CSIRO PUBLISHING
www.publish.csiro.au/journals/ajar *Australian Journal of Agricultural Research*, 2007, **58**, 75–86

Assessing the sustainability of wheat-based cropping systems using APSIM: model parameterisation and evaluation

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Abstract. Assessing the sustainability of crop and soil management practices in wheat-based rotations requires a well-tested model with the demonstrated ability to sensibly predict crop productivity and changes in the soil resource. The Agricultural Production Systems Simulator (APSIM) suite of models was parameterised and subsequently used to predict biomass production, yield, crop water and nitrogen (N) use, as well as long-term soil water and organic matter dynamics in wheat/chickpea systems at Tel Hadya, north-western Syria. The model satisfactorily simulated the productivity and water and N use of wheat and chickpea crops grown under different N and/or water supply levels in the 1998–99 and 1999–2000 experimental seasons. Analysis of soil-water dynamics showed that the 2-stage soil evaporation model in APSIM's cascading water-balance module did not sufficiently explain the actual soil drying following crop harvest under conditions where unused water remained in the soil profile. This might have been related to evaporation from soil cracks in the montmorillonitic clay soil, a process not explicitly simulated by APSIM. Soil-water dynamics in wheat–fallow and wheat–chickpea rotations (1987–98) were nevertheless well simulated when the soil water content in 0–0.45 m soil depth was set to 'air dry' at the end of the growing season each year. The model satisfactorily simulated the amounts of NO_3-N in the soil, whereas it underestimated the amounts of NH_4-N. Ammonium fixation might be part of the soil mineral-N dynamics at the study site because montmorillonite is the major clay mineral. This process is not simulated by APSIM's nitrogen module. APSIM was capable of predicting long-term trends (1985–98) in soil organic matter in wheat–fallow and wheat–chickpea rotations at Tel Hadya as reported in literature. Overall, results showed that the model is generic and mature enough to be extended to this set of environmental conditions and can therefore be applied to assess the sustainability of wheat–chickpea rotations at Tel Hadya.

Additional keywords: wheat, chickpea, Mediterranean, model evaluation, soil water, soil nitrogen.

Introduction

Crop production in the semi-arid regions bordering the Mediterranean is inherently constrained by variable, often deficient, rainfall (Cooper *et al*. 1987), fragile soil (Le Houérou 1981), and limited renewable water resources (Araus 2004). Today, the sustainability of crop production systems is at stake because of the degradation of agriculturally productive soil (Lal 2002) and water resources (Varela-Ortega and Sagardoy 2002). For agricultural production in the West Asia–North Africa (WANA) region to meet the demand imposed by today's demographic developments requires the more efficient use of water within cropping systems, and crop management techniques that maintain or improve soil quality (Araus 2004; Lal 2006).

In such water-limited environments, the long-term consequences of agricultural practices on crop productivity, water-use efficiency, and soil quality are difficult to assess because rainfall variability may mask existing trends. A complement to traditional field experimentation is cropping-systems analysis using simulation techniques that integrate long-term climatic records, and consequently allow the outcomes of agricultural interventions to be quantified across the observed rainfall variability (Meinke and Stone 2005). The cropping-systems model APSIM (Agricultural Production Systems Simulator) is designed to simulate, on a daily basis, the dynamics of crop growth, soil water, soil carbon, and nitrogen (N) as a function of climate, cropping history, and the crop/soil management in either individual seasons or crop sequences (Keating *et al*. 2003).

APSIM has proven suitable for the analysis of the complex issues arising in cropping systems. Jones *et al*. (1996), for example, assessed the N contributions of a legume ley to

 10.1071/AR06186 0004-9409/07/010075

subsequent maize in the semi-arid tropics of Australia. Carberry *et al*. (2002) researched issues related to improved nutrient efficiency (nitrogen, phosphorus) in low-input cropping systems of semi-arid Kenya. Murray-Prior *et al*. (2005) applied APSIM to quantify returns, risks, and environmental trade-offs (i.e. subsoil drainage, runoff) in rotations with and without lucerne in a subtropical environment of north-eastern Australia. In studies conducted in Mediterranean environments of Australia, Yunusa *et al*. (2004) used APSIM to predict growth and grain yield of wheat and barley, as well as the soil-water dynamics, in various rotations including pastures, and Asseng *et al*. (2001) analysed the water- and nitrogen-use efficiency of wheat.

So far, APSIM has not been applied in wheat-based systems of the semi-arid Mediterranean of WANA. The operation of a model under a new set of conditions requires input data with sufficient detail for the intended application (Hunt and Boote 1998), and the accuracy of model predictions needs to be aligned with the context of the study (Rykiel 1996). Accordingly, the objectives of this study were (*i*) to collect experimental crop and soil data for deriving the essential parameter settings for applying APSIM in systems with durum wheat (*Triticum turgidum* ssp. *durum*) and kabuli chickpea (*Cicer arietinum*) at Tel Hadya, north-western Syria, and (*ii*) to evaluate the capability of APSIM to simulate grain yield, biomass production, crop N uptake, the efficiency of crop water use, as well as the soil water, nitrogen, and carbon dynamics in wheat and chickpea systems at the study site. This study is an essential prerequisite for the application of ASPIM in scenario analyses, which will involve assessing sustainable management strategies for potential wheat–chickpea rotations. This will be presented in a subsequent paper.

Materials and methods

Site description

Field experiments were carried out during the 1998–99 and 1999–2000 seasons at the main experimental station of the International Center for Agricultural Research in the Dry Areas (ICARDA) at Tel Hadya, north-western Syria. The site (36°01′N, 36°56′E; elevation 284 m) has a semi-arid, continental Mediterranean climate with cool, wet winters and hot, dry summers. Average annual precipitation is 340 mm and the mean annual temperature is 17.6°C. The growing season for winter crops is from early/mid November to early/late May.

The soils at Tel Hadya belong to the Vertisol and Inceptisol Soil Group (Ryan *et al*. 1997). The parent material is limestone, and the pH is around 8 throughout the profile. The soil organic matter content is mostly lower than 1% in the 0–0.20 m layer. The principal clay mineral present is montmorillonite. In summer, soil cracks form that are 5.0–10.0 mm wide and up to 1.0 m deep (Ryan *et al*. 1997). The soils in the experimental fields varied in their texture (Moeller 2004), with clay contents (<2 µm) ranging from 40 to 50% in the 0–0.15 m depth, increasing to 50–60% in the 0.45–0.60 m layer. The sand fraction (63–2000 µm) ranged from 5 to 14% in the 0–0.15 m depth and from 5 to 11% in the 0.45–0.60 m depth, and the silt fraction (2–63 µm) was about 47% in the 0–0.15 m depth, decreasing to 35–37% in the 0.45–0.60 m depth.

Experiments for model parameterisation

Experiments with wheat (cv. Cham3) and chickpea (cv. Ghab2) were conducted to quantify crop productivity, crop N content, the soil-water dynamics, and changes in soil mineral N under different N fertiliser regimes and/or water supply. The experiments and data collection have been described in detail by Moeller (2004) and are summarised in Table 1. The experimental design was a randomised complete block with 4 replications. Individual plot size measured 10 by 6.3 m in 1998–99 and 7 by 4.2 m in 1999–2000. Following primary tillage with a plough, seedbed preparation was carried out with a harrow. Phosphorus fertiliser was applied prior to sowing at a rate of 13–22 kg P/ha as part of the standard on-station soil management. Pests, diseases, and weeds were controlled with common on-station measures.

Wheat was sown at 0.05-m depth, 0.175-m row spacing, and a target plant density of 300 plants/m^2 on land that was previously under either chickpea (1998–99) or cumin (*Cuminum cyminum*) (1999–2000). In 1999–2000, 30 mm of supplemental irrigation (SI) was applied at wheat sowing using sprinklers, and a total of 312 mm SI was applied between the late vegetative and grain-filling stage using a drip-irrigation system (Rain Tape PC, Rain Bird Corp.). Nitrogen fertiliser (urea) was applied only to wheat. Chickpea was sown at 0.06-m depth, 0.35-m row spacing, and a target plant density of 50 plants/m^2 on land previously cropped with wheat. In 1999–2000, the irrigated chickpea treatment received a total of 208 mm SI between the late vegetative and late flowering stage using the drip-irrigation system as specified above.

Table 1. Experimental conditions, Tel Hadya, 1998–2000: nitrogen (N) fertiliser rate (kg/ha), seasonal rainfall (mm), total supplemental irrigation (SI, mm), and dates of sowing (S), emergence (E), flowering (F), and physiological maturity (M)

Treatment	N	Rain	SI	S	E	F	M
				Wheat			
W_{99}W0-N60	60	307	0	25.xi.98	10.xii.98	19.iv.99	10.v.99
W_{00}W1-N0	0	261	342	23.xi.99	03.i.00	20.iv.00	21.v.00
W_{00}W1-N100	100	261	342	23.xi.99	03.i.00	20.iv.00	21.v.00
				Chickpea			
CP_{99}W0	0	307	0	29.xi.98	24.xii.98	16.iv.99	17.v.99
CP_{00}W0	0	261	0	22.xii.99	31.i.00	19.iv.00	19.v.00
CP_{00}W1	0	261	208	22.xii.99	31.i.00	24.iv.00	31.v.00

To monitor growth, crop data were collected throughout the seasons (9 harvests in 1998–99 and 4–5 harvests in 1999–2000). In each replication, a net area of 8.4 m^2 was available for destructive plant sampling. On each occasion, total above-ground biomass and the leaf area were assessed. The latter was measured with a leaf-area meter (LI-3100, Li-Cor, Lincoln, NE, USA). Phenological development was monitored in the field and on the samples collected. Straw N concentrations were assessed 3 times throughout the seasons. In 1999–2000, samples were partitioned into green leaf, stem, and reproductive organs prior to N analysis. At final harvest, total above-ground biomass, yield, and grain N concentrations were assessed.

Changes in soil-water profiles were monitored using a calibrated Wallingford neutron probe. Measurements were taken in 0.15-m increments to, depending on soil, 1.2–1.8 m depth in 2 replicates of each treatment at 1–4-week intervals. Soil water in the 0–0.15 m depth was measured gravimetrically. At each occasion, gravimetric sampling was replicated twice in 1998–99 and 4 times in the 1999–2000 season. Evapotranspiration (ET, mm) from sowing to maturity was calculated from rainfall, irrigation (1999–2000 only), and the soil moisture data. In the calculation of ET, we assumed that runoff was negligible because experiments were conducted on flat terrain, and the large amounts of irrigation were applied using a drip-irrigation system. There was also no drainage beyond the maximum depth of soil-water measurements. The water-use efficiency of total dry matter (WUE_{TDM}) and grain yield (WUE_{GY}) was calculated as total biomass or yield produced per unit ET from sowing to maturity and expressed in g/m^2.mm.

Six soil samples randomly taken prior to sowing were analysed for organic carbon (OC%), total N (N_{tot}, μg/g), nitrate (NO_3-N, μg/g), and ammonium (NH_4-N, μg/g). Samples collected from 2 replications in each treatment at around flowering and after harvest were analysed for mineral N. Soil samples were taken in 0.15-m increments to a maximum depth of 0.90 m, except in 1998–99, where the first samples were taken in 0.20-m increments. An estimate of the ability of the soil to mineralise and supply N to a well-watered crop was calculated with data on soil mineral N and total crop N content from the unfertilised and irrigated wheat treatment (W_{00}W1-N0). In a simple N balance it was assumed that all N taken up by unfertilised wheat originated from the soil, either from the mineral N pool or from mineralisation. N contributions from rain and other sources as well as N turnover within the soil were not included in the calculation.

Data analysis

Experimental data were subjected to the general linear model (GLM) univariate procedure in SPSS 10.0 (SPSS Inc. 1999). Sampling dates were analysed separately.

Experiment for model evaluation

Long-term soil-water data and information on trends in soil organic carbon from a rotation experiment conducted at Tel Hadya were used for model evaluation (Harris 1990, 1995). The experiment (Productivity of Cropping Systems Trial; PCS Trial, 1983–98) was not specifically designed for modelling purposes. Thus, the analysis was not conducted on yield data due to substantial parameter uncertainty such as crop phenology or damages to crops by diseases or weather hazards.

Detailed descriptions of the PCS Trial are given by Harris (1990, 1995) and are briefly summarised here. In the PCS Trial, durum wheat was rotated with fallow, chickpea, and 5 other crops (vetch, lentil, medic, wheat, water melon) from 1983–84 to 1997–98. In the first 2 years of the trial, no fertiliser was used. From 1985 onwards, treatments involved the application of N fertiliser to wheat at rates of 0, 30, 60, and 90 kg N/ha (N0, N30, N60, N90), and 3 intensities of grazing wheat stubble (heavy, moderate, and zero). Nitrogen fertiliser was applied only to wheat. During the early years of the trial, tillage was carried out with a tyned cultivator followed by a spade-tooth harrow. Since 1987, the soil was cultivated only once after the wheat phase, with a ducksfoot cultivator. Sowing dates varied between seasons, but were mostly in the second half of November for wheat and early December for chickpea. Seeding rate was 120 kg/ha for both wheat and chickpea. Soil water contents were measured in 0.15-m increments in 2-week to 2-month intervals in 2 replicates of the N0 and N90 treatments subjected to zero and heavy grazing. Soil water in the 0–0.15 m depth was measured gravimetrically, whereas a neutron-probe technique was used at depth greater than 0.15 m. Measurements were available from October 1986 to June 1989, and from October 1991 to June 1998. Information on trends in soil organic matter (1989–95) was taken from studies of Ryan (1997) and Masri and Ryan (2006).

Climatic data

Daily weather data (precipitation, minimum and maximum temperatures, solar radiation, class A pan evaporation) from 1985 to 2000 were recorded close to the experiments.

Model description and parameterisation

A configuration of APSIM version 4.2 was used, which included the WHEAT (version 3.1; Wang *et al*. 2003) and CHICKPEA crop modules (Robertson *et al*. 2002), and the SOILWAT2, SOILN2, and RESIDUE2 modules (Probert *et al*. 1998). A comprehensive description of the processes involved in modelling crops in APSIM as well as the origin of subroutines is given by Wang *et al*. (2002). Within APSIM, a concept of *specific* and *generic* parameters is used. *Specific* parameters need parameterisation before the model can be applied under a new set of conditions. *Generic* parameters are thought to apply across environments and crop cultivars and should therefore not require calibration. Details on *specific* parameters and their values in the present study are given by Moeller (2004).

Crop modules in APSIM predict phenological development, leaf-area growth, biomass accumulation, grain yield, N fixation by legumes, N and water uptake, and root growth. Temperature and photoperiod determine the rate of crop development. Potential biomass growth is a function of the intercepted radiation and the radiation-use efficiency. Water-limited growth is a function of water supply and the transpiration efficiency of the crop, which varies daily as a function of vapour pressure deficit. Actual biomass increase is simulated from either potential or water-limited growth as modified by temperature and N stresses. Crop N demand is driven by growth-stage-dependent optimum (critical) N concentration limits, which the crop attempts to maintain. For legumes, N comes from fixation if mineralised N supplies are not sufficient to maintain the optimum crop N concentration (for further details see Keating *et al*. 2003 and references therein).

Essential cultivar-specific parameters required by WHEAT and CHICKPEA are related to crop phenology. These parameters were obtained by calibration considering emergence and flowering dates from the 1998–99 and 1999–2000 seasons and dates of physiological maturity from the irrigated treatments.

Modules for soil N and carbon (SOILN2), soil water (SOILWAT2), and surface residues (RESIDUE2) dynamics operate for a 1-dimensional, layered soil. Processes are simulated for each soil layer, with water and nitrate moving between layers where gradients exist. SOILWAT2 is a cascading soil-water balance model. Soil water characteristics are specified in terms of saturated water content (SAT), drained upper limit (DUL), and the lower limit (LL15) of plant-extractable soil water. Saturated flow is calculated using a soil-specific portion of water above DUL that drains in one day to the soil layer below. Soil evaporation (E_s) may dry the topsoil layer to some specified value below LL15 (Air-Dry).

Evaporation from the soil surface is simulated using Ritchie's (1972) 2-stage evaporation model, which requires U (amount of water lost during the energy-limiting evaporation phase) and CONA (controls E_s during the soil-water-limiting phase) as input. Values for U and CONA were 4 mm and 4 mm/day$^{0.5}$, respectively, similar to those proposed by Stapper (1984) for soils at Tel Hadya. The magnitude of unsaturated flow was modelled using the default diffusivity parameter values from CERES (Jones and Kiniry 1986), i.e. the constant was 88 and the slope 35.4. Estimates of SAT, DUL, and LL15 were obtained for each individual experimental field from soil-water profiles measured throughout the 1998–99 and 1999–2000 seasons (Moeller 2004) and from soil-water measurements conducted in the PCS Trial (Harris 1994). Soil water measured prior to sowing defined the starting conditions of the simulations. The experimental soils have been described in detail by Moeller (2004). Soil-water characteristics of the soil of the chickpea experiment conducted in 1999–2000 are given in Table 2.

SOILN2 simulates the mineralisation and immobilisation of mineral N, nitrification, denitrification, and the hydrolysis of urea. Conceptual soil-carbon pools built into SOILN2 are BIOM, HUM, and FOM. BIOM represents the more active component of soil organic matter (SOM), and HUM the more stable pool. FOM is the fresh organic matter pool and consists of root residues and above-ground crop residues incorporated into the soil by tillage operations. Flows between pools are calculated in terms of carbon; the corresponding N flows depend on the C : N ratio of the receiving pool.

Input parameters related to decomposition are *finert* (fraction of HUM that is not susceptible to decomposition) and *fbiom* (BIOM as fraction of susceptible HUM) (Probert *et al*. 1998). Estimates of *finert* and *fbiom* for the upper 0–0.15 m layer were derived from data of Jenkinson *et al*. (1999) from the same site. Crop and soil data from the W_{00}W1-N0 treatment were used to calculate a simple N balance assuming that all N taken up by the crop originated from the soil. These data allowed assessment of the potential of the soil to supply N to an unfertilised and well-watered crop, and thus subsequent calibration of *finert* and *fbiom* for the rooted profile. Starting conditions of simulations were further defined by ammonium (NH_4-N), nitrate (NO_3-N), and percent organic carbon (OC) measured in the 1998–99 and 1999–2000 seasons (Table 3). The value of soil pH was set to pH 8 throughout the profile (Ryan *et al*. 1997).

Model evaluation

The capability of APSIM for simulating long-term soil-water dynamics and trends in soil organic carbon was tested against experimental data from the PCS Trial. The model was set up to simulate 4 treatments of the PCS Trial starting on 1 October 1985 and ending on 31 October 1998. The simulated rotations were wheat–chickpea with 0, 30, and 90 kg N/ha applied at wheat sowing (WN0-CP, WN30-CP, WN90-CP), and wheat–fallow with 0, 30, and 90 kg N/ha applied at sowing (WN0-F, WN30-F, WN90-F), both subjected to zero grazing. In the simulations, crops were sown at 0.05-m depth. Sowing dates varied between seasons. Wheat was sown between 9 November and 15 December, and chickpea between 18 November and 30 December. The target plant density was 300 plants/m^2 for wheat and 50 plants/m^2 for chickpea. After the wheat phase, 75% of straw residues were removed from the system; the remaining

Table 2. Saturated soil water content (SAT), upper (DUL) and lower (LL15) limit of plant-available soil water, air-dry soil water content (Air-Dry), initial soil water (SW), and bulk density (BD) used to initialise SOILWAT2 for 1999–2000 chickpea simulations

Depth (m)	SAT	DUL	LL15 (m^3/m^3)	Air-Dry	SW	BD (g/cm^3)
0–0.15	0.50	0.36	0.16	0.08	0.082	0.96
0.15–0.30	0.48	0.34	0.14	0.07	0.083	1.09
0.30–0.45	0.46	0.36	0.16	0.13	0.136	1.15
0.45–0.60	0.44	0.38	0.19	0.18	0.189	1.18
0.60–0.75	0.42	0.38	0.21	0.21	0.230	1.24
0.75–0.90	0.42	0.38	0.23	0.23	0.256	1.26
0.90–1.05	0.41	0.38	0.24	0.24	0.265	1.30
1.05–1.20	0.39	0.38	0.26	0.26	0.281	1.30
1.20–1.35	0.39	0.37	0.27	0.27	0.294	1.30
1.35–1.50	0.39	0.37	0.28	0.28	0.295	1.30

Table 3. Ammonium (NH_4-N) and nitrate (NO_3-N) nitrogen, soil organic carbon (OC), and values for the parameters *fbiom* and *finert* used to initialise the SOILN2 module of APSIM

Values for NH_4-N and NO_3-N are given for the 1999–2000 chickpea simulations only

Depth (m)	NH_4-N (µg/g)	NO_3-N	OC (%)	*fbiom*	*finert*
0–0.15	5.22	4.26	0.58	0.05	0.163
0.15–0.30	4.26	3.56	0.52	0.05	0.17
0.30–0.45	3.27	2.76	0.40	0.36	0.22
0.45–0.60	3.00	2.93	0.26	0.32	0.3
0.60–0.75	2.64	2.76	0.23	0.03	0.4
0.75–0.90	2.77	2.92	0.22	0.02	0.6
0.90–1.05	2.0	2.0	0.2	0.01	0.8
1.05–1.20	2.0	2.0	0.2	0.01	0.9
1.20–1.35	2.0	2.0	0.2	0.01	0.9
1.35–1.50	2.0	2.0	0.2	0.01	0.9

residues were left on the soil surface. After chickpea, 90% of surface residues were incorporated at 0.25-m depth.

Results and discussion

Growing conditions and crop development

Seasonal precipitation was 307 mm in 1998–99 and 261 mm in 1999–2000, which was 10 and 23% below the long-term average, respectively. The distribution of rainfall varied considerably between the two seasons (Fig. 1). Both the rainfall distribution and winter temperatures were more conducive to growth in 1998–99 compared with 1999–2000. In 1999–2000, cumulative rainfall until mid-November 1999 was only 13 mm, with individual rainfall events ranging from 0.1 to 7 mm/day. Most of this water evaporated and was not available to the crops. Effective winter rains started on 14 December 1999 with a rainfall event of 17 mm, which was 1 month later than in 1998–99. At this time, temperatures were low enough to inhibit crop growth. Frost occurred on 21 days in 1998–99 and on 53 days in 1999–2000.

Wheat emerged 24 days later in 1999–2000 compared with 1998–99, although sowing dates were similar (Table 1). The late emergence may have been a consequence of suboptimal temperatures that affected both germination (Wuest *et al.* 1999) and the time from germination to crop emergence (Khah *et al.* 1986) at times when the seedling layer was already sufficiently wet (i.e. after initial irrigation with 30 mm on 12 December 1999). APSIM predicted emergence 9 days earlier than observed, indicating that the effect of the adverse growth conditions on the duration of pre-emergence growth stages was not accurately simulated. In APSIM, germination depends on soil moisture only, which might have contributed to this. To allow appropriate evaluation of subsequent growth stages, the sowing depth for 1999–2000 was increased to 0.08 m and simulated emergence improved by 5 days. Emergence was well predicted for 1998–99.

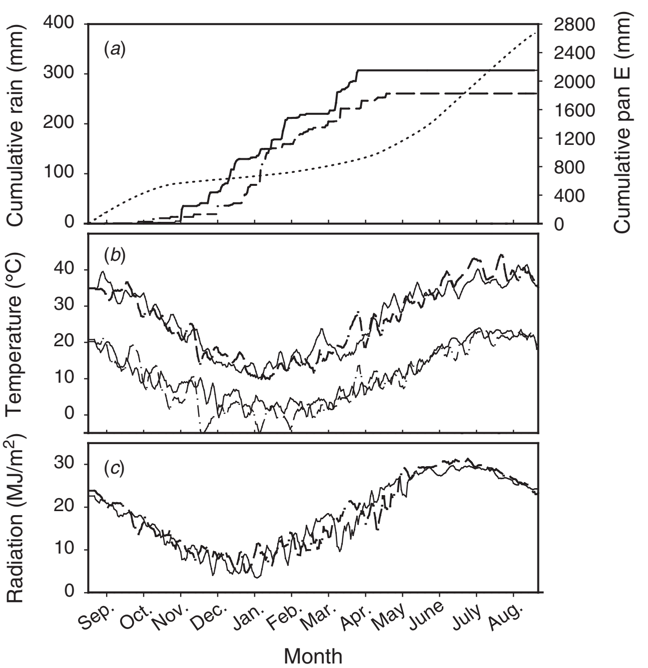

Fig. 1. Climatic conditions from 1 September to 31 August throughout the 1998–99 (—) and 1999–2000 (– –) cropping seasons at Tel Hadya, Syria: (*a*) cumulative daily rainfall and cumulative class A pan evaporation averaged across seasons (•••); (*b*) maximum and minimum temperatures (running means of 5 days); (*c*) solar radiation (running mean of 5 days).

As a consequence of late emergence observed in 1999–2000, the pre-flowering period was 21 days shorter in 1999–2000 compared with 1998–99, so that wheat flowered in the second half of April in both seasons (Table 1). The post-flowering phase (start flowering to physiological maturity) was 10 days longer when wheat was irrigated (1999–2000), indicating that physiological maturity was hastened under rainfed conditions (1998–99). This is supported by a study of McMaster and Wilhelm (2003) who found that the response of a range of wheat cultivars to water stress was to reach anthesis and maturity earlier.

Effects of water stress on phenological development are currently not simulated by WHEAT, and part of the differences between observed and predicted phenology can be attributed to this. The model predicted flowering 3 days earlier and 5 days later than observed in 1998–99 and 1999–2000, respectively. The length of the post-flowering phase was simulated well for the irrigated treatments, which were used to parameterise the thermal time requirement from the start of flowering to physiological maturity, but over-predicted for the rainfed W_{99}W0-N60 treatment.

Chickpea flowered from mid to late April in both 1998–99 and 1999–2000 seasons despite sowing being 3 weeks later and emergence being 5 weeks later in 1999–2000 (Table 1). Rainfed chickpea took 34 days more from emergence to flowering in the 1998–99 than in the 1999–2000 season. In 1999–2000, water stress significantly hastened crop development. Flowering occurred 5 days and physiological maturity 12 days earlier in the CP_{00}W0 than in the CP_{00}W1 treatment. This response has been previously described by Singh (1991) for chickpea and Desclaux and Roumet (1996) for soybean, but is currently left un-parameterised in CHICKPEA (Robertson *et al.* 2002). As a consequence, CHICKPEA simulated flowering 6 days later and maturity 16 days later than observed for the CP_{00}W0 treatment. The timing of these growth stages was well predicted for the CP_{00}W1 treatment. For 1998–99, flowering was simulated 6 days and physiological maturity 15 days earlier than observed.

Wheat and chickpea growth attributes

In wheat experiments conducted in 1999–2000, the application of 100 kg N/ha significantly increased total biomass, yield, total crop N content, and grain N content compared with the unfertilised treatment. Maximum measured leaf-area index (LAI) was 50% higher in the W_{00}W1-N100 treatment compared with the W_{00}W1-N0 treatment ($P \le 0.05$). Overall, WHEAT simulated total above-ground biomass, yield, and total N uptake well across the contrasting growth conditions in both seasons (Fig. 2).

During pre-anthesis growth at 90–130 days after sowing (DAS), WHEAT overestimated leaf-area growth for all

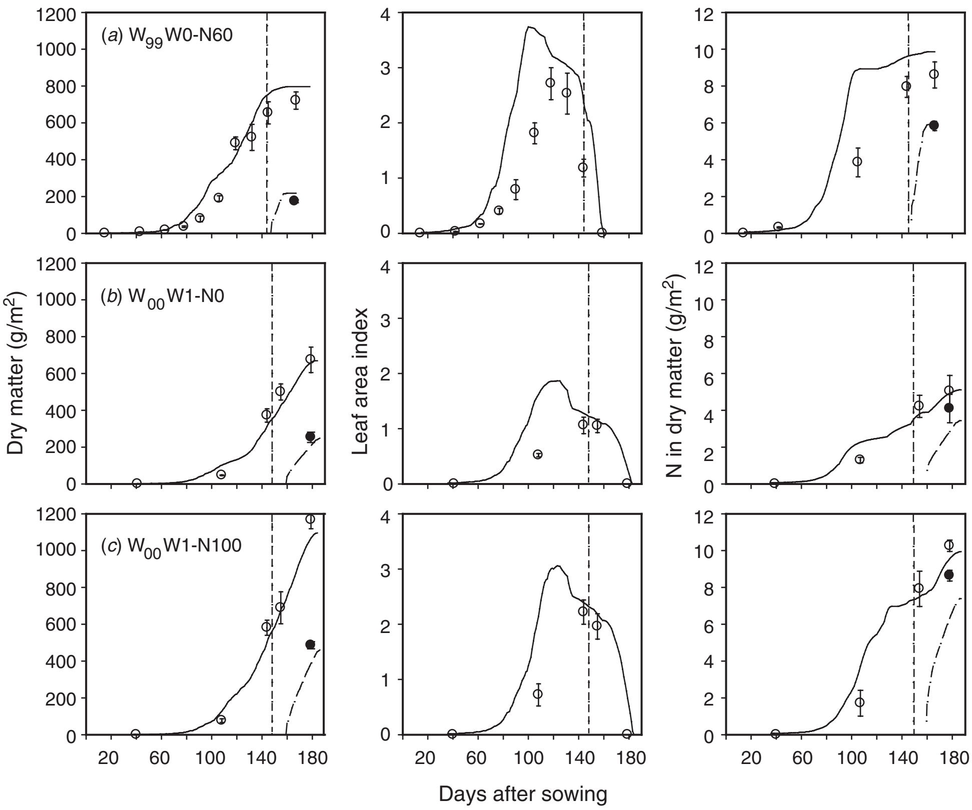

Fig. 2. Predicted (curves) and observed (symbols) above-ground dry matter [total biomass (○), yield (●)], leaf area development, and nitrogen (N) in dry matter [total N (○), grain N (●)] of wheat grown at Tel Hadya: (*a*) 1998–99 season, rainfed, fertiliser rate: 60 kg N/ha; (*b*) 1999–2000 season, supplemental irrigation, no N fertiliser; (*c*) 1999–2000 season, supplemental irrigation, fertiliser rate: 100 kg N/ha. The observed date of anthesis is indicated by the vertical line, and ± 1 s.e. by vertical bars.

treatments (Fig. 2). Crop N uptake and biomass accumulation were simultaneously overestimated, although this was less pronounced. Similar shapes of the LAI curves across treatments suggest that this is an intrinsic part of the model, possibly related to the function describing leaf-area growth. In WHEAT (Wang *et al.* 2003), potential leaf-area expansion is calculated from thermal time since emergence and is not linked to biomass accumulation (Meinke *et al.* 1998). Water and nitrogen limitations affect leaf area growth directly rather than via biomass production. However, leaf-area expansion affects biomass accumulation via radiation interception. Thus, the slight over-prediction of pre-anthesis biomass growth can be a consequence of the overestimation of leaf area. More rapid biomass growth increased simulated crop N demand and could have caused the overestimation of crop N uptake during the same period. However, total biomass and total N uptake were well predicted.

In 1998–99, wheat used all seasonal precipitation as evapotranspiration (ET), which was simulated well (Table 4). In 1999–2000, total water supply from rainfall and irrigation exceeded crop demand by 155 mm in the W_{00}W1-N0 and 136 mm in the W_{00}W1-N100 treatment. Total ET was well predicted for the W_{00}W1-N100 treatment but slightly underestimated (14%) for the W_{00}W1-N0 treatment. Drainage below 1.50 m soil depth, which could have potentially biased calculated ET, did not occur (not shown). Similarly, runoff was not observed as the experiment was conducted on flat terrain and the large amounts of irrigation were applied using a drip-irrigation system. A possible reason for the underestimation of ET is the appearance of shrinkage cracks (Ryan *et al.* 1997) in the upper soil layer beneath the sparse canopy of the W_{00}W1-N0 treatment. Such cracks may have opened additional pathways for

Table 4. Observed (obs.) and simulated (sim.) evapotranspiration (ET) from sowing to crop maturity (mm), and water-use efficiency of total dry matter (WUE_{TDM}) and of grain yield (WUE_{GY}) for wheat and chickpea crops (g/m².mm) grown at Tel Hadya, Syria

Treatment	ET		WUE_{TDM}		WUE_{GY}	
	obs.	sim.	obs.	sim.	obs.	sim.
			Wheat			
W_{99}W0-N60	303	309	2.35	2.57	0.57	0.70
W_{00}W1-N0	448	387	1.50	1.73	0.56	0.64
W_{00}W1-N100	467	467	2.50	2.35	0.98	0.99
			Chickpea			
CP_{00}W0	208	238	1.13	0.75	0.19	0.14
CP_{00}W1	403	411	1.44	1.31	0.38	0.45

evaporation (Ritchie and Adams 1974), which are not simulated by the model.

In irrigated wheat, the application of 100 kg N/ha reduced unproductive, evaporative water losses and resulted in significantly higher water-use efficiencies compared with the unfertilised treatment ($P \leq 0.05$). Similar responses have been reported for bread wheat grown under Mediterranean conditions (Zhang *et al*. 1998), with WUE_{GY} ranging from 0.25 to 1.05 g/m^2.mm. Overall, WHEAT simulated the water-use efficiencies with reasonable accuracy (Table 4).

In chickpea experiments, measured total biomass production, grain yield, maximum LAI, crop N, and grain N content were significantly lower in the $CP_{00}W0$ treatment than in the $CP_{00}W1$ treatment ($P \leq 0.05$). In 1998–99, a fungal disease (*Ascochyta rabiei*) was observed one week before flowering and subsequently affected leaf area. As APSIM does not simulate effects of pests and diseases, only data of the 1999–2000 season are shown here.

Overall, CHICKPEA simulated yield and leaf-area development well for chickpea cv. Ghab2 grown under 2 contrasting water regimes in 1999–2000 (Fig. 3). The model reproduced the response of total biomass production to different levels of water supply, although total biomass was slightly underestimated (<25%). Using the observed dates of phenology as input to the model did not improve biomass predictions (not shown), suggesting that differences between observed and simulated crop growth were not a result of errors in phenology. Total crop N content was slightly overestimated for the $CP_{00}W1$ treatment (19%) and under-predicted for the $CP_{00}W0$ treatment (35%).

CHICKPEA simulated the proportion of N in above-ground biomass derived from biological N fixation as 27 and 69% in the rainfed and irrigated treatment, respectively. These values are within the range of reported observations. Beck *et al*. (1991) reported percentages of N derived from fixation of 8–21% for spring-sown chickpea grown at Tel Hadya, which typically experiences severe water-stress conditions. Reported values for winter-sown chickpea grown at Tel Hadya range from 14 to 80% (Beck *et al*. 1991; Beck 1992; McNeill *et al*. 1996).

Observed ET in the $CP_{00}W0$ treatment was around 50 mm less than the amount of water supplied by seasonal rainfall (Tables 1 and 4). Thomas *et al.* (1995) reported available soil water remaining in the profile at maturity when chickpea was grown under conditions of water stress. The reason for this could not be established. CHICKPEA over-predicted ET for this treatment, possibly because the amount of soil water taken up by the crop was overestimated as a consequence of an over-prediction of rooting depth (not shown). The water-use efficiencies in the $CP_{00}W0$ treatment were significantly lower than in the $CP_{00}W1$ treatment ($P \leq 0.05$) (Table 4). Our observations are within the range of values reported by Zhang *et al*. (2000), who calculated WUE_{GY} ranging from 0.19 to 0.55 g/m^2.mm and WUE_{TDM} from 0.5 to 1.42 g/m^2.mm for rainfed chickpea grown at Tel Hadya.

The prediction accuracy of both the WHEAT and CHICKPEA modules has been extensively tested under a wide range of management and environmental conditions. For example, the WHEAT module within APSIM explained over 80% of the variation in total biomass (RMSD = 162 g/m^2) and grain yield (RMSD = 74 g/m^2), and 79% of the variation in total N uptake (RMSD = 2 g/m^2) and 75% of the variation in grain N content (RMSD = 1.8 g/m^2) when compared with experimental data from Queensland, Australia ($n = 106$) (Wang *et al*. 2003). When compared with data from a Mediterranean environment in Western Australia ($n \geq 36$) the model accuracy was lower. However, WHEAT still explained over 65% of the variation in total biomass (RMSD = 139 g/m^2) and yield (RMSD = 56 g/m^2). In a similar meta-study, the CHICKPEA

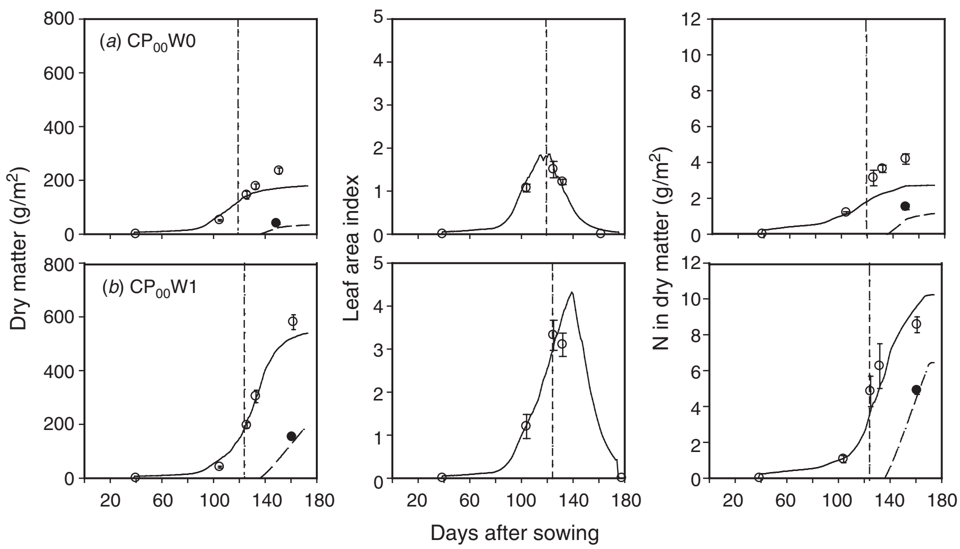

Fig. 3. Predicted (curves) and observed (symbols) above-ground dry matter [total biomass (○), yield (●)], leaf area development, and nitrogen (N) in dry matter [total N (○), grain N (●)] of (*a*) rainfed and (*b*) irrigated chickpea grown in 1999–2000 at Tel Hadya. The observed date of anthesis is indicated by the vertical line, and ± 1 s.e. by vertical bars.

module was found to explain 71% of the variation in total biomass (RMSD = 125 g/m^2) and 70% of the variation in grain yield (RMSD = 46 g/m^2) (n = 31) (Robertson *et al*. 2002). Given the overall satisfactory performance of these modules in the present study, we conclude that an extrapolation to different seasons at Tel Hadya is sound.

Soil-water dynamics

Under all conditions, there was a good agreement between observed and simulated soil-water dynamics from sowing to physiological maturity. Following crop maturity, the drying of the upper soil layers (0–0.15, 0.15–0.30 m) was well predicted for rainfed wheat and chickpea (W_{99}W0-N60, CP_{00}W0) and irrigated chickpea (CP_{00}W1). In the W_{00}W1-N0 and W_{00}W1-N100 treatments, large amounts of residual plant-available soil water (PAW) remained in the soil profile after crop maturity (155 and 136 mm, respectively). Under these conditions, the model considerably underestimated the subsequent water loss from the soil profile (Fig. 4).

The difference between simulated and observed soil drying in the 0–0.30 m depth under conditions with significant amounts of PAW left in the profile after crop maturity is likely to be related to the swell and shrink behaviour of the montmorillonitic clay soils at Tel Hadya, which is not simulated by APSIM's cascading water-balance model. In clay soils at Tel Hadya and elsewhere in the Mediterranean region (Cooper *et al*. 1987; Corbeels *et al*. 1998), water loss induces a marked change of soil volume, as a consequence of which, cracks open. The width of shrinkage cracks in the soils at Tel Hadya is 5.0–10.0 mm, and they can be up to 1.0 m deep (Ryan *et al*. 1997). It has been shown that E_s from the crack wall area can occur at significant rates in addition to E_s from the soil surface (Ritchie and Adams 1974).

In SOILWAT, E_s is from the surface layer only, which is thought to comprise a homogenous compartment. During simulated soil drying, water moves gradually upwards by unsaturated flow and is lost from the surface layer by second-stage evaporation. Given sufficient evaporative demand, upward movement proceeds until the lower limit (LL15) is reached in layers below the topsoil layer. Only the surface layer can dry down to 'air-dry'. At Tel Hadya, however, air-dry moisture contents have been repeatedly observed to a depth of 0.45–0.60 m at the end of the dry summer fallow period following the growth of wheat and chickpea crops (Harris 1994).

Soil nitrogen

The W_{00}W1-N0 treatment was used to assess the potential of the soil to supply mineral N to a well-watered but unfertilised crop, and to parameterise *fbiom*. A simple N balance was calculated

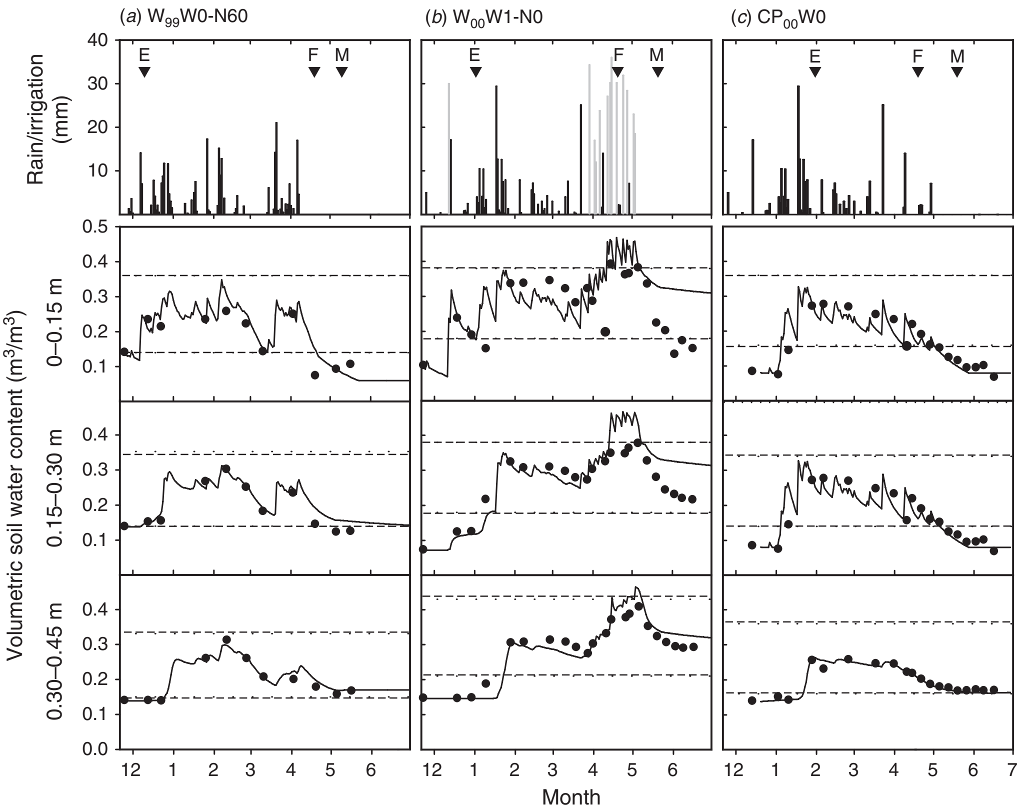

Fig. 4. Rain (black bars) and supplemental irrigation (grey bars), and predicted (—) and observed (●) soil-water dynamics in 3 soil layers (0–0.15, 0.15–0.30, and 0.30–0.45 m depth) for (*a*, *b*) wheat and (*c*) chickpea grown at Tel Hadya: (*a*) rainfed wheat grown in 1998–99 with a nitrogen (N) fertiliser rate of 60 kg N/ha; (*b*) irrigated wheat grown in 1999–2000 without N fertiliser; (*c*) rainfed chickpea grown in 1999–2000. Also shown: observed dates of crop emergence (E), flowering (F), and physiological maturity (M). The plant-available water capacity of the 3 different experimental soils is shown between the dashed lines.

for this treatment: unfertilised wheat took up 51 kg N/ha of which 16 kg N/ha originated from the soil mineral N pool and 35 kg N/ha from mineralisation. Residual mineral N in the 0–0.90 m depth was >40 kg N/ha, of which over 40% was present as NH_4-N. Similar amounts of NH_4-N were found at any sampling date under both wheat and chickpea (Fig. 5), and have been elsewhere reported for different sites in Syria and Lebanon (Ryan *et al*. 1997) and for a Vertisol in Morocco (Corbeels *et al*. 1999). Our findings and results reported in literature are an indication that nitrification may be restricted under the pedo-climatic conditions at Tel Hadya, and that part of the observed, apparently plant-available NH_4-N was not taken up by crops. A process that may have restricted the uptake is the adsorption of NH_4-N (NH_4-N fixation) on montmorillonite (Black and Waring 1972; Elmaci *et al.* 2002), which is the dominant clay mineral in soils at Tel Hadya.

With the derived parameterisation of *fbiom* (Table 3), total crop N uptake was well predicted for the W_{00}W1-N0 treatment (Fig. 2*b*). In general, SOILN2 simulated the dynamics of soil NO_3-N within acceptable limits for both the wheat and chickpea treatments. At the end of the cropping season, the differences between simulated and observed NO_3-N in the 0–0.90 m soil depth were in the range of 4–15 kg N/ha (Fig. 5). The observed amounts of NH_4-N in 0–0.90 m depth were under-predicted by 20 to 35 kg N/ha. Nitrification was simulated to occur rapidly and was unrestricted so that virtually no NH_4-N was present except at model initialisation and after the application of urea N fertiliser (Fig. 5*a*, *c*). This indicates that SOILN2 does not adequately describe the dynamics of NH_4-N in the clay soil at Tel Hadya.

Model evaluation

Water is the most critical factor in cropping systems in the semi-arid Mediterranean region (Cooper *et al*. 1987), and accurate prediction of soil-water dynamics and crop–water relations is required to identify management strategies that maximise yield on limited available water resources. Because an under-prediction of E_s over the dry summer fallow period (June–October) can cause carry-over errors when simulating rotations, we used soil-water measurements from the PCS Trial to test whether the accuracy of predictions can be enhanced by resetting the soil-water contents in the upper 3 soil layers (0–0.45 m depth) to air-dry between rotational cycles (Fig. 6). At Tel Hadya, the soil profile is most likely affected by E_s to a depth of 0.45–0.60 m (Harris 1994).

Overall, the model simulated the long-term soil-water dynamics with reasonable accuracy when the soil-water contents were reset to air-dry on 19 June in the upper 2 soil layers (0–0.30 m depth) and subsequently on 4 July in the upper 3 soil layers (0–0.45 m depth). Figure 6 shows the simulated and observed soil-water dynamics in the WN0-CP treatment. At the end of the summer fallow period in 1988, for example, when the lowest soil-water contents were measured (15 September), the amount of soil water in 0–0.15 m depth was over-predicted by 200% without reset but accurately simulated with reset to air-dry. At this date, the predictive accuracy for the whole profile improved by 12% when soil water was reset.

In contrast to our findings, the restriction of soil evaporation to the upper soil layer did not obstruct the predictive performance of SOILWAT2 when applied to simulate the fallow water dynamics on a cracking clay soil (Vertosol) at Warra, Queensland. For this soil, changes in soil water were well predicted over the summer fallow period (November–May) following the growth of wheat (Probert *et al*. 1998). However, the comparability of simulation results for the fallow water dynamics from Warra and Tel Hadya is somewhat limited by major differences in the rainfall regime. At Warra, summer rainfall dominates, and winter wheat is mainly grown on stored soil moisture (Perry 1992). At Tel Hadya, wheat is grown during the wet winter season following the generally arid summer (Fig. 1). Consequently, Probert *et al*. (1998) simulated the recharge of the soil profile over a wet summer fallow period, with soil-water contents at the start of the simulation being lower than at the end of the simulated fallow. In contrast, the soil at Tel Hadya continuously loses water as E_s over the dry summer fallow period (Fig. 6).

A major determinant of soil fertility is soil organic matter (SOM), which influences crop productivity through the plant-

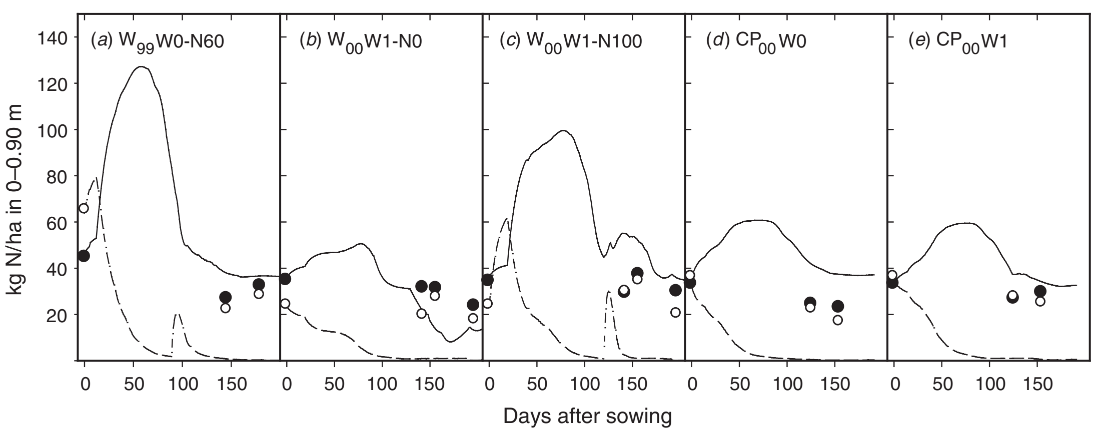

Fig. 5. Observed (symbols) and simulated (curves) NO_3-N and NH_4-N over a soil profile of 0.90-m depth in wheat and chickpea experiments conducted at Tel Hadya: (*a*) rainfed wheat, 1998–99 season, nitrogen (N) fertiliser rate: 60 kg N/ha; (*b*) irrigated wheat, 1999–2000 season, no N fertiliser was applied; (*c*) irrigated wheat, 1999–2000 season, N fertiliser rate: 100 kg N/ha; (*d*) rainfed chickpea, 1999–2000 season; (*e*) irrigated chickpea, 1999–2000 season. Observed NH_4-N (○), observed NO_3-N (●), simulated NH_4-N (– –), simulated NO_3-N (—).

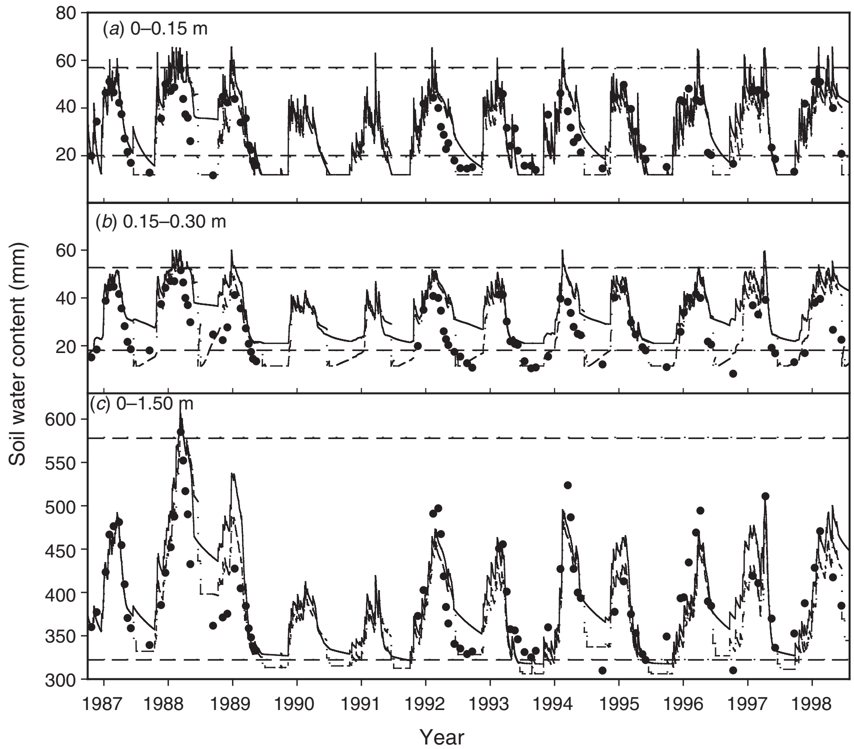

Fig. 6. Soil-water dynamics in the (*a*, *b*) upper 2 soil layers and (*c*) the entire profile in a rainfed wheat–chickpea rotation at Tel Hadya. Observed (●) and simulated soil-water dynamics without (—) and with reset (– –) to initial air-dry moisture contents in 0–0.30 and 0–0.45 m soil depth on 19 June and 4 July, respectively. No nitrogen fertiliser was applied. The plant-available water capacity of the soil is shown between the horizontal dashed lines. Ticks indicate 1 January.

available water capacity, supply and retention of nutrients, soil structure, and other physical properties (Lal 2006; Masri and Ryan 2006). Consequently, for a sustainability analysis the model needs to predict trends in SOM as imposed by agricultural management practices. In the PCS Trial, soil organic matter was measured from 1989 to 1995 (Ryan 1997). Observed SOM values in the 0–0.20 m soil depth were lowest in the wheat–fallow rotation and ranged from 1.01 to 1.17% across N treatments. The wheat–chickpea rotation was found to enrich SOM from an average SOM content across N fertiliser rates of 1.09% in 1989 to 1.23% in 1995. SOM increased with increasing N fertiliser levels, with a grand mean of 1.11 for 0 kg N/ha and 1.19 for 90 kg N/ha applied N fertiliser (Ryan 1997).

Simulations were performed on the wheat–fallow and wheat–chickpea treatments with 0, 30, and 90 kg N/ha of N fertiliser applied to wheat. Soil organic carbon on 1 October in each year was converted to SOM (SOM = OC% * 1.724). Overall, APSIM simulated the dynamics of SOM within realistic limits. At the start of the simulation, SOM in the 0–0.15 m soil depth was 1.07%. Over 13 cropping seasons, simulated SOM in the upper soil layer in the wheat–chickpea rotation increased by 0.01, 0.03, and 0.07% with 0, 30, and 90 kg N/ha of N fertiliser applied, respectively. SOM was simulated to decrease by 0.06 and 0.03% in the wheat–fallow rotation with 0 and 30 kg N/ha of N fertiliser applied, respectively. Levels of SOM remained almost unchanged at around 1.07% in the WN90-F treatment.

Conclusions

Overall, the results of our analysis showed that generally, APSIM is generic and mature enough to be extended to this set of environmental conditions. The model is suitable for the intended assessment of the sustainability of wheat–chickpea rotations at Tel Hadya, where APSIM satisfactorily simulated crop productivity and N content of wheat and chickpea crops. This supports the conclusion that the model provides sensible estimates of the amount of crop residues and N returned to the soil in rotations. Long-term trends in SOM as observed in rotations at the study site were well predicted. APSIM was capable of simulating the long-term soil-water dynamics observed in rotations at the study site when the soil-water content in the 0–0.45 m soil depth was set to air-dry at the end of the growing season in each year. Scope for model improvements include the representation of water-stress effects on phenological development, the effects of the soil's cracking behaviour on the depth to which soil evaporation can occur, and the NH_4-N dynamics and their possible interlinkage with the amount of montmorillonitic clay minerals in the soils at Tel Hadya.

Acknowledgments

We wish to thank the staff at ICARDA for the technical support and their hospitality, Peter deVoil for his help with the simulations, Drs Adriana Bruggeman, Jan Grenz, Phil Ward and Steve Milroy for the discussions and their valuable comments. The study was supported by German Academic Exchange Service (DAAD), Eiselen Foundation Ulm, Ministry of Science, Research and the Arts of the state of Baden-Württemberg, Germany.

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Manuscript received 8 June 2006, accepted 29 September 2006