between soil water contents at 0.05 and 15 bar. So, an exponential curve was fitted to the data for each layer to estimate the soil water content at 0.05 bar (Figure 1). Then, the overall average soil water contents within the four soil layers are calculated at 0.05 and 15 bar and SAWC is accordingly calculated (Table 3). These are the SAWC that are used in testing the Broom's Barn sugar beet growth model. Table 3 also shows the SAWC calculated using soil water content between 0.1 and 15 bar.

Sowing and harvesting dates

Table 4 shows the sowing and harvesting dates for each field at each farm in 1999 and 2000. These data are used in the sugar beet growth simulation model.

Indicator of the model performance in the simulated sugar yields

The root mean squared error (RMSE) is calculated to indicate the model's goodness of fit. It measures the scatter of observations around the 1:1 relationship line and is calculated as below:

$$RMSE = \sqrt{\frac{1}{n}\sum (O_i - P_i)^2}$$

where n, O_i and P_i are the number of observations, the observed and simulated sugar yields, respectively.

Results

The Broom's Barn sugar beet growth model can simulate the crop growth and yield with and without the effects of soil water stresses. When soil water stress effects are not incorporated, the model simulates the potential crop growth and sugar yield as they are determined only by solar radiation and temperature. However, when soil water stress effects are incorporated, the model simulates the obtainable crop growth and sugar yield as they are determined by solar radiation, temperature, rainfall/irrigation, potential evapotranspiration and soil available water in the rooting zone.

Figure 2 shows the simulated obtainable sugar yield versus the harvested sugar yield in different fields at each farm in 1999 and 2000. Clearly, except farm3 and farm13 in 2000, most other fields exceeded the simulated sugar yields. Figure 3 shows the ratio of harvested sugar yield by simulated sugar yield, which indicate the extent the harvested sugar yield outperformed the simulated sugar yield. In several fields the harvested sugar yields were higher than the simulated sugar yields by more than 20%.

Figure 4 shows the simulated potential sugar yield against the harvested sugar yield in different fields at various farms in 1999 and 2000. Overall, there is a sizable reduction in the model's performance indicator - *RMSE* at all four farms. So, the harvested sugar yields seem to be more a reflection of the simulated potential sugar yields (i.e. crops grown without any water stress). The ratio of harvested sugar yield by the simulated potential sugar yield is shown in Figure 5. Still, Some of the fields produced yields equal to or higher than the simulated potential sugar yields (i.e. the ratio $\geq$1).

Figure 6 and 7 show the actual measurements of foliage cover in relation to the simulated foliage developments in each field on all four farms in 1999 and 2000, respectively. On the whole the observations corresponded remarkably well with the simulated foliage developments. However, closer examinations indicated that (1): the early foliage cover development was more rapid than the model simulated (e.g. on farm3 and farm11) in 1999; (2) it is difficult to know how the foliage cover developed after it reached the maximum foliage cover because of lacking measurements in the later part of the crop growing season.

Discussion

Comparison of the harvested sugar yield with the simulated sugar yield suggests that sugar beet crops are so well grown and produce admirably high yields relatively to the growing conditions in the UK. It is difficult at this stage to know exactly either the variations in the natural growing conditions or the differences in the agronomic practices that cause this disparity.

The Broom's Barn sugar beet growth model assumes a crop population $\geq$75,000/ha and the maximum rooting depth of 150 cm. Table 5 shows the observed maximum rooting depth and final plant population per hectare in each field at each farm in 1999 and 2000. All fields but one (at farm11 in 2000) had plants with maximum rooting depth of less than 150 cm. However, the great majority of fields had a crop population $\geq$75,000/ha. So, we do not think these factors are the reasons for higher yields observed in **T**he **T**en **T**on **T**arget (4T) project.

In the UK, the major sugar beet growing areas lie in the latitude of around 52°. The latitude of the four farms reported here is around 55° in Sweden. As shown in Figure 8, the day length is longer during the sugar beet growing period in Sweden than in the UK. The longer day length can lead to a higher daily solar radiation and/or a more efficient conversion rate of canopy intercepted radiation. The latter hypothesis needs to be tested with sequential measurements of total dry matter and crop foliage cover. In the Broom's Barn model, average potential radiation use efficiency is estimated at 1.8 g MJ^{-1} and it is adjusted by the daily proportion of diffuse radiation each day in the crop growing period and by the crop dry matter as the crop canopy ages.

The Broom's Barn model simulates a sugar beet crop that is sown at a row spacing of 50 cm. The 50% seedling emergence date occurs when an accumulated thermal time reaches 120°Cd, with a base air temperature T_b=3°C. We have seen in the Summary Report of 4T project that the thermal time needed to reach 45,000 plants per hectare ranges from 108 to 122°Cd. So on the whole, this difference is not significant. We have also noted that in the statistical yield model described in the 4T report, the sowing date is one of the important yield determinants. We have simulated the sowing date effect in April 2000 in field 1 at Farm1 assuming a common harvesting date, on 31 October 2000 (Figure 9a). Within the sowing date range of 1 to 30 April, the total yield reduction is around two tons per hectare. Depending on the prevailing temperature, the reduction in sugar yield is more in late than in early part of the April, suggesting that crop emergence date may be a more reliable indicator for the effects of sowing date on sugar yield. We were surprised that the statistical yield model has not included harvesting date as one of the yield determining variables. Again, we have simulated the harvesting date effect on sugar yield in October 2000 in field 1 at Farm1 assuming a common sowing date of 10 April 2000 (Figure 9b). Within the harvesting date range of 1 to 30 October, the total sugar yield increase can reach around two tons per hectare. The extent of this yield increase will depend on the prevailing radiation conditions during October.

A harvested sugar yield that was larger than the simulated could be due to early crop foliage development that was more rapid than was predicted and late crop foliage development that declined at a slower rate than the model applied. Figure 6 and Figure 7 definitely indicate something that needs our attention in the future.

We have been aware that beet root yields were estimated through crop samples both in July and August in the database. We would like to know on what dates these crop samples were taken and what were the estimated sugar and total crop dry matter yields. These data together with the sequential crop foliage cover measurement, might enable us to improve the validity of the Broom's Barn growth model under Swedish conditions.

Figures 10-15 show the changes in important variables simulated over time in different fields at each farm in 1999 and 2000. These have been plotted in order to facilitate discussion when we meet to try to find adjustments to the model to improve its robustness (i.e. goodness of fit of the model).
Figure 10 shows the crop total dry matter and sugar yield increases after sowing in field 1 at different farms in 1999 and 2000. These are achieved through the corresponding crop foliage cover development (Figure 11a), rooting depth increases (Figure 11b), accumulated thermal time (figure 12a), accumulated canopy intercepted

solar radiation (Figure 12b), soil moisture deficit changes (Figure 13a) and actual crop evapotranspiration (Figure 13b). Soil moisture deficit is calculated as the amount of water needed to fill the soil to its field water holding capacity.

Similar simulated patterns also occurred in field 2 and field3 at different farms and those for total crop dry matter production and sugar yield are shown in Figure 14 and in Figure 15.

Conclusions

As the Broom's Barn sugar beet growth model currently stands, some fields (particular those from farm11) outperformed the simulated potential sugar yield. Investigations are therefore needed first to identify what contributed to those extra-ordinary beet yields. Then we may be able to adapt the Broom's Barn model to improve its performance. At this stage we start to feel optimistic about its prospects. Examining the observations collected in the 4T project indicates that some data can be used to test and calibrate the individual component in the Broom's Barn model. However, extra information needs to be provided before further work can be carried out.

Our impression with the weather records at Ädelholm and Jordberga in 1999 and 2000 suggests that the solar radiation is more variable than we thought. So, apart from variations in rainfall and temperature, the appreciable variation in solar radiation across sites would compound the evaluation of growers' skills in managing sugar beet crops. We believe that both the sowing date (more precisely the seedling emergence date) in April and the harvesting date in late September or October have an appreciable effect on sugar yield.

References

Spitters, C.J.T., Toussaint, H.A.J.M. and Goudriaan, J. (1986). Separating the diffuse and direct component of global radiation and its implications for modelling canopy photosynthesis. Part I. components of incoming radiation. Agricultural and forest meteorology, 38: 217-229.

Table 1 The monthly mean maximum (Max T) and minimum (Min T) temperatures together with the monthly total radiation, rainfall and potential evapotranspiration (PET) in 1999 and 2000 at Ädelholm, Sweden.

Year	Month	Max T (°C)	Min T (°C)	Radiation (MJ)	Rainfall (mm)	PET (mm)
1999	April	12.6	3.7	373.2	9.4	53.3
	May	15.3	5.7	565.5	37.9	89.5
	June	18.6	9.7	628.4	58.5	94.9
	July	22.8	12.6	642.7	43.6	112.0
	August	22.0	11.5	493.7	181.1	86.5
	September	20.3	11.4	365.2	42.8	58.6
	October	12.0	6.0	169.3	52.4	28.9
	Sum	**-**	**-**	**3238.0**	**425.7**	**523.7**
2000	April	13.4	4.1	435.6	40.0	62.1
	May	18.7	7.4	654.4	37.4	107.4
	June	18.3	10.4	601.4	48.6	94.7
	July	19.3	11.3	521.0	55.6	81.1
	August	20.4	11.0	457.8	51.6	75.6
	September	17.1	9.1	325.6	79.2	48.6
	October	14.2	8.5	131.3	61.6	19.6
	Sum	**-**	**-**	**3127.1**	**374.0**	**489.1**

Table 2 The monthly mean maximum (Max T) and minimum (Min T) temperatures together with the monthly total radiation, rainfall and potential evapotranspiration (PET) in 1999 and 2000 at Jordberga, Sweden.

Year	Month	Max T (°C)	Min T (°C)	Radiation (MJ)	Rainfall (mm)	PET (mm)
1999	April	11.4	3.8	435.6	51.2	54.0
	May	14.4	5.9	658.3	53.0	91.0
	June	18.2	10.7	707.5	46.1	102.2
	July	22.4	13.1	717.7	18.1	118.6
	August	21.5	12.4	579.6	112.1	93.3
	September	19.5	12.0	406.5	37.6	58.4
	October	12.2	6.4	179.3	54.4	26.6
	Sum	**-**	**-**	**3684.5**	**402.5**	**544.1**
2000	April	12.3	4.6	478.2	37.0	61.5
	May	17.3	8.2	707.9	34.5	106.1
	June	18.1	11.0	665.6	58.2	100.0
	July	19.2	11.8	556.7	71.8	85.1
	August	19.5	11.7	498.7	56.7	77.3
	September	16.0	10.5	364.6	135.6	49.1
	October	14.0	9.8	145.2	59.4	18.7
	Sum	**-**	**-**	**3416.9**	**453.2**	**497.8**

Table 3 The measured and estimated mean soil water content (%, v/v) in the 90 cm soil profile at soil water tensions of 0.05, 0.1 and 15 bar together with soil available water content (SAWC) (%, v/v) in different fields at different farms in 1999 and 2000.

Year	Farm	Field	0.05*	0.1	15	SAWC[1]	SAWC[2]
1999	Farm1	Field1	32.29	31.31	13.67	17.63	18.61
		Field2	30.81	29.74	14.20	15.53	16.61
		Field3	32.99	31.65	15.16	16.49	17.83
	Farm3	Field1	32.11	31.35	14.77	16.57	17.33
		Field2	32.89	32.48	16.79	15.69	16.10
		Field3	34.57	33.77	16.71	17.06	17.86
	Farm11	Field1	29.94	28.99	14.00	14.99	15.94
		Field2	27.36	25.61	11.60	14.01	15.76
		Field3	29.77	28.31	12.29	16.02	17.48
	Farm13	Field1	29.66	29.24	13.75	15.49	15.91
		Field2	30.23	29.15	13.81	15.34	16.43
		Field3	28.61	27.91	12.58	15.33	16.02
2000	Farm1	Field1	30.37	29.88	11.52	18.36	18.85
		Field2	32.64	31.51	11.81	19.70	20.83
		Field3	29.05	28.67	8.40	20.27	20.65
	Farm3	Field1	31.37	30.24	12.48	17.76	18.89
		Field2	33.99	31.60	10.51	21.09	23.49
		Field3	34.94	32.62	11.36	21.26	23.57
	Farm11	Field1	28.83	27.59	13.67	13.92	15.16
		Field2	30.29	29.55	14.84	14.72	15.46
		Field3	31.49	30.86	15.16	15.70	16.33
	Farm13	Field1	29.59	28.40	14.32	14.09	15.27
		Field2	30.33	29.49	15.55	13.94	14.77
		Field3	30.82	29.46	16.09	13.38	14.73

* Water content at 0.05 bar is estimated through fitting observations at 0.005, 0.1, 0.6, 5 and 15 bar.

[1] SAVC is calculated as difference between soil water content at 0.1 and 15 bar.

[2] SAVC is calculated as difference between soil water content at 0.05 and 15 bar and this is used in the sugar beet growth simulation exercise reported herein.

Table 4 The sowing and harvesting dates in different fields at different farms in 1999 and 2000.

Year	Farm	Field	Sowing date	Harvesting date
1999	Farm1	Field1	25 April	29 September
		Field2	25 April	29 September
		Field3	25 April	29 September
	Farm3	Field1	28 April	14 October
		Field2	28 April	14 October
		Field3	28 April	14 October
	Farm11	Field1	25 April	7 October
		Field2	25 April	7 October
		Field3	25 April	7 October
	Farm13	Field1	26 April	5 October
		Field2	26 April	5 October
		Field3	26 April	5 October
2000	Farm1	Field1	10 April	22 September
		Field2	10 April	22 September
		Field3	10 April	22 September
	Farm3	Field1	24 April	21 September
		Field2	24 April	21 September
		Field3	24 April	21 September
	Farm11	Field1	9 April	6 October
		Field2	9 April	6 October
		Field3	9 April	6 October
	Farm13	Field1	9 April	23 October
		Field2	9 April	23 October
		Field3	9 April	23 October

Table 5 The observed maximum rooting depth (cm) and final number of plants per hectare in different fields at different farms in 1999 and 2000.

Year	Farm	Field	Maximum Root depth	Final plant Number per ha
1999	Farm1	Field1	110	101,042
		Field2	120	99,479
		Field3	95	96,875
	Farm3	Field1	110	88,021
		Field2	95	95,313
		Field3	95	100,000
	Farm11	Field1	115	71,354
		Field2	80	77,604
		Field3	80	83,854
	Farm13	Field1	115	93,085
		Field2	115	89,362
		Field3	115	81,915
2000	Farm1	Field1	98	75,521
		Field2	93	70,833
		Field3	85	56,250
	Farm3	Field1	82	94,792
		Field2	120	95,313
		Field3	97	95,833
	Farm11	Field1	153	92,188
		Field2	100	86,458
		Field3	160	88,021
	Farm13	Field1	112	75,521
		Field2	137	75,521
		Field3	115	63,021

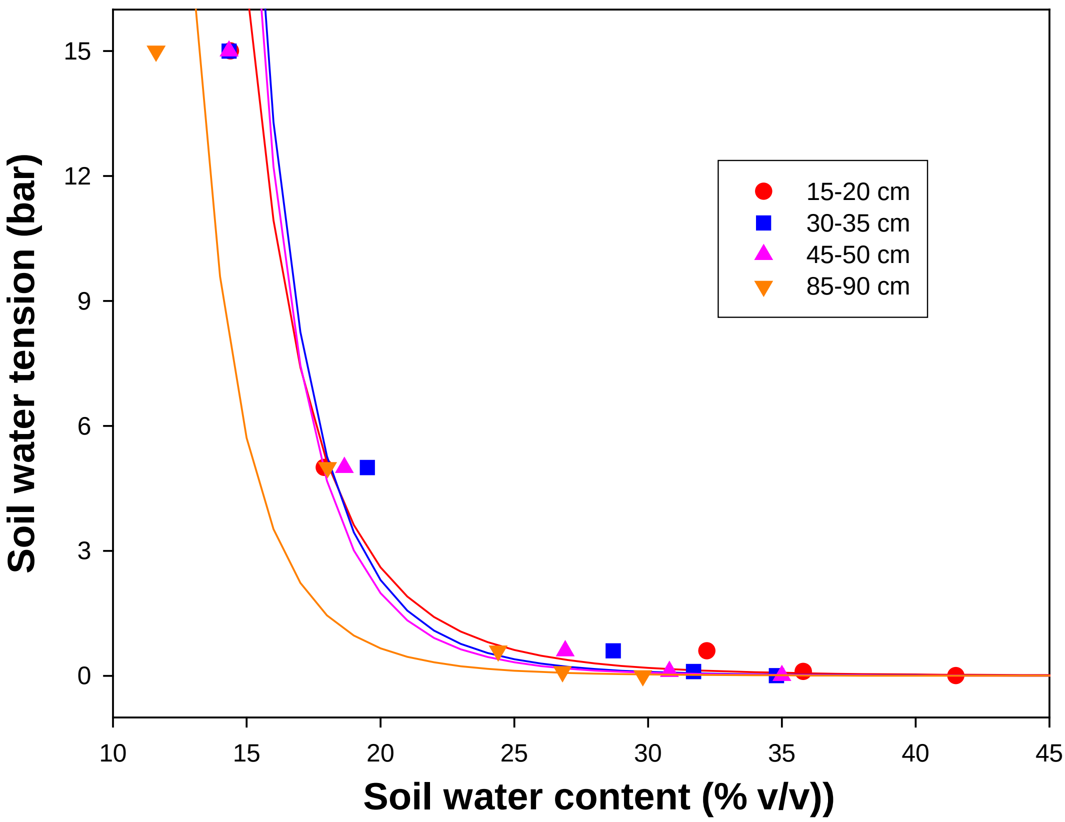

Figure 1 The fitted relationship between soil water content and soil water potential at various layers in field 1 at farm1 in 1999

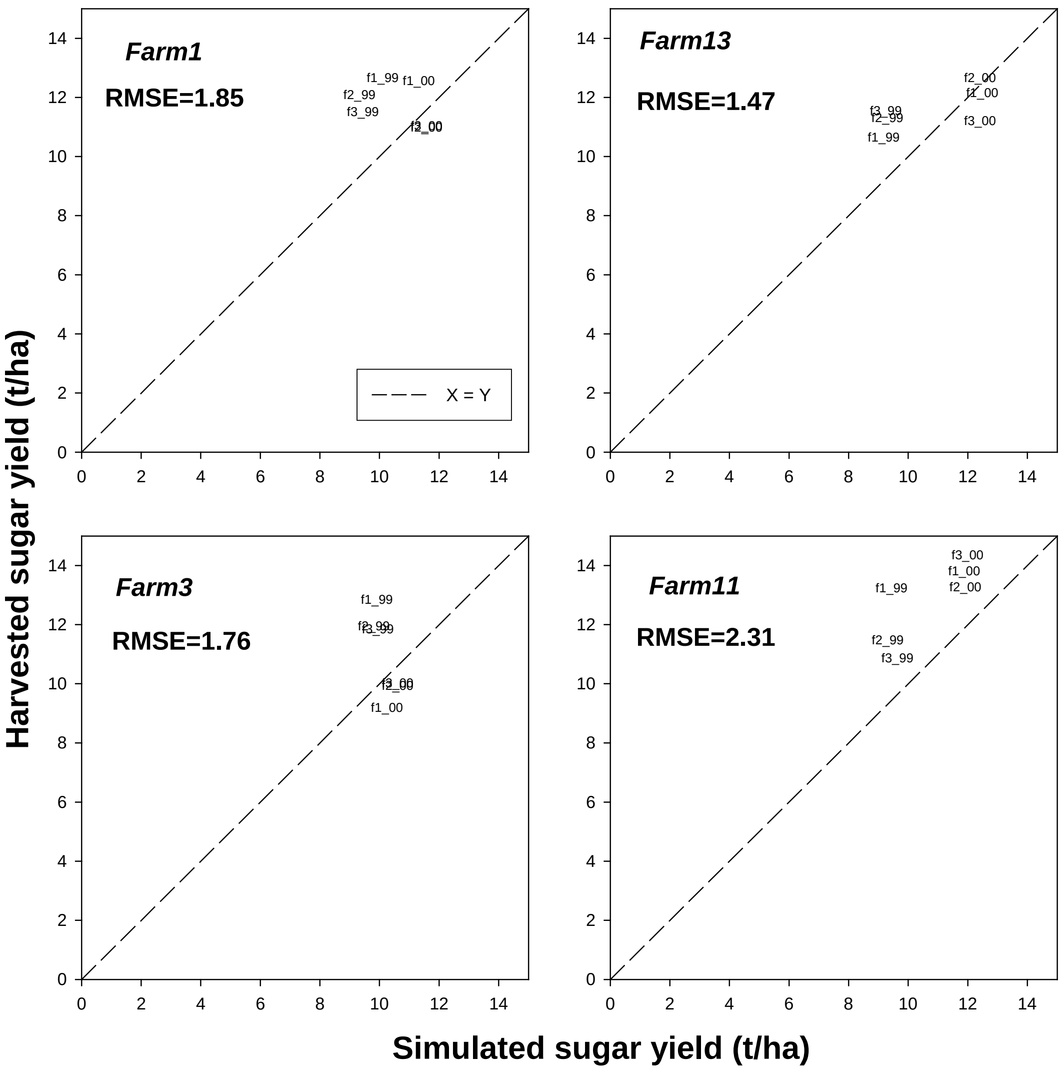

Figure 2 The Relationship between the harvested and the simulated obtainable sugar yield in different fields at different farms in 1999 and 2000. The symbols of f1_99, f2_99, f3_99, f1_00, f2_00 and f3_00 indicates field number 1, 2, and 3 in 1999 and 2000, respectively.

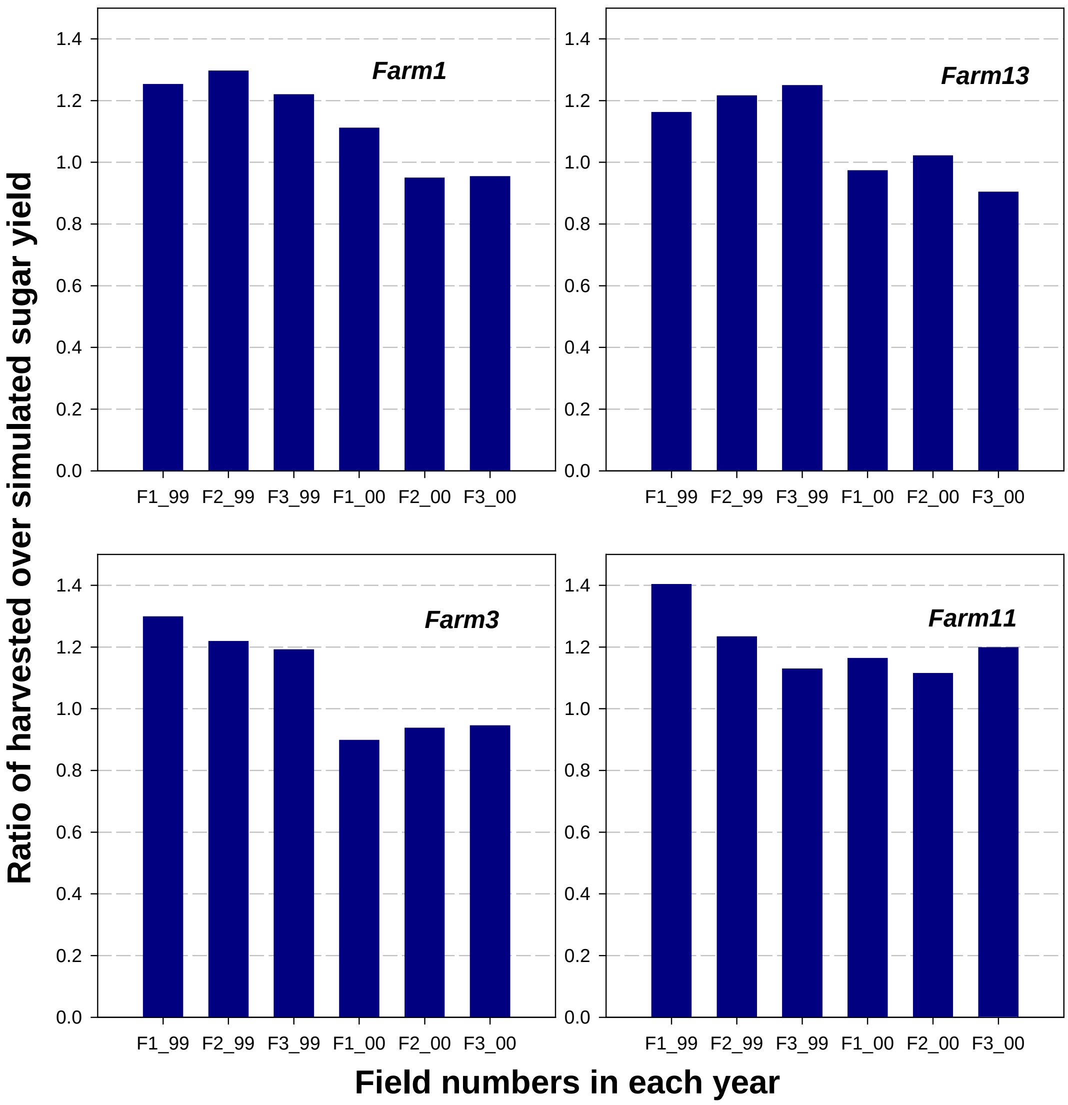

Figure 3 The ratio of harvested sugar yield by simulated obtainable sugar yield among different fields at different farms in 1999 and 2000.

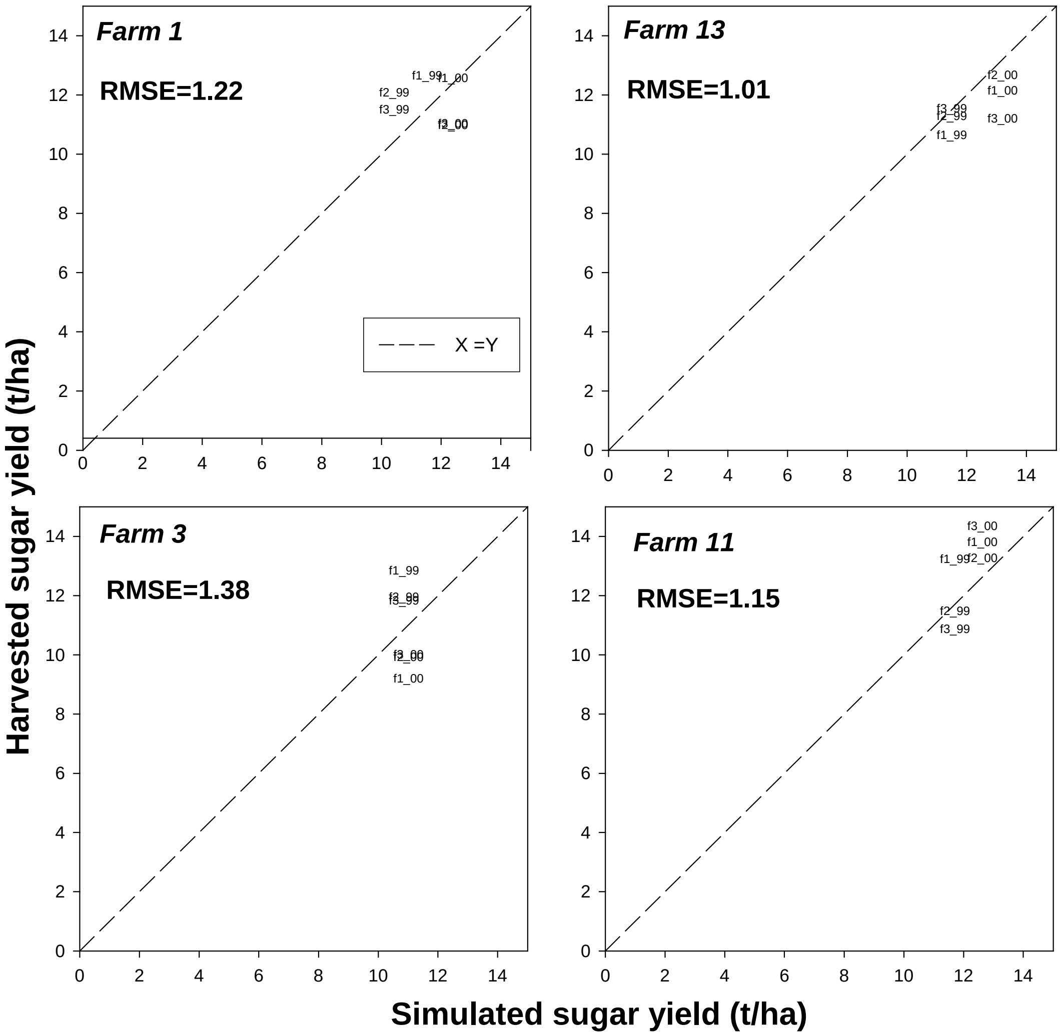

Figure 4 The Relationship between the harvested and the simulated potential sugar yield in different fields at different farms in 1999 and 2000. Explanations of symbols are referred to Figure 2.

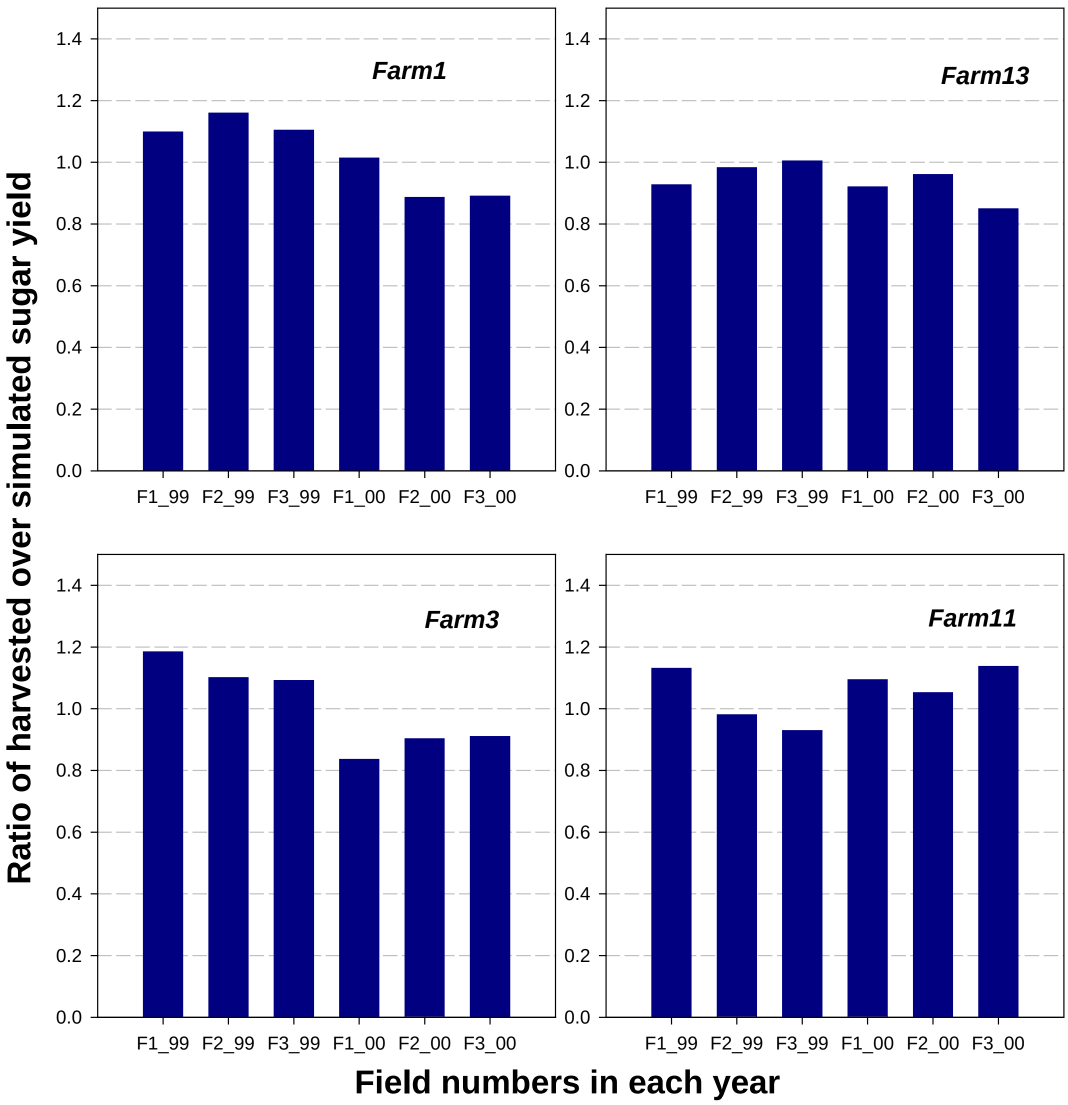

Figure 5 The ratio of harvested sugar yield by simulated potential sugar yield among different fields at different farms in 1999 and 2000.

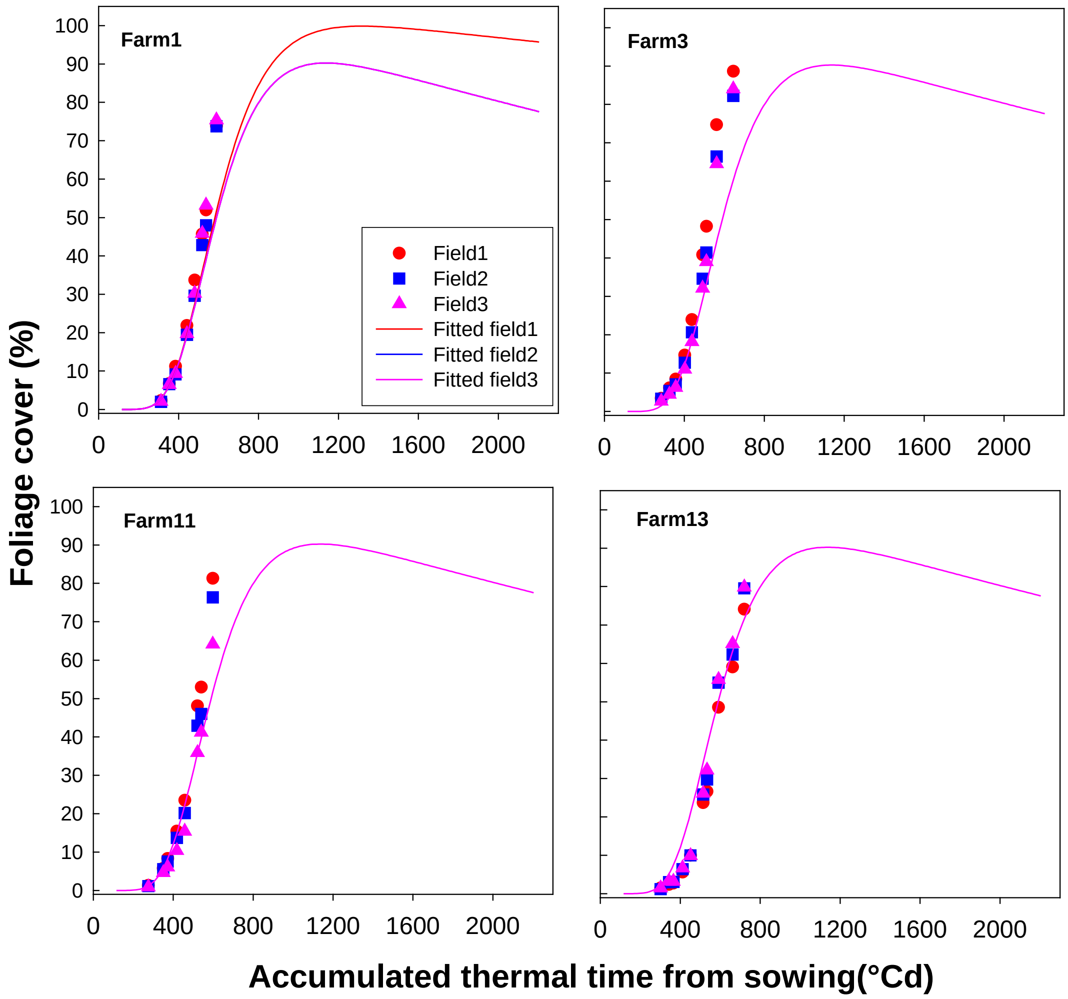

Figure 6 The measured foliage cover developments in relation to the simulations in each field on four farms in 1999.

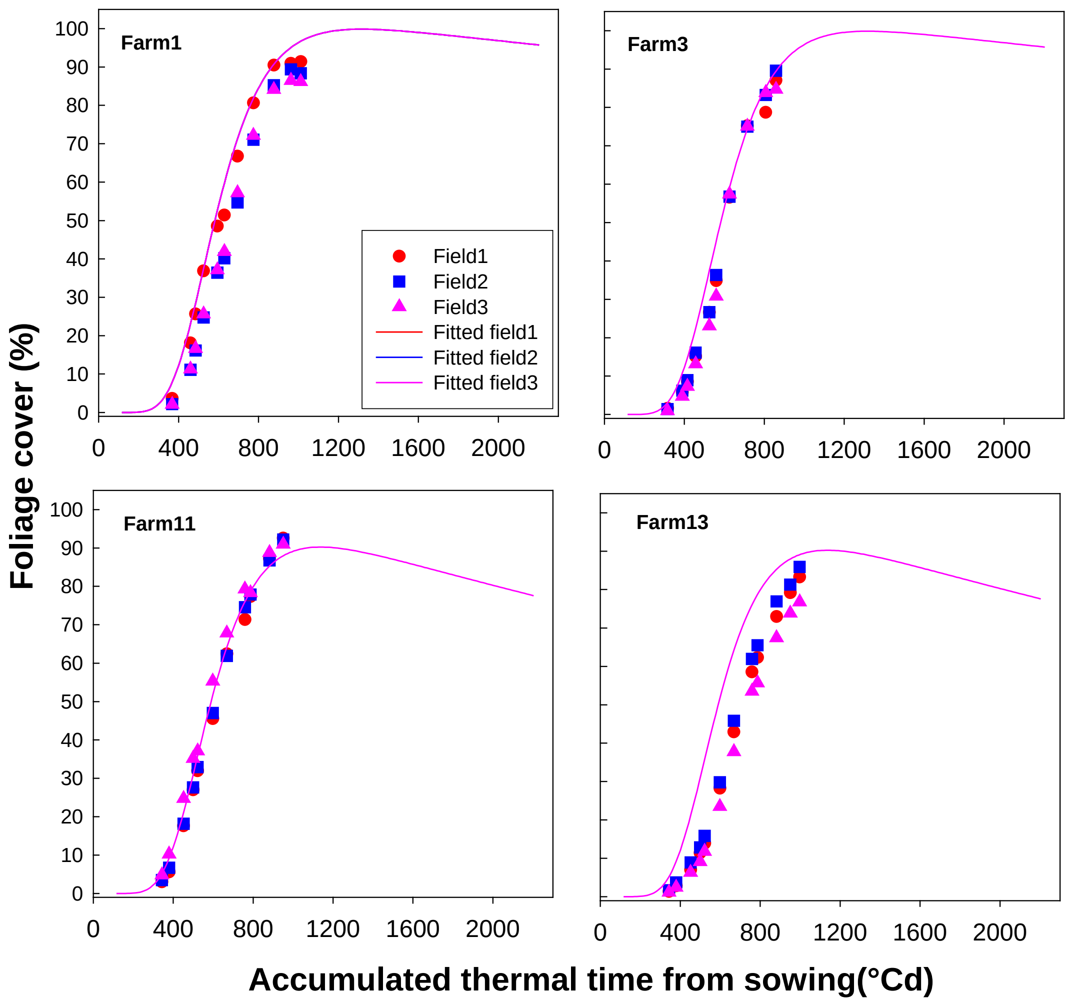

Figure 7 The measured foliage cover developments in relation to the simulations in each field on four farms in 2000.

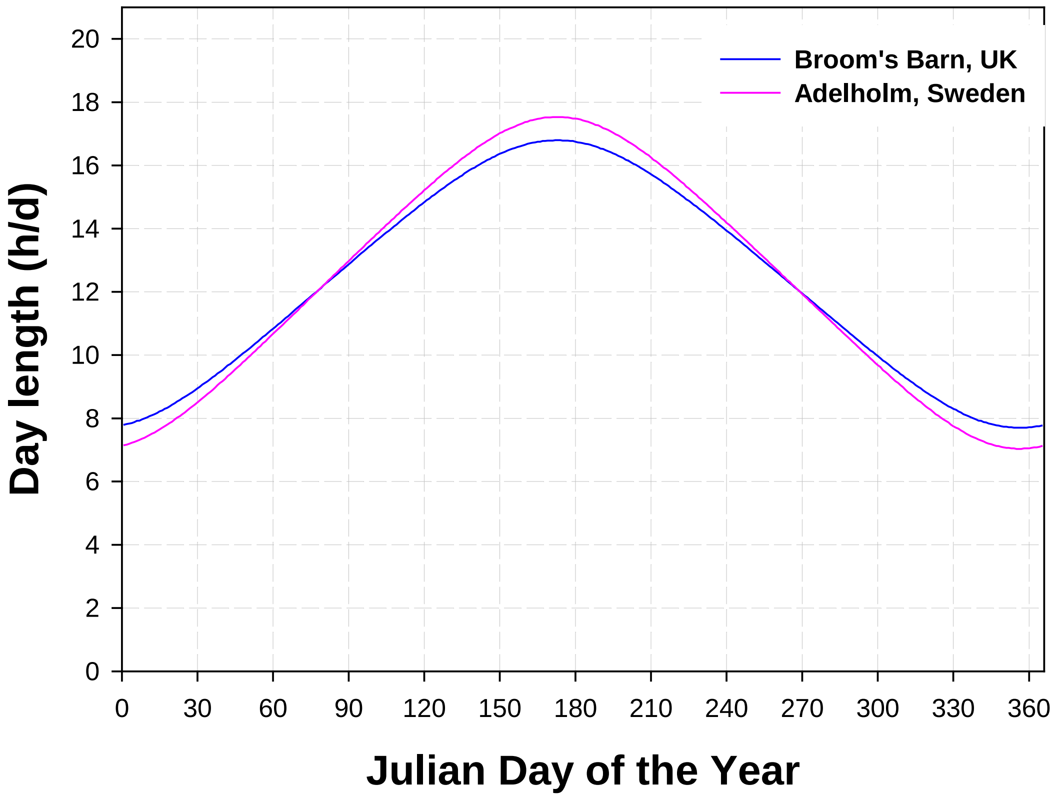

Figure 8 The day length (duration from sunrise to sunset) at Ädelholm, Sweden and at Broom's Barn, United Kingdom.

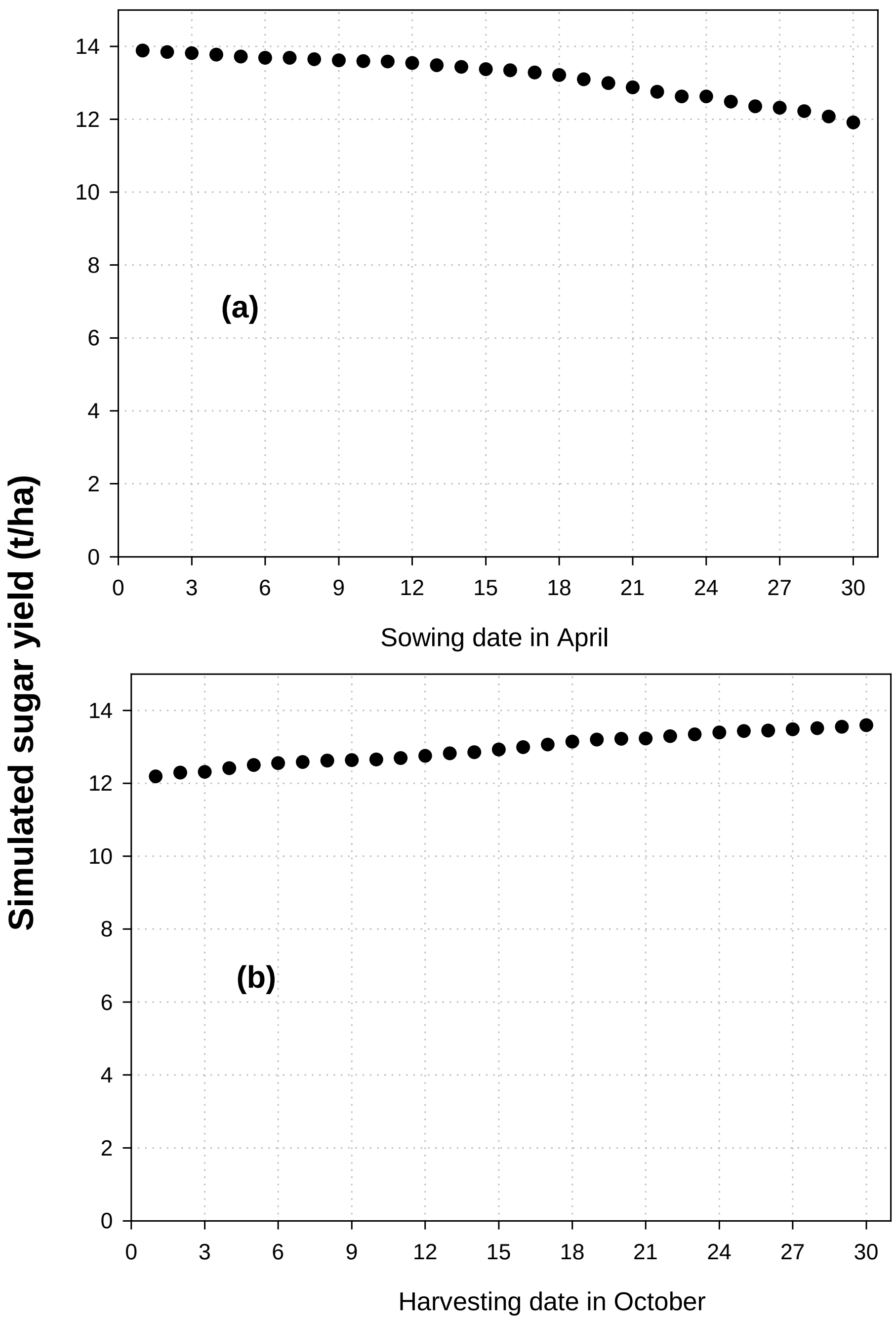

Figure 9 The simulated effect of sowing date in April 2000 (a) and of harvesting date in October 2000 (b) on sugar yield in field 1 at Farm1.

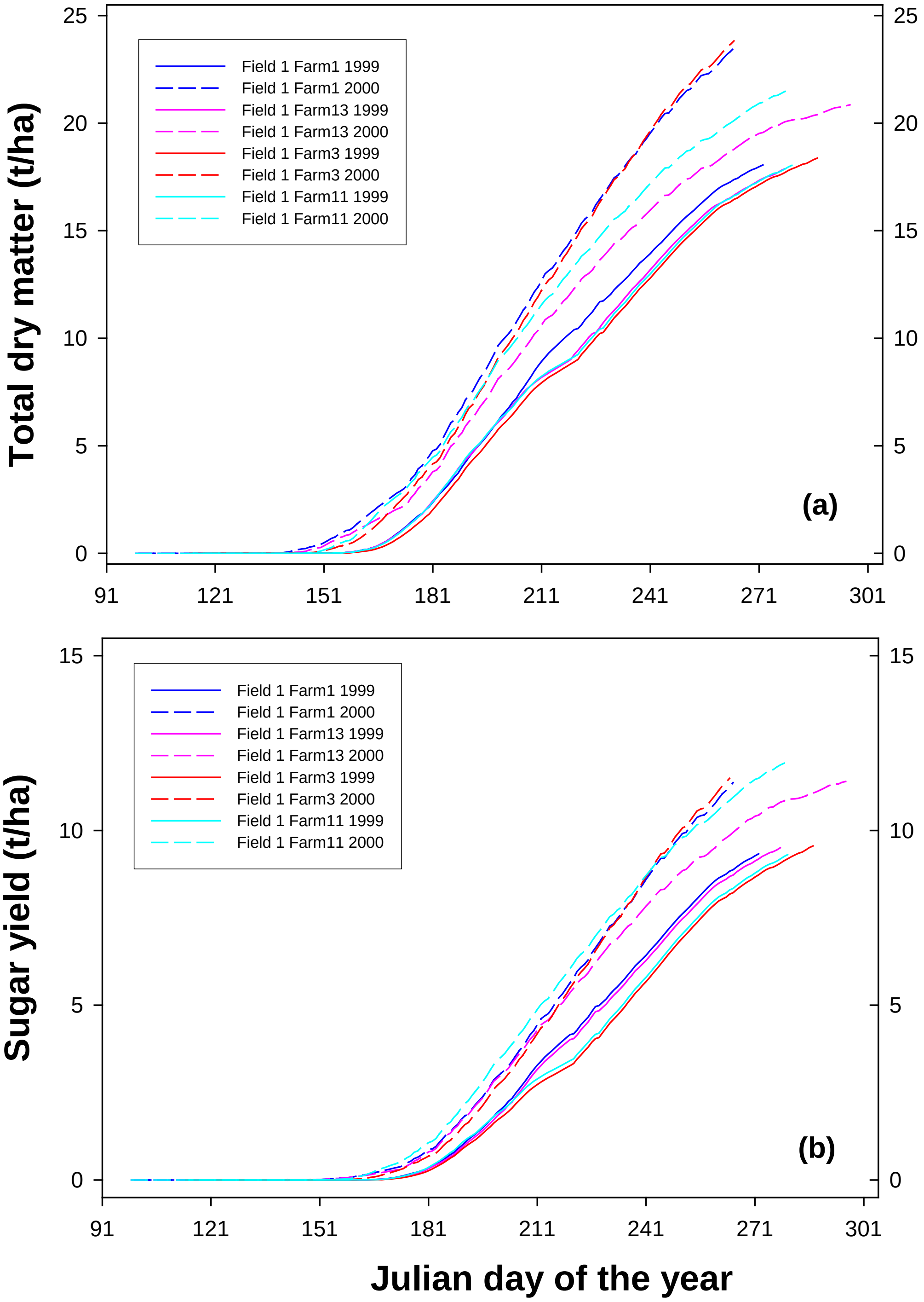

Figure 10 The simulated total crop dry matter (a) and sugar yield (b) increases after sowing in field 1 at different farms in 1999 and 2000.

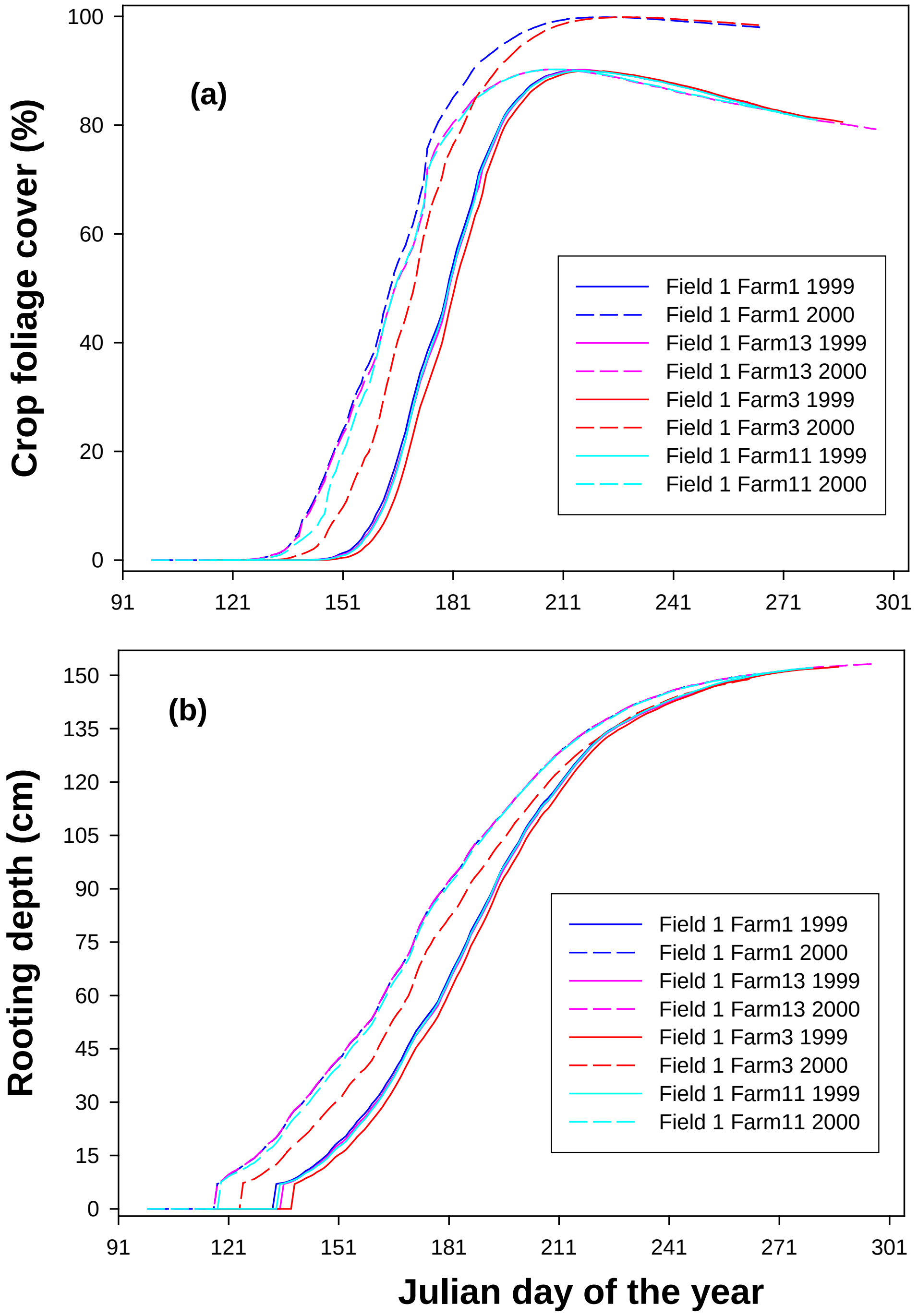

Figure 11 The simulated crop foliage cover development (a) and rooting depth increases (b) after sowing in field 1 at different farms in 1999 and 2000.

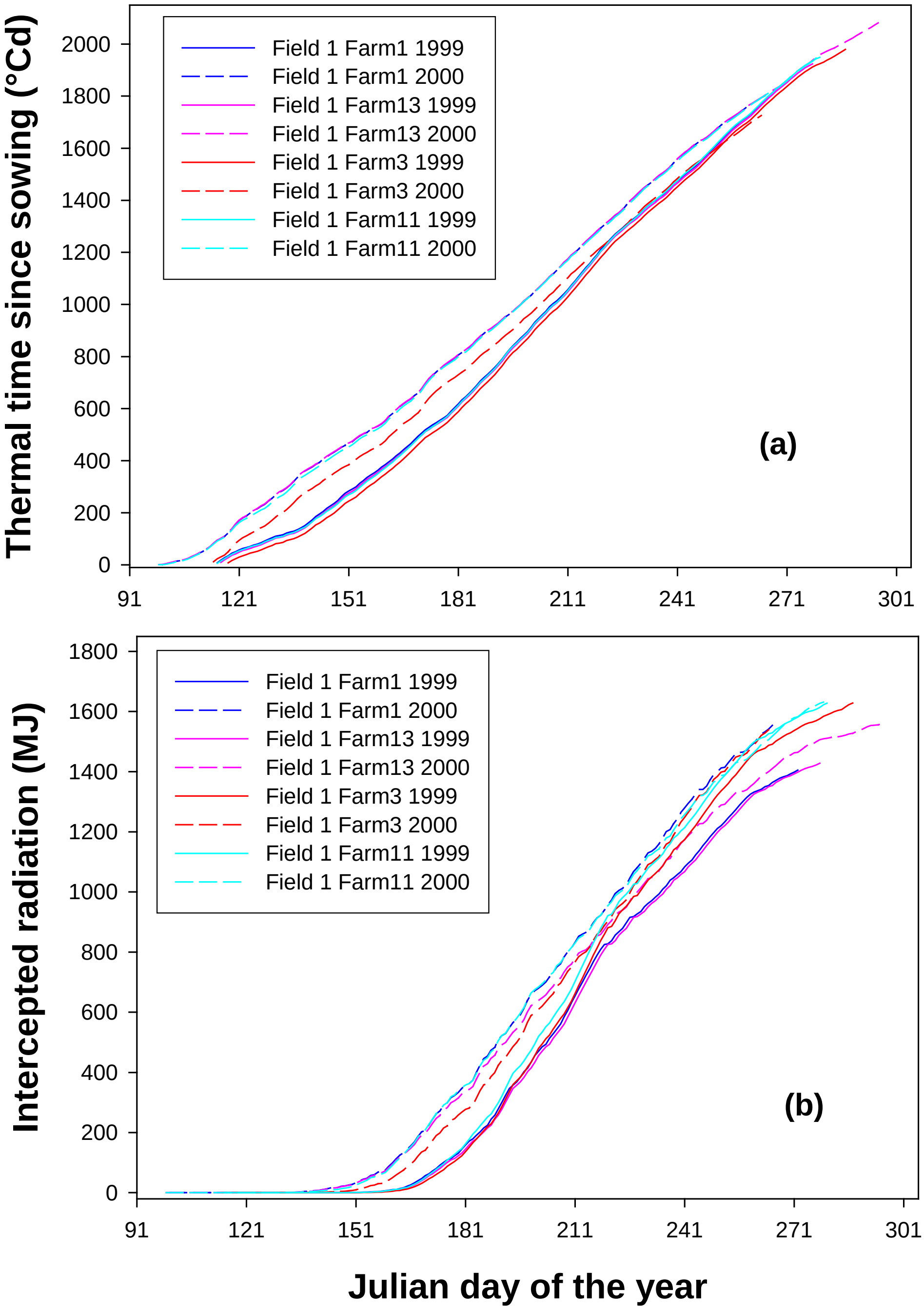

Figure 12 The accumulated thermal time (a) and the simulated canopy intercepted radiation (b) after sowing in field 1 at different farms in 1999 and 2000.

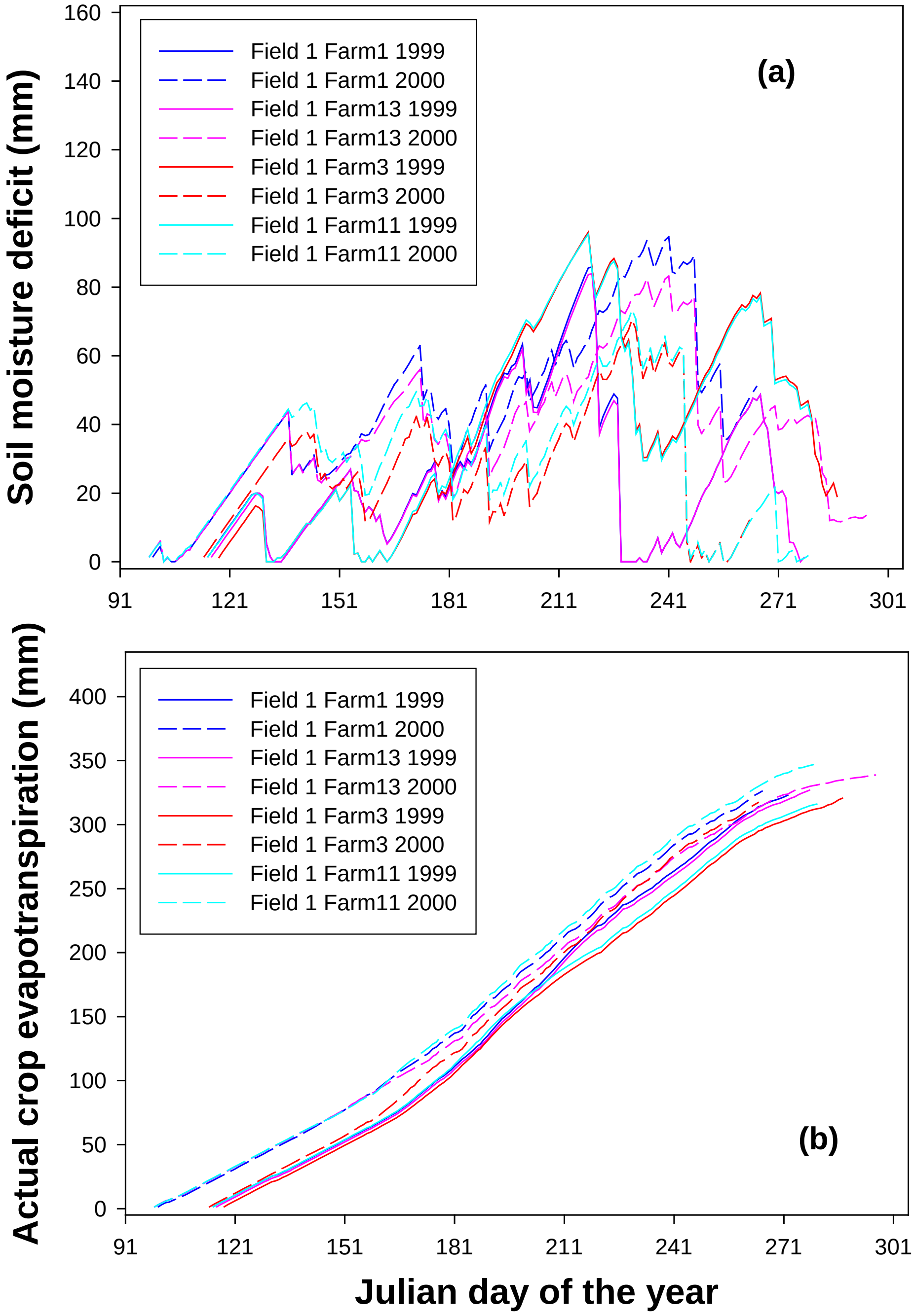

Figure 13 The simulated soil moisture deficit changes (a) and actual crop evapotranspiration (b) after sowing in field 1 at different farms in 1999 and 2000.

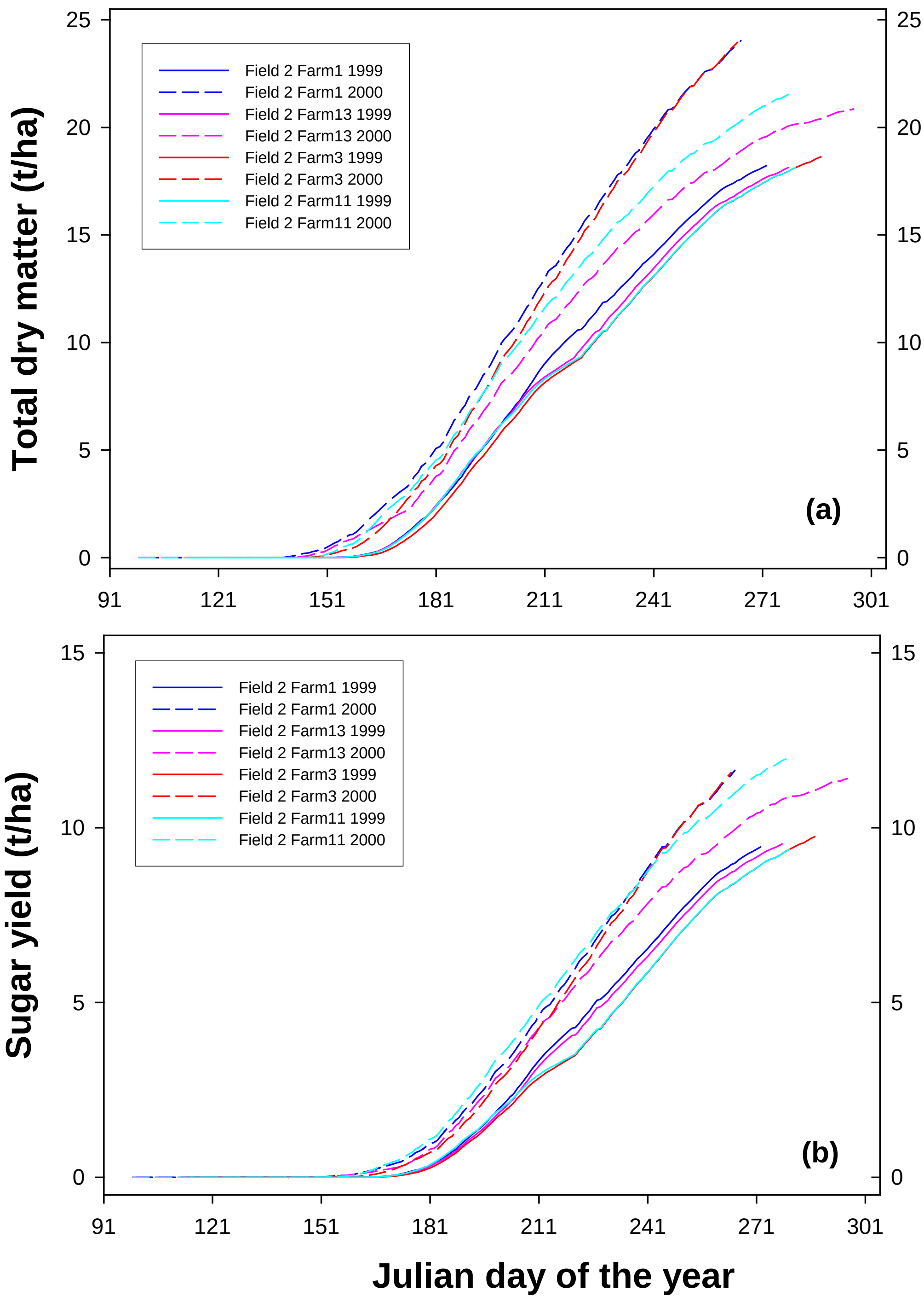

Figure 14 The simulated total crop dry matter (a) and sugar yield (b) increases after sowing in field 2 at different farms in 1999 and 2000.

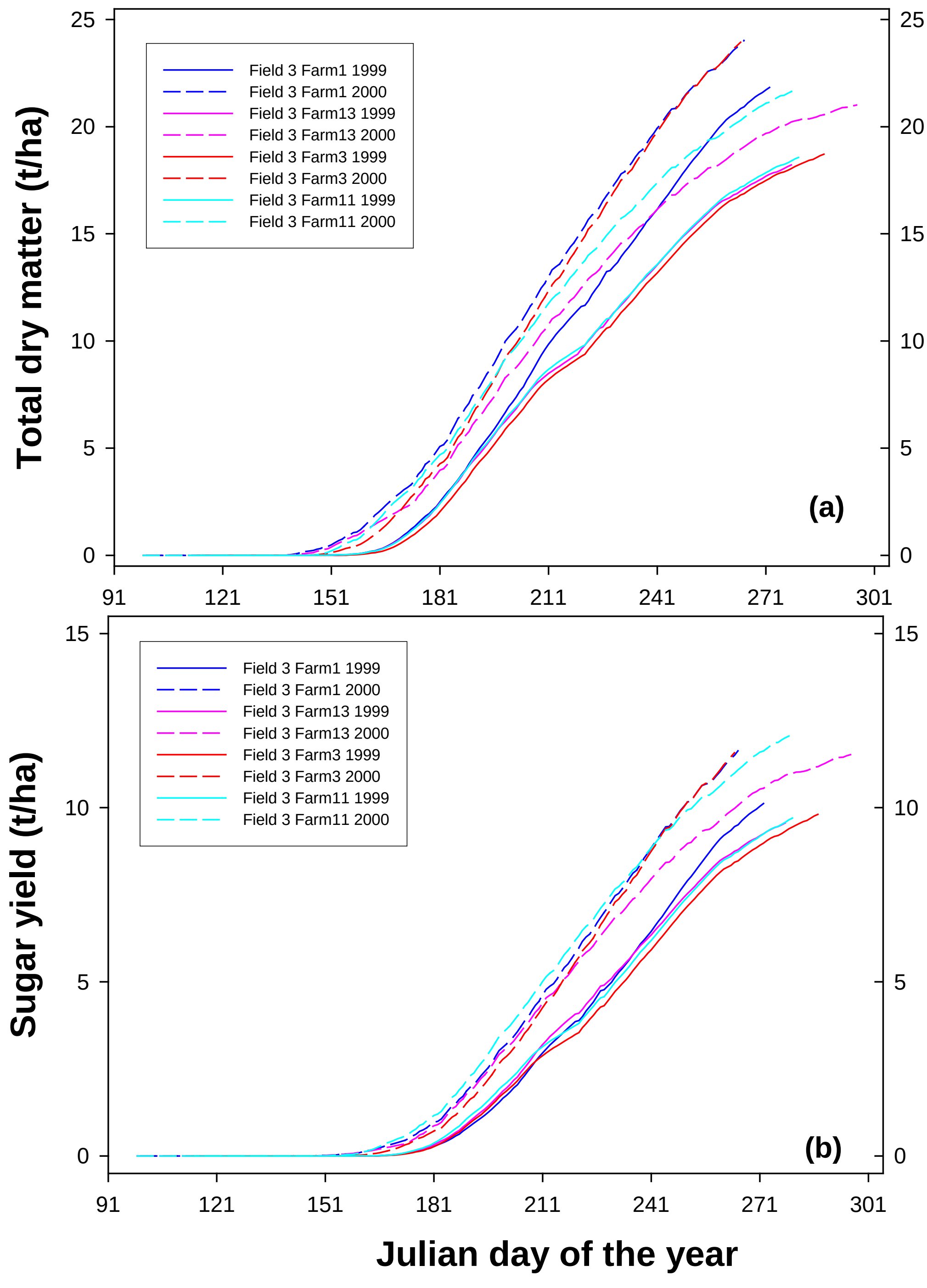

Figure 15 The simulated total crop dry matter (a) and sugar yield (b) increases after sowing in field 3 at different farms in 1999 and 2000.