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A preliminary evaluation of the simulation model CropSyst for alfalfa

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Abstract

This work stems from the need to set-up appropriate simulation models for scenario analysis of intensive forage cropping systems in northern Italy, where alfalfa plays a major role. CropSyst is a deterministic, process-based, with daily time-step cropping systems simulation model. It can simulate crop growth and development, water and nitrogen balance for herbaceous annual and perennial crops. In this work, it was used to simulate aboveground biomass (AGB) accumulation and soil water content (SWC) for two alfalfa meadows seeded in 1996 and 1997 in Lodi, northern Italy (45°N latitude). The crop was parameterised with data from the literature, local experience and calibration with measured data from the first 2 years. Data from the third year were used for validation.

The cumulative yields of the 3-year periods were 38.2 and 36.9 t AGB ha^{-1}, obtained with a total of 14 cuts. The set of crop parameters is consistent with values reported in the literature. For most of the cuts, the model simulates appropriately the growth of the crop: the relative root mean squared error (RRMSE) between observed and measured AGB ranged between 3 and 6% after calibration and between 3 and 5% after validation. RRMSE for SWC ranged between 13 and 21% after calibration and between 10 and 20% after validation. Even if some limitations are explicitly addressed, this crop parameter set can be already used for explorative scenario simulations in the study area. This work has demonstrated the robustness of the model for perennial forage crops simulations and has suggested some improvements of the model (automatic scheduling of cuts, role of crown reserves).

Keywords: Alfalfa; Simulation model; Forage crops; Growth and development; Northern Italy; Soil water content

1. Introduction

Alfalfa (*Medicago sativa* L.) is an important crop for economic and ecological reasons: it increases soil quality by fixing nitrogen (N), improving soil structure (thanks to the deep root system) and increasing soil organic matter (the tillage is reduced compared to annual crops); moreover, among different forage species, alfalfa has high yields (Bourgeois, 1990). Due to its extraordinary adaptability, the cultivation area of alfalfa is very wide, being now extended from Scandinavia to northern Africa. In northern Italy, alfalfa plays an important role in dairy farms; in northern and central Italy, alfalfa is cultivated in about 620,000 ha (ISTAT, 2001).

Today, the complex relations between crop management, crop growth and environmental issues for intensive forage systems are to be analysed to maximise

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economic return and to minimise environmental impact. In northern Italy, this is particularly true for N management in animal farms, where N losses from the system can be relevant (Ceccon et al., 1993; Giardini and Borin, 1996; Borin et al., 1997; Maggiore et al., 1998; Grignani and Zavattaro, 2000). Studies to understand N fate in cropping systems can be successfully conducted with dynamic simulation models (Morari and Giupponi, 1997; Smith et al., 1997; Acutis et al., 2000).

Up to now, several simulation models have been specifically developed for alfalfa (Holt et al., 1975; Schreiber et al., 1978; Parsch, 1982, 1987; Fick and Onstad, 1983; Savoie et al., 1985; Denison and Loomis, 1989; Bourgeois, 1990). Some of them are very detailed in describing crops physiological and morphological aspects. For example, ALF2LP (Bourgeois, 1990) considers the effects of total non-structural carbohydrates reserves for the spring restart; it also simulates daily biomass increments of different components of the plant (leaves, stems, basal buds) and considers alfalfa forage quality (crude protein, in vitro dry matter digestibility and crude fiber); moreover, it considers the age of the crop as a limiting factor on radiation use efficiency. The same observations also apply to ALSIM1 (Parsch, 1987) which is the previous version of ALF2LP and which was introduced into DAFOSYM (Parsch, 1982), a system simulation model for analysing the economics of forages on dairy farms. SIMED (Holt et al., 1975; Schreiber et al., 1978) is a crop growth model which takes into account dry matter partitioning into leaves, stems and roots. Compared to these models, ALFALFA (Denison and Loomis, 1989) uses a more detailed formalisation of several morphological and physiological issues (e.g. crop geometry, reserve accumulation and mobilisation, root types).

This level of detail is coherent with the choice of a species-specific simulation model and with the objective to describe morphological and physiological processes at the level of plant components. However, detailed simulation models dedicated to a single species cannot simulate cropping systems; moreover, models developed for alfalfa usually do not simulate nutrient limitations on crop growth. Therefore, for management and planning purposes, a generic simulation model which includes simulation of N processes may be more useful.

Simplifications introduced in generic crop simulators for the description of some processes (e.g. monolayer canopy, absence of daily partitioning of assimilates, and of forage quality simulation) make these models able to work with a more reduced set of crop parameters and to be used at a larger scale.

CropSyst (Stöckle and Nelson, 1999; Stöckle et al., 2003) is a process-based simulation model. It is a generic crop simulator, which uses the same approach to simulate the growth and development of a wide range of herbaceous crops, including meadows. It can simulate rotations and is continuously being developed. Although it has been widely applied to cereals and other cropping systems (Stöckle et al., 1994; Pala et al., 1996; Donatelli et al., 1997; Stöckle and Debaeke, 1997; Giardini et al., 1998; Pannkuk et al., 1998), no published results exist to describe the performance of this model when used with perennial crops.

Finally, when using CropSyst for scenario analysis, automatic scheduling of management operations may be useful to run long simulations (which capture effects of weather variability) and/or to run simulations at many locations in a study area (to capture cropping systems and pedological variability). CropSyst already includes rules to set-up automatic irrigation, automatic nitrogen applications and automatic cuts of perennials.

Therefore, the objectives of this study were:

- to assess the feasibility of simulating the growth and development of perennial crops with CropSyst, in particular for processes connected with dormancy and spring restart;
- to calibrate and validate the simulation model CropSyst in simulating alfalfa growth for one site in Italy and
- to evaluate CropSyst's criterion for automatic cuts of forage crops.

2. Materials and methods

2.1. Experimental data

Experimental data were collected in Lodi at the Istituto Sperimentale per le Colture Foraggere (Experimental Institute for Forage Crops; northern Italy, latitude 45°19′N, longitude 9°28′E, altitude 80 m a.s.l.) between 1995 and 1999 in a medium-term experiment on forage systems. The soil is a Typic

Table 1
Soil water content (SWC) at field capacity and wilting point

Layer number	Thickness (m)	SWC at field capacity ($m^3 m^{-3}$)	SWC at wilting point ($m^3 m^{-3}$)
1	0.50	0.380	0.098
2	0.50	0.330	0.072
3	0.35	0.338	0.189
4	0.30	0.214	0.040
5	0.25	0.254	0.041

Haplustalf coarse-loamy, mixed, mesic (Soil Survey Staff, 1999) and has a medium–low organic matter content, is subacid, has sufficient available phosphorous and a low potassium content. Field capacity (FC) and wilting point (WP) were measured for each layer of a representative soil profile (Table 1). Very rare fine roots were found down to 1.9 m. Daily meteorological data (rainfall, maximum and minimum air temperatures, global solar radiation) were measured in Lodi.

The climate of the experimental area belongs to the mesoclimate of the Po valley; it is characterised by a discrete level of continentality, mitigated by the relative closeness of the Mediterranean. The mean annual temperature is about 13 °C; the absolute minimum is attained between January and February and the absolute maximum between July and August. Total precipitation (about 800 mm) is relatively well distributed (about 75 rainy days per year). Precipitation regime shows two maxima (the principal in fall and the secondary in spring) and two minima (the principal in winter and the secondary in summer). Average wind speed is about 1.5 $m s^{-1}$.

The experiment compares two forage rotations: a 1-year rotation (Italian ryegrass, *Lolium multiflorum* Lam.; silage maize, *Zea mays* L.) and a 6-year rotation (3 years of Italian ryegrass–silage maize and 3 years of alfalfa) under four fertilisation treatments: two different manures (solid and liquid, applied before ploughing) with or without topdressed ammonium nitrate (not applied to alfalfa). The experimental factors (rotation, organic fertiliser, mineral N fertiliser) are arranged in a strip–split–plot design with three replicates. The 84 elementary plots are 84 m^2 (12 m × 7 m) wide.

Alfalfa (cv. Lodi) was sown in March (1600 seeds m^{-2}), following the harvest of maize in September. Alfalfa was cut four times in the first year of the meadow and five times in the second and third year. No evident crop stresses were noticed. The agro-techniques applied to the two alfalfa meadows are shown in Table 2(a) (for 1996 sowing) and (b) (for 1997 sowing).

The measured variables were: aboveground biomass (AGB) and plant nitrogen concentration (PNC) at harvest, soil water content (SWC) every month (every 15 days in the 1995) for soil layers 0.00–0.30 and 0.30–0.60 m. AGB was determined by sampling a 18 m^2 area for each plot and by storing the samples in oven at 60 °C until constant weight, and will be always expressed as dry matter in this text. Soil was sampled by extracting one core (100 g) per plot and per soil layer at each sampling date. SWC was determined with the gravimetric method on a fraction of the soil sample, while the other fraction was kept frozen at −20 °C until soil nitrogen content was determined.

2.2. Simulation model

CropSyst (Stöckle et al., 1994, 2003; Stöckle and Nelson, 1999) is a deterministic, multi-year multi-crop daily time step simulation model. The model simulates the soil water budget, soil-plant nitrogen budget, crop canopy and root growth, dry matter production, yield, residue production and decomposition, and soil erosion. Management options include: cultivar selection, crop rotation (including fallow years), irrigation, nitrogen fertilisation, tillage operations and residue management. The most important model inputs are: daily weather data, dates and amounts of products applied for each fertilisation and irrigation event, sowing date, hydraulic characteristics of the soil profile, crop parameters, initial conditions of the soil profile (crop residues, water content, mineral nitrogen and organic matter). Main daily model outputs are AGB, leaf area index (LAI), root depth, potential and actual evapotranspiration, soil water and nitrogen balance.

Crop development is simulated as a function of thermal time accumulated between a base temperature (T_{base}) and a maximum temperature (T_{cutoff}), and of daylength and vernalisation requirements. Crop growth is simulated for the whole canopy as a function of intercepted radiation, water availability, air temperature and nitrogen availability. Radiation-dependent growth is calculated with a simplified monolayer canopy sub-model as a function of intercepted photosynthetically active radiation (PAR), radiation use

Table 2
Management operations

Date	Operation	Amount
(a) Alfalfa meadow seeded in 1996		
14/03/1996	Fertilisation	149 kg N ha^{-1} (from manure) 100 kg P_2O_5 ha^{-1} (from mineral fertiliser) 250 kg K_2O ha^{-1} (from mineral fertiliser)
14/03/1996	Plowing (0.3 m depth)	
14/03/1996	Harrowing	
15/03/1996	Sowing	
09/06/1996	1st cut	
10/07/1996	Irrigation	110 mm water
17/07/1996	2nd cut	
02/08/1996	Irrigation	110 mm water
23/08/1996	3rd cut	
30/09/1996	4th cut	
15/05/1997	1st cut	
20/05/1997	Irrigation	100 mm water
24/06/1997	2nd cut	
17/07/1997	Irrigation	110 mm water
25/07/1997	3rd cut	
23/08/1997	4th cut	
10/10/1997	5th cut	
19/05/1998	1st cut	
24/06/1998	2nd cut	
09/07/1998	Irrigation	100 mm water
23/07/1998	3rd cut	
29/07/1998	Irrigation	100 mm water
10/09/1998	4th cut	
20/10/1998	5th cut	
(b) Alfalfa meadow seeded in 1997		
11/03/1997	Fertilisation	122 kg N ha^{-1} (from manure) 100 kg P_2O_5 ha^{-1} (from mineral fertiliser) 250 kg K_2O ha^{-1} (from mineral fertiliser)
11/03/1997	Plowing (0.3 m depth)	
11/03/1997	Harrowing	
11/03/1997	Sowing	
20/05/1997	Irrigation	100 mm water
30/05/1997	1st cut	
10/07/1997	2nd cut	
17/07/1997	Irrigation	110 mm water
18/08/1997	3rd cut	
10/10/1997	4th cut	
19/05/1998	1st cut	
24/06/1998	2nd cut	
09/07/1998	Irrigation	100 mm water
23/07/1998	3rd cut	
29/07/1998	Irrigation	100 mm water
10/09/1998	4th cut	
20/10/1998	5th cut	
12/05/1999	1st cut	
17/06/1999	2nd cut	
05/07/1999	Irrigation	50 mm water
15/07/1999	3rd cut	
22/07/1999	Irrigation	100 mm water
19/08/1999	4th cut	
11/10/1999	5th cut	

efficiency and a temperature limitation factor:

$$G_\mathrm{R} = \mathrm{LtBC} \times 0.5 \times \mathrm{Rad} \times (1 - \mathrm{e}^{-k \times \mathrm{LAI}}) \times T_\mathrm{lim} \qquad (1)$$

where G_R (kg m^{-2} per day) is the daily radiation-dependent biomass production, LtBC (light-to-biomass conversion; kg MJ^{-1}) is the net radiation use efficiency (ratio of AGB accumulated to intercepted PAR), Rad (MJ m^{-2} per day) is the daily global solar radiation (with 0.5 × Rad being an estimate for PAR), $1 - \mathrm{e}^{-k \times \mathrm{LAI}}$ is the fraction of PAR intercepted by the canopy, k is the radiation extinction coefficient for PAR, LAI is the leaf area index, T_lim is a temperature-dependent limiting factor (0 if $T_\mathrm{a} \leq T_\mathrm{base}$; 1 if $T_\mathrm{a} \geq T_\mathrm{opt}$), with T_a: average air temperature and T_opt: optimum mean daily temperature for growth.

Water-dependent growth is calculated as

$$G_\mathrm{W} = \mathrm{Tr}_\mathrm{act} \frac{\mathrm{BTR}}{\mathrm{VPD}} \qquad (2)$$

where G_W (kg m^{-2} per day) is the daily crop transpiration-dependent biomass production, Tr_act (m per day) is the actual transpiration, BTR (kg m^{-2} kPa m^{-1}) is the biomass-transpiration coefficient, VPD (kPa) is the daily mean vapor pressure deficit.

Model robustness is ensured by calculating daily leaf area growth as a function of daily accumulated biomass and not the other way round. Green LAI increase is calculated as

$$\Delta\mathrm{GAI} = \frac{\Delta\mathrm{LAERB} \times \mathrm{SLA}}{(\mathrm{SLP} \times \mathrm{LAERB}_\mathrm{cum} + 1)^2} \qquad (3)$$

where ΔGAI (m^2 m^{-2}) is the daily growth in green leaf area index, ΔLAERB (kg m^{-2}) is the daily leaf area expansion-related biomass, $\mathrm{LAERB}_\mathrm{cum}$ (kg m^{-2}) is the LAERB accumulated from sowing until today, SLA (m^2 kg^{-1}) is the ratio leaf area/leaf biomass (specific leaf area for the early growth phase), SLP (stem/leaf partition coefficient; m^2 kg^{-1}) is an empirical coefficient for partitioning accumulated biomass between “green” and “non-green” crop surfaces. As plant grows, $\mathrm{LAERB}_\mathrm{cum}$ increases and therefore ΔGAI decreases. Therefore, Eq. (3) simulates the effects of crop development on biomass partitioning to leaf area. Root depth is simulated as a function of leaf area development, and reaches its maximum when the plant flowers.

Soil water infiltration is simulated with a cascade approach or with the more complex finite difference solution of the Richard’s equation. Potential evapotranspiration is estimated with the Penman–Monteith equation or, if air humidity and/or wind speed data are missing, with the Priestley–Taylor equation.

2.3. Perennial crops

For perennial crops, CropSyst simulates the start of dormancy when, starting from a day in autumn (SD), T_a falls below a threshold (T_dormancy) for 7 consecutive days. In spring, the crop restarts when the reverse occurs ($T_\mathrm{a} > T_\mathrm{dormancy}$ for 7 consecutive days), starting from a date in spring (ED). The model simulates LAI and biomass after dormancy and after cuttings. LAI for the day after dormancy ($\mathrm{LAI_i}$) is calculated as (Nelson, personal communication):

$$\mathrm{LAI_i} = \mathrm{SLA} \times \mathrm{AGB_i}$$

where $\mathrm{AGB_i}$ is the biomass after dormancy (0.005 kg ha^{-1}). Accumulation of carbohydrates in the crown is not simulated by CropSyst, and therefore the crown cannot affect crop growth rate after cuttings and after dormancy. We would like to underline that a calibrated perennial crop parameter set implicitly incorporates information on the crown role.

For perennials, CropSyst considers LAI = GAI. Everyday a pair of values consisting of the daily increment of GAI and the corresponding increment of biomass is appended to a list which serves as a history for the crop to remember the GAI/biomass pairs for everyday of its life. In the case of perennials, all these pairs are removed at the beginning of dormancy. When the meadow is cut, CropSyst determines the amount of biomass to be removed (percentage on total AGB) and removes the latest pairs of values starting from the more recent ones, until the amount of biomass to be removed is reached; in this way, it is possible to recalculate a value of LAI after the cut which is coherent with the amount of AGB after the cut.

2.4. Model parameterisation and validation

CropSyst version 2.02.31 (14 September 1999) was used. Potential evapotranspiration was calculated with the Priestley–Taylor equation. Soil water redistribution was simulated with the cascade method.

The starting point for the calibration of crop parameters involved in AGB accumulation was the alfalfa default parameter's set of CropSyst. Nine parameters were subjected to sensitivity analysis, which indicated SLA, SLP, BTR and T_{opt} as the parameters which cause significant variations in AGB accumulation. Three of them (SLA, SLP and T_{opt}) were calibrated as described below; BTR was set to the default value. The other five parameters were parameterised using CropSyst's default values (Table 3). The parameters base temperature (T_{base}) and cutoff temperature (T_{cutoff}) did not cause significant AGB variations in the conditions of this experiment. The parameters involved in dormancy (T_{dormancy}, SD, ED) were not calibrated because sensitivity analysis has shown that these parameters cannot significantly influence AGB accumulation. A possible explanation is that weather conditions between November and February do not allow significant biomass accumulation.

The cascade model was preferred to the one based on the Richard's equation because using the first option the model resulted more stable, in particular with very wet or dry soil. Although FC was one of the measured hydrological properties, we have chosen to calibrate it because FC was measured on disturbed samples, whose structure was destroyed during sieving (2 mm) and, by using measured values of FC, simulated SWCs were lower than the measured ones.

For the calibration of the parameters involved with AGB accumulation, we used data from the first 2 years of the meadows seeded in 1996 and 1997. Data from the third year of the two meadows were used to test the calibrated parameters. For the calibration of FC, data collected between June 1995 and April 1996 for the 1-year rotation and between March 1996 and March 1997 for the 6-year rotation were used. Data collected in the period between May 1996 and March 1997 for the 1-year rotation and in the period between June

Table 3
Crop model parameters for alfalfa (cv. Lodi) and source of information (C: calibrated parameters; D: CropSyst default values; L: local experience)

Parameter	Determination	Value	Units
Photosynthetic pathway	–	$C3$	–
Perennial	–	True	–
Aboveground biomass-transpiration coefficient (BTR)	D	5	$\text{kPa}\,\text{kg}\,\text{m}^{-3}$
Light to aboveground biomass conversion (LtBC)	D	3	$\text{g}\,\text{MJ}^{-1}$
Actual to potential transpiration ratio that limits leaf area growth	D	0.8	–
Actual to potential transpiration ratio that limits root growth	D	0.5	–
Optimum mean daily temperature for growth (T_{opt})	C	30	°C
Maximum water uptake	D	14	mm per day
Leaf water potential at the onset of stomatal closure	D	1300	$\text{J}\,\text{kg}^{-1}$
Wilting leaf water potential	D	2000	$\text{J}\,\text{kg}^{-1}$
Maximum rooting depth	D	1.8	m
Maximum expected leaf area index (LAI)	D	5	$\text{m}^2\,\text{m}^{-2}$
Fraction of maximum LAI at physiological maturity	D	0.8	–
Specific leaf area (SLA)	C	26	$\text{m}^2\,\text{kg}^{-1}$
Stem/leaf partition coefficient (SLP)	C	3.5	–
Extinction coefficient for solar radiation (k)	D	0.5	–
ET crop coefficient at full canopy	D	1.2	–
Degree days emergence	C	50	°C-days
Base temperature (T_{base})	L	5	°C
Cutoff temperature (T_{cutoff})	C	30	°C
Phenologic sensitivity to water stress	D	0	–
Average temperature for 7 consecutive days to induce dormancy	L	5	°C
First date to start looking for dormancy (SD)	L	15 November	–
First date to start looking for restart after dormancy (ED)	L	15 February	–
Sensitive to cold temperatures	D	Disabled	–

1995 and March 1996 for the 6-year rotation were used for validation.

The criterion implemented in CropSyst for automatic cuts is based on biomass: the crop is cut when the AGB reaches a user-defined threshold. In farming practices, however, forage crops are cut at a specific phenological stage to maximise forage quality (e.g. from late vegetative to early-bud for alfalfa). With the aim of understanding if such a criterion could be implemented in the simulation model, we compared biomass-based simulations with phenology-based simulations. In the first case (SimBio), the threshold was set to the average of measured yields; in the second case (SimPh), we calculated the growing degree days (GDD) required to reach either (i) the first cut from the end of dormancy or (ii) the next cut from the previous one; the average of these GDDs was used to schedule the cutting dates. For the first year, a combination of the two criteria was also tested. (The first cut was based on a biomass threshold of 2.5 t AGB ha^{-1} and the others on phenology (SimBioPh), because of the lower crop growth rates of young alfalfa plants compared to well-established plants.) Simulated AGB harvested at each cutting date with the three methods and measured AGB were compared.

The agreement between observed and predicted values was expressed by using the indices proposed by Loague and Green (1991): the relative root mean squared error (RRMSE; minimum and optimum = 0%), the coefficient of determination (CD; minimum = 0, optimum = 1, indicates whether the model reproduces the trend of measured values or not), the modelling efficiency (EF; $-\infty$ to $+\infty$, optimum = 1, if positive, indicates that the model is a better predictor than the average of measured values), the coefficient of residual mass (CRM; 0–1, optimum = 0, if positive, indicates model underestimation) and the parameters of the linear regression equation between observed and predicted values.

3. Results and discussion

3.1. Experimental results

Accumulated alfalfa yields for both 3-year periods are reported in Table 4. Yields of the first year are the lowest (9.60–11.33 t AGB ha^{-1}), due to crop establishment. Yields were highest in the second year and decrease slightly in the third one. The yields of the 3-year period measured in this experiment (38.17–36.87 t AGB ha^{-1}) are lower than those normally obtained for irrigated alfalfa meadows in northern Italy (yields reported in the literature range from 41.7 to 50.0 t AGB ha^{-1}: Onofrii et al., 1994, 1997; Romani et al., 1992). This behaviour is due to the low yield obtained in this experiment in the second year (14.14–13.92 t AGB ha^{-1}) compared to data from the literature (16.6–20.4 t AGB ha^{-1}). Soil water content (Figs. 3–6) showed higher temporal variation in the summer than in the winter, when it was frequently around 0.35 $\mathrm{m}^3\,\mathrm{m}^{-3}$ for the 0–30 cm layer and 0.30 $\mathrm{m}^3\,\mathrm{m}^{-3}$ for the 30–60 cm layer.

Table 4
Yields (t AGB ha^{-1}) and standard deviations (in italic) of the 3-year meadows sown in 1996 and 1997

Sowing year	First year		Second year		Third year	
1996	11.33	*0.63*	14.14	*1.06*	12.70	*1.12*
1997	9.60	*0.56*	13.92	*0.77*	13.35	*1.62*

3.2. Model results

3.2.1. Calibration

Calibrated crop model parameters are shown in Table 3. The set of temperatures reflects the origin of the cultivar used, selected in the same Institute where the experiment was carried out. Cv. Lodi can be sown in autumn or in spring ($T_{\mathrm{base}} = 5\,°\mathrm{C}$, the same value used by Bourgeois, 1990 and by Sanderson, 1992) and has good productive performance at high temperatures ($T_{\mathrm{opt}} = T_{\mathrm{cutoff}} = 30\,°\mathrm{C}$). Many papers show lower values for alfalfa optimal temperatures: Arbi et al. (1979) obtained the highest growth rates when a combination of 21 °C during the day and 12 °C during the night was used; Fick (1984) used a functional relationship to describe the effect of temperature on physiological processes for alfalfa, with an optimum temperature below 20 °C; Bula (1972), for three alfalfa cultivars, obtained the highest biomass yields at 25 °C, but one cultivar was performing well in the range 20–30 °C; Gowgani (1977) obtained the highest daily AGB at first flowering when a 20 °C/10 °C (day/night) regime was used. However, most of these papers deal only with few cultivars. A study carried out in growth chambers by McLaughlin and Christie (1980) analysed the temperature effects on AGB yield for 300 alfalfa genotypes, which were separated in three groups: the first had high yields at high temperature only (30 °C/25 °C, day/night), the second at low temperature only (20 °C/15 °C) and the third at both temperatures. Therefore, we believe that the origin of this cultivar justifies the optimal temperature chosen as a model parameter.

On the basis of local experience, we used a value of 5 °C for T_{dormancy} and the dates 15 November for SD and 15 February for ED. However, in our environment, growing conditions (temperature and radiation) do not contribute substantially to biomass accumulation between the beginning of November and the end of March; therefore SD and ED parameters have a low impact on crop yield.

The solar radiation extinction coefficient for PAR was left to the default value of 0.5; this is consistent with the results of Sheehy and Popple (1981) who measured values between 0.42 and 0.57. The default value for radiation use efficiency (LtBC: 3 g AGB MJ^{-1} intercepted PAR) is higher than the values measured by some authors for well-watered alfalfa canopies (e.g. 1.71 g MJ^{-1} by Duru and Langlet, 1989; 1.72 g MJ^{-1} by Durand et al., 1989; 2.15 g MJ^{-1} by Whitfield et al., 1986); in fact, the parameter used by the model is defined for optimal temperature conditions, while in the field experiments the efficiency may be limited by temperature.

The calibrated value for SLA is consistent with the one (26.5 $\mathrm{m}^2\,\mathrm{kg}^{-1}$) reported by Bourgeois (1990) for its model, and with the one (28.2 $\mathrm{m}^2\,\mathrm{kg}^{-1}$) measured by Antolin et al. (1995) for well-watered nitrogen-fixing alfalfa plants. Other measured values reported in the literature are 30.3 $\mathrm{m}^2\,\mathrm{kg}^{-1}$ (average of the first two sampling dates after cutting; Sheehy and Popple, 1981), and 22.7 $\mathrm{m}^2\,\mathrm{kg}^{-1}$ (Buntin and Pedigo, 1985, for rainfed alfalfa plants).

The default value for the ET crop coefficient at full canopy (1.2) is consistent with the value of crop coefficient suggested by FAO (Allen et al., 1998) at full cover for alfalfa.

The agreement between observed and simulated AGB values is shown in Figs. 1 and 2, and in Table 5: the model is accurate in the simulation of AGB accumulation. The values of the indices shown in Table 5 confirm the goodness of model performance (low RRMSE, EF, CD and slope of the regression line close to 1, while CRM is close to 0). The agreement between measured and simulated values is very satisfactory for the first year of the meadow seeded in 1996 (Fig. 1). The first cut of 1997 is correctly simulated by the model: this is important considering that it is the first cut after the end of dormancy; subsequently the model is less accurate, underestimating biomass for the third and the fourth cuts and overestimating the fifth. Cumulative biomass, however, is well simulated. The simulation results for the meadow seeded in 1997 (Fig. 2) are similar to the measured values

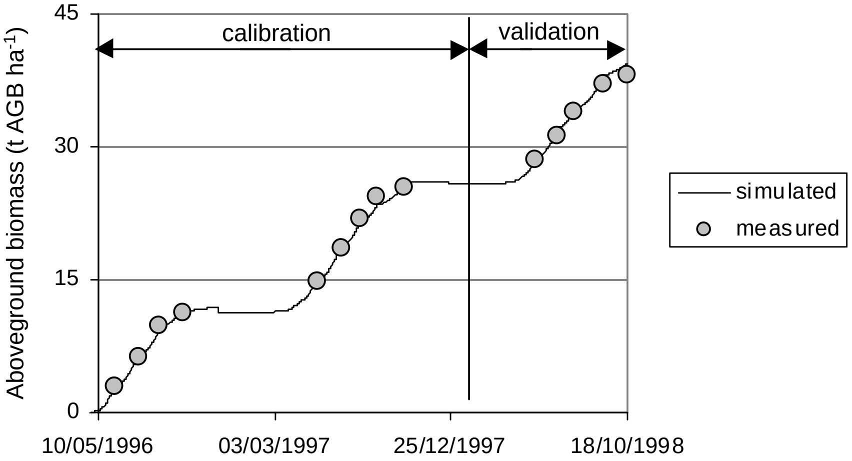

Fig. 1. Cumulated aboveground biomass of meadow seeded in 1996 after calibration (first and second year) and after validation (third year).

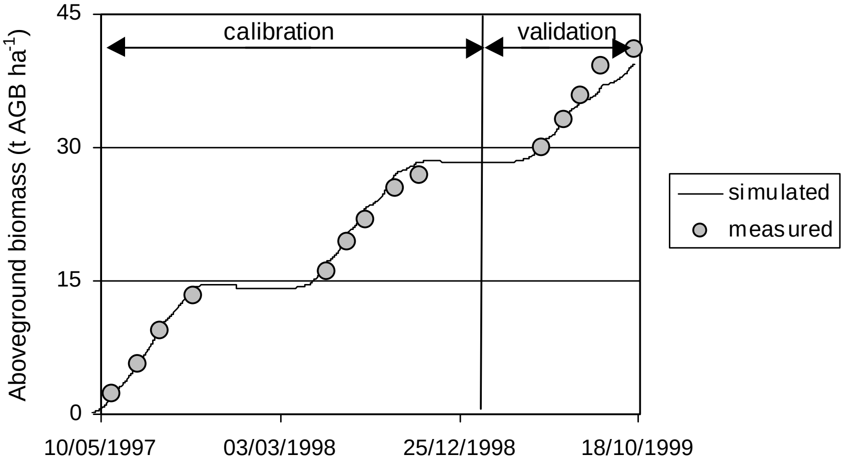

Fig. 2. Cumulated aboveground biomass of meadow seeded in 1997 after calibration (first and second year) and after validation (third year).

until the end of the second year, when the model does not correctly simulate the decreasing production typical of the last cut of the season.

Figs. 3 and 4 and Table 6 show the comparison between measured and simulated values of SWC: the model is accurate in simulating this variable, especially for the soil layer 0.00–0.30 m. For the soil layer 0.30–0.60 m, the simulated temporal variability is lower than the measured one. The values of RRMSE are low, the values of CD are very close to 1 and CRM is close to 0, except for the soil layer 0.30–0.60 m for the 6-year rotation. For the soil layer 0.00–0.30 m, the poor model performance might be due to reduced drainage (caused by intense rainfall in autumn and winter and deep soil layers with low hydraulic conductivity), which is not simulated with the cascading approach.

3.2.2. Validation

Results of crop parameters test are shown in Figs. 1 and 2 and in Table 5. In general, model performance is still satisfactory: the AGB accumulation of alfalfa is well reproduced. The simulation is more accurate for the first data set (meadow seeded in 1996; Fig. 1), while for the second one (Fig. 2) the biomass of the last two cuts of the third year is underestimated.

Measured and simulated values of SWC after validation are shown in Figs. 5 and 6 and in Table 6. As already pointed out, simulations for the upper soil layer are more in agreement with measurements than for the deepest layer. In general, however, the indices show a discrete model performance: RRMSE range from 10 to 20% and CD from 0.62 to 2.17.

We should remember that CropSyst does not explicitly simulate the role of crown and roots for regrowth after dormancy and after cuts. For this reason we believe that our crop parameter set incorporates part of this behaviour, in particular for empirical parameters such as SLP. Therefore, we think that the application of these parameters to other environments should be

Table 5
Indices of agreement between observed and simulated cumulated AGB

	Sowing year	RRMSE (%)	EF	CRM	CD	Slope	Intercept (t AGB ha^{-1})	R^2
Calibration	1996	3	1.00	−0.01	1.04	0.98	0.14	1.00
	1996	6	0.99	0.05	0.91	1.06	0.01	1.00
Validation	1996	3	1.00	0.01	0.95	1.02	−0.40	1.00
	1997	5	0.99	0.01	1.09	0.95	1.37	0.99

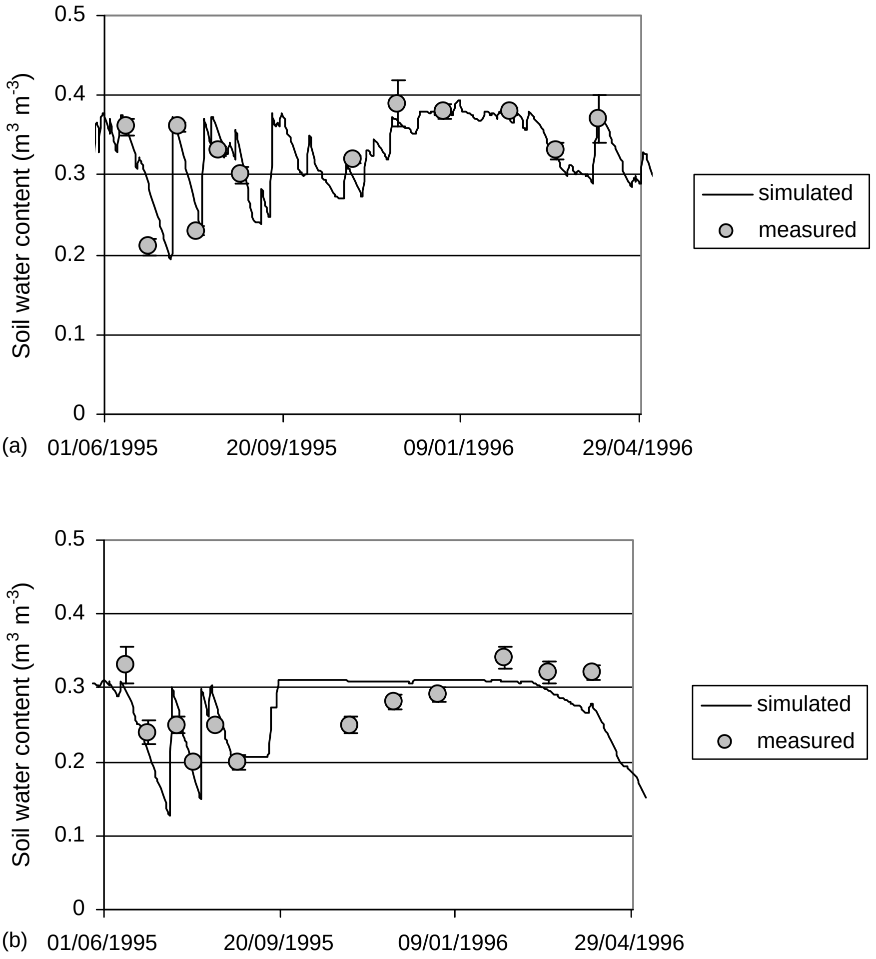

Fig. 3. Measured and simulated soil water content after calibration—1-year rotation, June 1995–April 1996: (a) soil layer 0.0–0.3 m; (b) soil layer 0.3–0.6 m.

Table 6
Indices of agreement between observed and simulated soil water content

	Rotation	Soil layer (m)	RRMSE (%)	EF	CRM	CD	Slope	Intercept (t AGB ha^{-1})	R^2
Calibration	1-year	0.0–0.3	13	0.34	0.03	1.16	0.67	0.11	0.50
	1-year	0.3–0.6	16	0.43	−0.01	1.02	0.71	0.07	0.52
	6-year	0.0–0.3	15	0.50	0.02	0.89	0.79	0.07	0.55
	6-year	0.3–0.6	21	−1.00	−0.07	2.32	0.31	0.19	0.20
Validation	1-year	0.0–0.3	19	0.20	0.05	0.62	0.72	0.10	0.29
	1-year	0.3–0.6	20	0.38	−0.03	0.99	0.70	0.07	0.48
	6-year	0.0–0.3	10	0.18	0.07	2.17	0.69	0.12	0.81
	6-year	0.3–0.6	17	0.01	0.06	1.43	0.55	0.13	0.39

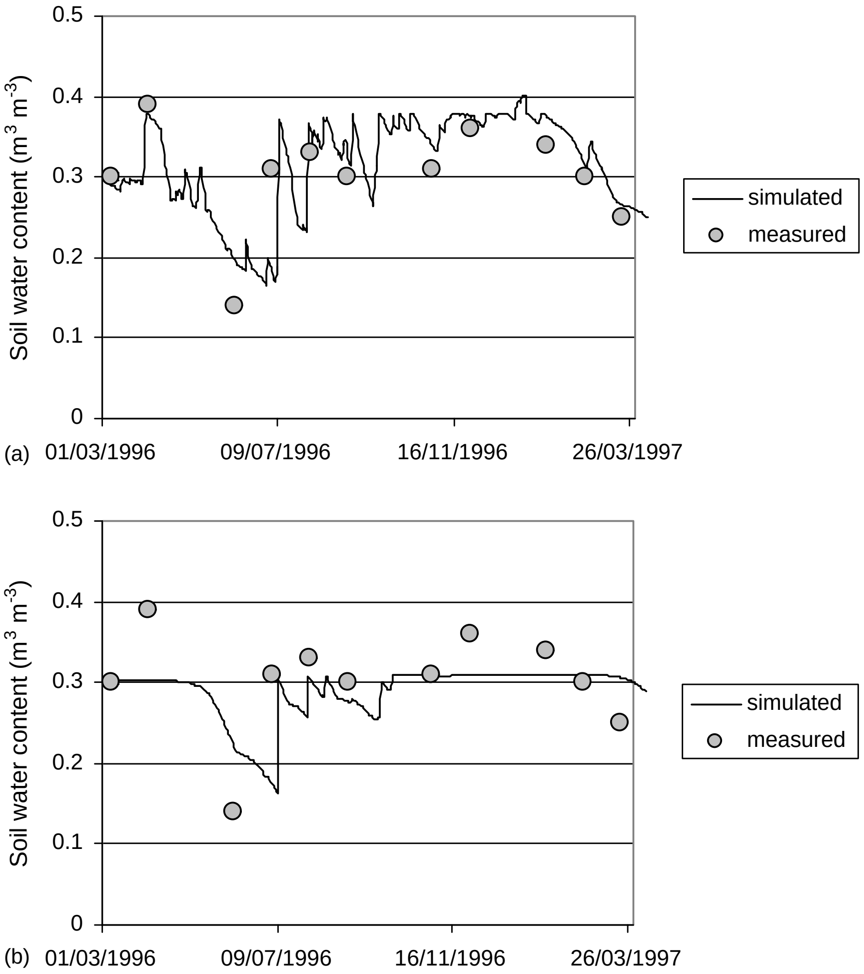

Fig. 4. Measured and simulated soil water content after calibration—6-year rotation, March 1996–March 1997: (a) soil layer 0.0–0.3 m; (b) soil layer 0.3–0.6 m.

made with caution. Moreover, simulation of the effects of different cutting frequencies (affecting the rate of biomass accumulation and depletion from crown) would not be possible with this simulation model. To overcome this limitation, simple approaches like the one suggested by Fick (1984) could be used, where a factor for regrowth potential (representing the effect of storage and root reserves on daily crop growth rate) is calculated as a function of GDD accumulated since the last cut. This factor decreases immediately after cut, and increases again while new reserves are accumulated.

3.2.3. Criteria for automatic cuts

The results of the comparison between automatic cutting methods may be summarised as follows: (i) the average value for GDD used to schedule the cutting events is 635 °C-days (with $T_{\mathrm{base}} = 5\,^{\circ}\mathrm{C}$) and its standard deviation is 137 °C-days; (ii) the method which best reproduces the harvested biomass is the SimBioPh: its RRMSE (see Table 7) is relatively low (20% in 1996 and 29% in 1997), and its CD has values very close to 1. These results might not be considered completely satisfactory. In fact, as pointed out by Sanderson et al. (1994), a general relationship between

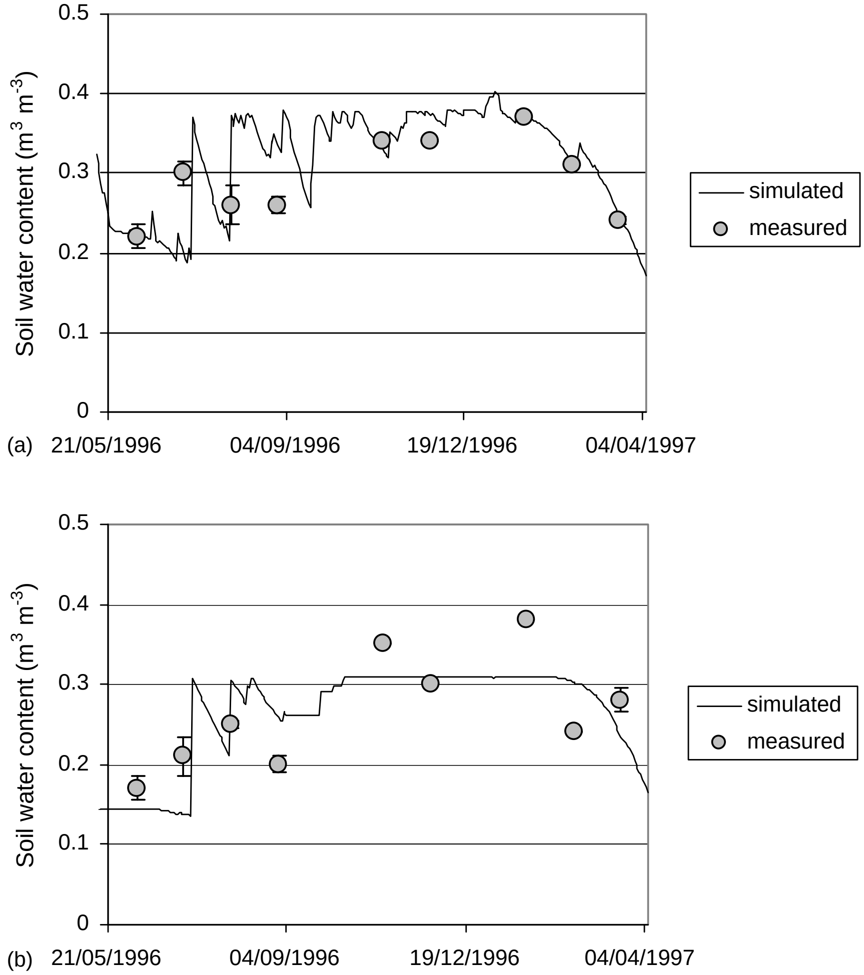

Fig. 5. Measured and simulated soil water content after validation—1-year rotation, May 1996–March 1997: (a) soil layer 0.0–0.3 m; (b) soil layer 0.3–0.6 m.

Table 7
Automatic scheduling of cutting events: indices of agreement between observed and simulated (with the three criteria described in the text) aboveground biomass (t AGB ha^{-1})

Year	Criterion	RRMSE (%)	EF	CRM	CD	Slope	Intercept (t AGB ha^{-1})	R^2
1996	SimBio	24	−0.11	0.06	0.07	−5.01	16.85	0.10
1996	SimPh	29	−0.31	−0.01	1.15	0.37	1.79	0.16
1996	SimBioPh	20	0.16	0.04	1.26	0.58	1.32	0.41
1997	SimBio	25	−4.75	−0.01	7.69	0.19	2.17	0.26
1997	SimPh	28	0.00	0.03	1.26	0.50	1.38	0.32
1997	SimBioPh	29	−0.07	0.02	0.93	0.46	1.50	0.20

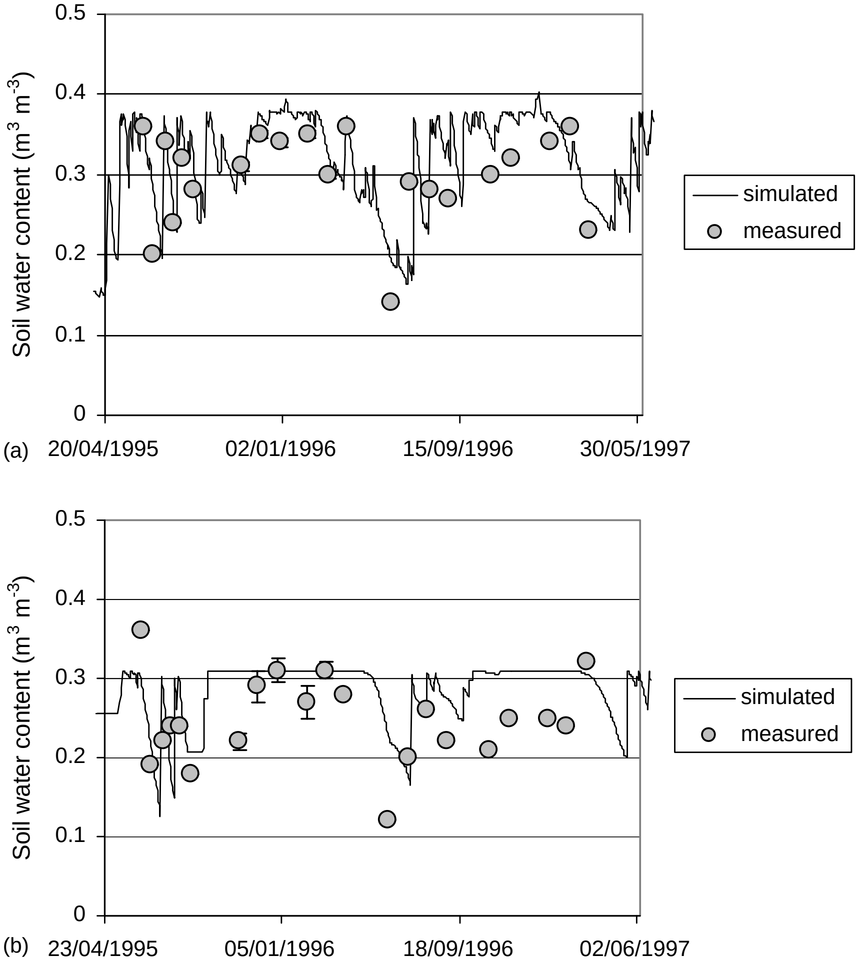

Fig. 6. Measured and simulated soil water content after validation—6-year rotation, June 1995–March 1996: (a) soil layer 0.0–0.3 m; (b) soil layer 0.3–0.6 m.

phenological stage and GDD in alfalfa for predicting morphological development may not be possible. However, when the purpose is to run scenarios comparisons, we believe that the SimBioPh method would allow to carry out better simulations than SimBio (which has comparable RRMSEs but worse CDs).

4. Conclusions

Even if CropSyst is a generic cropping systems simulation model, the cumulative simulated aboveground alfalfa biomass for the 3-year periods is consistent with measured values, and, in general, the biomass harvested at most of the cuts is properly simulated. Soil water content simulations are satisfactory as well. Even if some limitations have been underlined, this crop parameter set may be already used for explorative scenario simulations in the study area.

Besides the parameterisation of alfalfa, this work has demonstrated the robustness of the model for perennial forage crops simulation and has suggested improvements of the model (automatic scheduling of cuts, role of crown reserves). These improvements may be very important for CropSyst, which is increasingly used for management and planning purposes.

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References

Acutis, M., Ducco, G., Grignani, C., 2000. Stochastic use of LEACHN model to forecast nitrate leaching in different maize cropping systems. Eur. J. Agron. 13 (2/3), 191–206.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration—guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO, Food and Agriculture Organization of the United Nations, Rome, 300 pp.

Antolin, M.C., Yoller, J., Sánchez-Díaz, M., 1995. Effects of temporary drought on nitrate-fed and nitrogen-fixing alfalfa plants. Plant Sci. 107, 159–165.

Arbi, N., Smith, D., Bingham, E.T., 1979. Dry matter and morphological responses to temperatures of alfalfa strains with differing ploidy levels. Agron. J. 71 (4), 573–577.

Borin, M., Giupponi, C., Morari, F., 1997. Effects of four cultivation systems for maize on nitrogen leaching. 1. Field experiment. Eur. J. Agron. 6 (1/2), 101–112.

Bourgeois, G., 1990. Evaluation of an alfalfa growth simulation model under Quebec conditions. Agric. Syst. 32, 1–12.

Bula, R.J., 1972. Morphological characteristics of alfalfa plants grown at several temperatures. Crop Sci. 12 (5), 683–686.

Buntin, G.D., Pedigo, L.P., 1985. Alfalfa development, dry matter accumulation, and partitioning after surrogate insect defoliation of stubble. Crop Sci. 25 (6), 1035–1040.

Ceccon, P., Borin, M., Giupponi, C., 1993. Nutrients removed by pipe drains in two cropping systems. Eur. J. Agron. 2 (3), 223–230.

Denison, R.F., Loomis, R.S., 1989. An integrative physiological model of alfalfa growth and development. Publ. No. 1926. Division Agricultural Natural Research, University of California, Oakland, CA, 73 pp.

Donatelli, M., Stöckle, C., Ceotto, E., Rinaldi, M., 1997. Evaluation of CropSyst for cropping systems at two locations of northern and southern Italy. Eur. J. Agron. 6 (1/2), 35–45.

Durand, J.L., Lemaire, G., Gosse, G., Chartier, M., 1989. Analyse de la conversion de l'énergie solaire en matière sèche par un peuplement de luzerne (*Medicago sativa* L.) soumis à un déficit hydrique. Agronomie 9, 599–607.

Duru, M., Langlet, A., 1989. Dynamiques de croissance et installation de la surface foliaire de repousses de dactyle et de luzerne en conditions hydriques non limitantes. Agronomie 9, 973–984.

Fick, G.W., 1984. Simple simulation model for yield prediction applied to alfalfa in the Northeast. Agron. J. 76 (2), 235–238.

Fick, G.W., Onstad, D.W., 1983. Alfalfa growth models: ALSIM 1 (level zero) description, performance and user instructions for a base-line model of alfalfa yield and quality. Mimeo 83-26. Cornell University, Ithaca.

Giardini, L., Borin, M., 1996. Effects of annual set-aside on nitric-nitrogen content in the shallow water-table. Rivista di Agronomia 30 (3), 205–211.

Giardini, L., Berti, A., Morari, F., 1998. Simulation of two cropping systems with EPIC and CropSyst models. Ital. J. Agron. 2 (1), 29–38.

Gowgani, G.G., 1977. The effects of termoperiod on growth and development of *Medicago sativa* L. Dissert. Abstr. Int. B 37 (7), 3235–3236.

Grignani, C., Zavattaro, L., 2000. A survey on actual agricultural practices and their effects on the mineral nitrogen concentration of the soil solution. Eur. J. Agron. 12 (3/4), 251–268.

Holt, D.A., Bula, R.J., Miles, G.E., Schreiber, M.M., Peart, R.M., 1975. Environmental physiology, modelling, and simulation of alfalfa growth. I: Conceptual development of SIMED. Res. Bull. 907. Agricultural Experiment Station, Purdue University, West Lafayette, IN.

ISTAT, 2001. Fifth general census of Agriculture. http://agricoltura.censimenti.it/, on 25 June 2002.

Loague, K.M., Green, R.E., 1991. Statistical and graphical methods for evaluating solute transport models: overview and application. J. Contam. Hydrol. 7, 51–73.

Maggiore, T., Spallacci, P., Tano, F., 1998. Agronomic aspects of animal manures utilization. Rivista di Agronomia 32 (4), 173–195.

McLaughlin, R.J., Christie, B.R., 1980. Genetic variation for temperature response in alfalfa (*Medicago sativa* L.). Can. J. Plant Sci. 60, 547–554.

Morari, F., Giupponi, C., 1997. Effects of four cultivation systems for maize on nitrogen leaching. 2. Model simulation. Eur. J. Agron. 6 (1/2), 113–123.

Onofrii, M., Tomasoni, C., Borrelli, L., 1994. Effects of sowing dates on yeild, botanical composition and persistence of meadows on the Lombardy plain. Rivista di Agronomia 28 (3), 206–213.

Onofrii, M., Tomasoni, C., Borrelli, L., 1997. Performance of lucerne (*Medicago sativa* L.) cultivars subjected to two different cutting regimes. Part I. Yeilds. Rivista di Agronomia 31 (Suppl. 1), 187–191.

Pala, M., Stöckle, C.O., Harris, H.C., 1996. Simulation of durum wheat (*Triticum turgidum* spp. Durum) growth under differential water and nitrogen regimes in a Mediterranean environment using CropSyst. Agric. Syst. 51 (2), 147–163.

Pannkuk, C.D., Stöckle, C.O., Papendick, R.I., 1998. Evaluating CropSyst simulations of wheat management in a wheat-fallow region of the US Pacific Northwest. Agric. Syst. 57, 121–134.

Parsch, L.D., 1982. DAFOSYM: a system simulation model for analyzing the economics of forages on commercial dairy farms. Ph.D. thesis.

Parsch, L.D., 1987. Validation of ALSIM 1 (level 2) under Michigan conditions. Agric. Syst. 25, 145–157.

Romani, M., Onofrii, M., Maggiore, T., 1992. Yeilds of lucerne cultivars on the irrigated Lombardy Plain. Informatore Agrario 48 (44), 35–39.

Sanderson, M.A., 1992. Predictors of alfalfa forage quality: validation with field data. Crop Sci. 32 (1), 245–250.

Sanderson, M.A., Karnezos, T.P., Matches, A.G., 1994. Morphological development of alfalfa as a function of growing degree days. J. Prod. Agric. 7 (2), 239–242.

Savoie, P., Parsch, L.D., Rotz, C.A., Brook, R.C., Black, J.R., 1985. Simulation of forage harvest and conservation on dairy farms. Agric. Syst. 17, 117–131.

Schreiber, M.M., Miles, G.E., Holt, D.A., Bula, R.J., 1978. Sensitivity analysis of SIMED. Agron. J. 70 (1), 105–108.

Sheehy, J.E., Popple, S.C., 1981. Photosynthesis, water relations, temperature and canopy structure as factors influencing the growth of sainfoin (*Onobrychis viciifolia* Scop.) and Lucerne (*Medicago sativa* L.). Ann. Bot. 48, 113–128.

Smith, J.U., Glendining, M.J., Smith, P., 1997. The use of computer simulation models to optimise the use of nitrogen in whole farm systems. Aspects Appl. Biol. 50, 147–154.

Soil Survey Staff, 1999. Soil Taxonomy, second ed. Agricultural Handbook No. 436, USDA-NRCS, 869 pp.

Stöckle, C.O., Debaeke, P., 1997. Modeling crop nitrogen requirements: a critical analysis. Eur. J. Agron. 7, 161–169.

Stöckle, C.O., Nelson R.L., 1999. CropSyst User's Manual. Biological Systems Engineering Department, Washington State University, Pullman, WA, USA.

Stöckle, C.O., Martin, S.A., Campbell, G.S., 1994. CropSyst, a cropping systems simulation model: water/nitrogen budgets and crop yield. Agric. Syst. 46 (3), 335–359.

Stöckle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. Eur. J. Agron. 18 (3/4), 289–307 (Second special issue "2nd International Symposium on Modelling Cropping Systems, Florence, Italy").

Whitfield, D.M., Wright, G.C., Gyles, O.A., Taylor, A.J., 1986. Effects of stage growth, irrigation frequency and gypsum treatment of CO_2 assimilation of lucerne (*Medicago sativa* L.) grown on a heavy clay soil. Irrig. Sci. 7, 169–181.