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Evaluation of the agricultural production systems simulator simulating Lucerne and annual ryegrass dry matter yield in the Argentine Pampas and south-eastern Australia

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ABSTRACT

Modelling plant growth provides a tool for evaluating interactions between environment and management of forage crops for pasture-based livestock systems. Consequently, biophysical and farm systems models are becoming important tools for studying production systems that are based on forage crops. The Agricultural Production Systems Simulator (APSIM) is a model with the potential to compare the growth of annual forage crops and perennial pastures. However, information is limited about how accurately the *Lucerne* and *Weed* modules represent the growth and development of forage crops and pastures under different managements, soil types and environments in South America. This study evaluated the capacity of APSIM to simulate the growth rates and predict the dry matter (DM) yield of Lucerne (*Medicago sativa* L.) and annual ryegrass (*Lolium multiflorum* Lam.) in contrasting climatic regions of Argentina. In addition, at several Australian locations, DM yields of both crops were simulated to ensure that possible changes to the model not interfere with the robust APSIM performance that was already shown in south-eastern Australia. Initial simulations for Lucerne and ryegrass were made with original *Lucerne* and *Weed* modules of APSIM, respectively. Simulated DM yield was then compared with field data collected from the same crops grown in five locations in the Argentine Pampas and seven locations in south-eastern Australia over 5 of years. APSIM predicted DM yield of Lucerne at each harvest with reasonable accuracy [0.59, 0.77 and 0.77 for R^2, correlation coefficient and concordance correlation coefficient (CCC), respectively]. However, these statistics improved when the DM yield was analysed by annual accumulation, with values of 0.87, 0.93 and 0.92 for R^2, correlation coefficient and CCC, respectively. APSIM, generally, over-predicted DM yield of annual ryegrass at the first harvest. Nonetheless, when the *Weed* module was modified through changes in phenology and transpiration efficiency, performance improved (values of 0.89, 0.94 and 0.93 for R^2, correlation coefficient and CCC, respectively). This study showed that annual DM yield of Lucerne can be successfully modelled by the APSIM *Lucerne* module without any modifications, using a crop modelling approach. However, successfully modelling of Lucerne DM yield by harvest will require further development of the model. Moreover, modification of model parameters associated with phenology and transpiration was required to enable the *Weed* module of APSIM simulate growth and yield of annual ryegrass in a range of geographic locations within the Argentine Pampas.

1. Introduction

Over the last decade, the Argentine Pampas have experienced a process of agricultural expansion that has recently been accompanied by a demand for enhancing livestock for meat and milk. A greater demand for animal products, together with the increased pressure for land by grain crops, has resulted in an intensification of animal production systems in this region, including a shift towards annual forage crops (i.e. annual ryegrass, *Lolium multiflorum* L.) at the expense of perennial forages (e.g. Lucerne, *Medicago sativa*, also known as alfalfa).

Biophysical simulation models can be used as cost effective tool for the evaluation of yield capacity of a range of forage species, across the broad range of environments that make up the Argentine Pampas. Biophysical models incorporate climate, soil, crop and management interactions to

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simulate plant growth and yield processes and are becoming an accepted tool in the evaluation of pasture-based livestock production systems (Chapman et al., 2008; Cullen et al., 2009; Rawnsley et al., 2009). The agricultural production systems simulator (APSIM) framework (Keating et al., 2003) is a biophysical model with potential to simulate growth of annual forage crops and perennial pastures. However, previous studies concerning APSIM accuracy as a predictor of dry matter (DM) yield in Lucerne (Robertson et al., 2002; Dolling et al., 2005; Pembleton et al., 2011) and annual ryegrass (Deen et al., 2003; Pembleton et al., 2013) have been largely restricted to southern and Western Australia, with the exception of Chen et al. (2008) and Moot et al. (2015) who reported data from central China ?thyc=5?> and New Zealand, respectively. Although some similarities in seasonal rainfall patterns and forage cropping systems exist between Southern Australia and the Argentine Pampas, the seasonal temperatures and soil types are markedly different. Consequently, differences in the models capacity to predict DM yield between these environments is expected. As the accurate simulation of plant growth relies on an adequate description of soil hydraulic properties (Smeal et al., 1991), the model requires a thorough evaluation by region of how water and other environmental factors, such as solar radiation, interact to affect plant growth and DM yield (Smeal et al., 1991), before it can be relied on to predict growth patterns and yields of different crops.

APSIM estimates above ground growth from two calculations per day, one limited by radiant energy and the other limited by water available for transpiration (Robertson et al., 2002). The lesser of these two values gives the biomass production for the day. Radiation limits on daily aboveground biomass production are related to leaf area index, the fractions of light intercepted by the plant, radiation received and the crop's efficiency of conversion of radiation into biomass (or radiation use efficiency, RUE) (Dolling et al., 2005). Water limitations on the daily biomass production depend on soil water supply in the root zone and on the efficiency of conversion of water into biomass (or transpiration efficiency, TE), based on a transpiration efficiency coefficient (Kc) (Dolling et al., 2005). When the RUE and intercept of radiation are not limiting, the crop DM yield modelled by APSIM will depend only on soil water supply (SWS) and TE, which is the ratio of biomass produced per unit of water transpired by a crop. Transpiration efficiency is derived from the vapour pressure deficit, estimated from mean daily temperatures (Tanner and Sinclair, 1983), and a Kc that is held constant in the model. Therefore, the climate of the location where the crops are being grown has a direct influence on TE. Variations in this parameter were found in different seasons for maize, sorghum, potato, Lucerne and soybean (Tanner and Sinclair, 1983). Similarly, Kemanian et al. (2005) found TE variations in the order of 250% for barley and wheat in North America, the UK and Australia. Variations in SWS depend on the soil water balance between offer (rainfall), demand (evapotranspiration) and initial water supply at crop sowing (Sinclair et al., 1992, 2007; Caviglia et al., 2004). Also, SWS can change depending on the soils and crops types, as was studied by Meinke et al. (1993) for sunflower in five soil types and by Dardanelli et al. (2004) for several species including cotton, maize, pearl millet, grain sorghum, soybean, wheat and sunflower in thirteen types of soils. Therefore, an analysis of parameters that define the prediction capacity of DM yield in APSIM is needed in order to understand the variations that may occur when comparing forage growth rates or yields in different environments.

Before APSIM can be adopted as a possible predictor of forage production of Lucerne and annual ryegrass in the Argentine Pampas, an evaluation of its accuracy under each environment is needed. Hence, we used experimental field data collected in several locations of Argentina to evaluate the ability of APSIM to simulate the growth patterns of Lucerne and ryegrass, and to predict DM yields in this region. In addition, Lucerne and annual ryegrass DM yields at several Australian locations were simulated to ensure that possible changes into the model not ruin the well APSIM performance that was already shown in these environments.

2. Materials and methods

2.1. Experimental locations

2.1.1. Argentine Pampas

The Argentine Pampas are situated between 28 and 40°S and 68 and 57°W (Caviglia and Andrade, 2010); they occupy a vast area of ca. 52 million ha of land, suitable for agricultural and livestock production (Hall et al., 1992). The Pampas have a warm temperate climate. Mean annual rainfall increases from 400 mm in the SW to more than 1200 mm in the NE, whereas the rainfall regime shifts from monsoonal in the NW to more evenly distributed in the SE (Hall et al., 1992). The north and south potential evapotranspiration values are between 850 and 750 mm $yr.^{-1}$, respectively. Mean annual temperature increases from around 13.5 in the south to 18.5 °C in the north of the region (Hall et al., 1992). Soils of the Argentine Pampas belong, predominantly, to the order of Mollisols, being Argiudols and Haplustols the most representative great groups of soils (INTA-SAGyP, 1990).

Data relating to forage crop DM yield were collected from five locations of the Argentine Pampas: Rafaela, Pergamino, General Villegas, Trenque Lauquen and Balcarce (Fig. 1a). Experimental sites were within research stations of the National Institute of Agriculture Technology (INTA). The location, climate and soil characteristics of each site are provided in Table 1. This information was used in the APSIM calibration. Daily meteorological data (maximum and minimum air temperatures, rainfall and incident radiation) for each location were sourced from the corresponding meteorological station of each INTA research station. Any missing data of maximum and minimum temperatures and/or incident radiation were sourced from an international meteorological database (http://power.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi?email=agroclim@larc.nasa.gov).

2.1.2. South-eastern Australia

Three locations in Victoria, Terang, Flynn and Yarram and four locations in Tasmania, Elliot, Cambridge, Cranbrook and Forth were used as experimental locations. A summary of these data from each location is given in Table 1. Daily meteorological data (maximum and minimum temperatures, rainfall, solar radiation) at Terang, Flynn and Yarram were sourced from the SILO meteorological database (www.longpaddock.qld.gov.au/silo) as patched point datasets (Jeffrey et al., 2001). Climate data from Elliot and Forth were collected from weather stations of the Australian Bureau of Meteorology, at the locations. Climate data for Cranbrook were generated as a patched-point dataset (Jeffrey et al., 2001). Meteorological data at Cambridge were collected at 10 minute intervals with a HOBO weather station and data logger (Onset Computer Corporation, Bourne, MA, USA). In consultation with agronomists and scientists working in each location, soil parameters as drained upper limit (DUL) and the lower limit (LL), used to calculate the maximum plant-available water capacity (PAWC) were chosen from the available Tasmanian and Victorian soils in APSIM, that best reflected the soil types at each location (Table 1). Initial soil water values were set, based on observations made in the field (Table 2). The Australian soil information provided by agronomists/scientists was, initially, classified by Isbell (2002). This nomenclature was converted to that of Soil Survey Staff (2010) of the United States Department of Agriculture, as noted by Morand (2013).

2.2. Climatic and soil conditions

Data used for testing the model were from experiments conducted under rainfed and irrigated conditions in the Argentine Pampas and south-eastern Australia. Long-term mean maximum air temperature ranged from 13.6 to 24.6 °C and the mean minimum air temperature between 3.9 to 12.1 °C (Table 1). The mean annual rainfall varied from 500 to 1200 mm for Cambridge and Elliot, respectively. Similarly, the plant

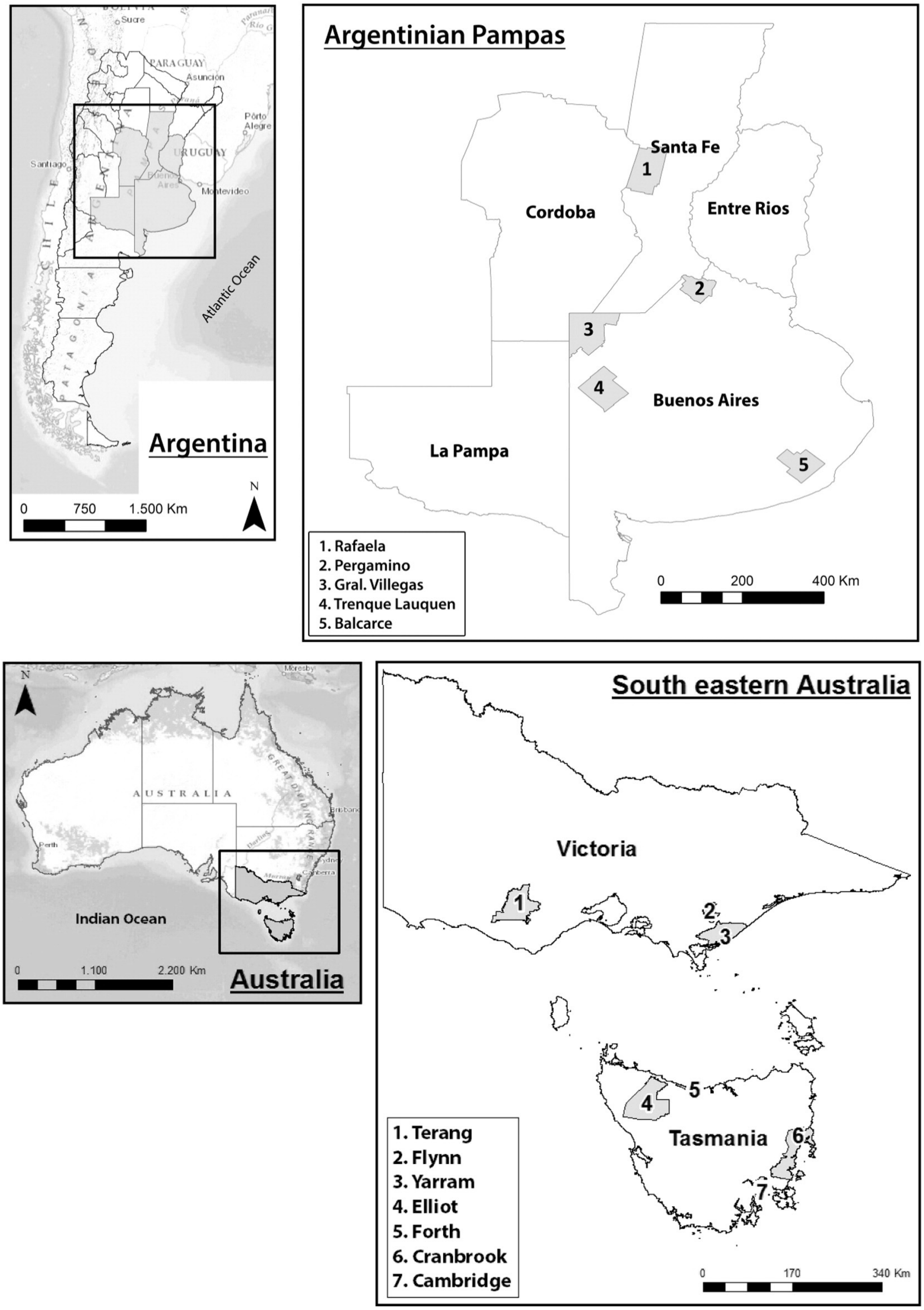

Fig. 1. Map of (a) Argentine Pampas and (b) South-eastern Australia, with collection locations for datasets describing annual ryegrass forage and Lucerne growth.

available water capacity between locations ranged from 113 mm in Trenque Lauquen to more than double in Rafaela (264 mm). The climate and soil information of all locations is provided in Table 1.

2.3. Forage growth

2.3.1. Argentine Pampas

Data were collected from unpublished experiments undertaken at INTA research stations. A summary of datasets of forage crops of Lucerne and annual ryegrass, used for the APSIM calibration, is provided in Table 2. Forages represented in the datasets included Lucerne and annual ryegrass grown during period 2010 to 2013, depending on the location (Table 2). Annual ryegrass and Lucerne were represented for at least two and one growing seasons, respectively. All field experiments were conducted under rainfed conditions. The winter activity rating of Argentine Lucerne genotypes was 6 in Balcarce and Pergamino and 8–9 in Trenque Lauquen and Rafaela. Where biomass N concentrations were available, the Nitrogen Nutrition Index (NNI) (Agnusdei et al.,

Table 1
Climate and soil characteristics of each location used for the calibration of the Agricultural Production Systems Simulator (APSIM).

Location	Site description	Rainfall (mm)	Tmax/Tmin (°C)												Soil type[8]
			Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	
Argentine Pampas[1]															
Rafaela	31°11′S, 61°30′W Northern Santa Fe Province	987	17.4/5.4	20.1/6.7	22.1/8.6	25.5/12.3	28.1/14.9	30.1/16.9	31.5/18.4	29.9/17.6	28.1/16.3	24.2/12.8	20.7/9.5	17.8/6.7	Typic Argiudoll
Pergamino	33°56′S 60°33′W Northern Buenos Aires Province	1002	15.4/3.6	18.1/4.9	20.3/6.9	23.3/10.7	26.8/13.4	29.3/15.6	30.6/17.0	28.6/16.0	26.9/14.2	23.1/10.4	19.4/7.4	16.0/4.8	Typic Argiudoll
General Villegas	35°01′S 63°01′W North-western Buenos Aires Province	814	13.9/3.9	17.4/5.8	20.5/8.0	24.2/11.3	27.9/14.2	30.5/16.7	31.8/18.1	29.9/17.1	27.5/15.7	22.6/11.6	18.1/8.2	14.9/4.9	Typic Hapludoll
Trenque Lauquen	36°04′S 62°45′W North-eastern Buenos Aires Province	780	13.1/2.9	16.2/4.8	19.5/7.2	23.7/10.7	27.4/13.6	30.4/16.3	31.8/17.8	30.0/16.8	27.1/15.1	22.1/10.9	17.2/7.0	13.8/3.8	Entic Hapludoll
Balcarce	37°45′S 58°18′W South-eastern Buenos Aires Province	917	12.3/4.0	14.8/4.9	17.3/5.7	21.5/8.5	25.2/11.2	28.3/13.8	28.7/16.1	27.2/15.5	24.5/14.1	20.7/10.4	16.5/7.3	13.2/5.0	Petrocalcic Paleoudoll
South Eastern Australia															
Terang[2]	38°14′S, 142°55′E South-western Victoria	731	12.8/5.0	13.7/5.5	15.4/6.5	17.5/7.5	19.7/8.9	22.0/10.3	24.3/11.8	24.5/12.3	22.6/11.1	19.2/9.1	15.9/7.4	13.5/5.7	Argiudoll
Flynn[3]	38°10′S, 146°41′E South-eastern Victoria	640	13.6/4.2	14.8/4.8	17.0/6.3	19.4/7.9	21.5/9.9	23.7/11.6	25.6/13.0	25.8/13.3	23.6/11.7	20.1/9.1	16.7/6.9	14.1/5.0	Argiudoll
Yarram[3]	38°33′S, 146°40′E South-eastern Victoria	724	12.8/5.6	13.8/5.9	15.7/6.9	17.9/8.2	19.8/9.9	21.8/11.4	23.7/12.8	24.0/13.3	22.0/12.0	18.8/10.1	15.7/7.9	13.3/6.3	Argiudoll
Elliot[4]	41°4′S, 145°46′E North-western Tasmania	1200	11.1/4.2	11.6/4.5	13.0/5.2	14.9/6.3	16.8/7.9	18.6/9.3	20.3/10.9	20.7/11.3	19.0/10.1	16.3/8.2	13.7/6.5	11.8/5.0	Oxisol
Cambridge[5]	42°49′S, 147°30′E South-eastern Tasmania	500	10.5/4.3	11.9/4.3	14.1/5.0	16.4/6.5	18.7/8.2	20.7/9.7	22.4/11.1	22.0/11.2	20.0/10.1	16.7/8.3	13.4/6.7	10.8/4.9	Alfisol
Forth[6]	41°12′S, 146°16′E North Tasmania	960	11.8/4.1	12.5/4.6	13.8/5.6	15.5/6.8	17.4/8.4	19.2/9.9	20.8/11.5	21.0/11.7	19.6/10.3	17.2/8.4	14.7/6.9	12.5/4.7	Oxisol
Cranbrook[7]	42°00′S, 148°10′E Eastern Tasmania	830	8.1/0.3	8.2/0.0	10.8/1.3	14.1/3.8	15.5/5.3	17.1/7.4	18.7/7.8	18.2/7.3	18.2/6.5	14.3/5.1	11.3/1.8	8.6/0.3	Oxisol

Rainfall, mean annual rainfall in long term; Tmax/Tmin, average maximum and minimum air temperatures in long term; PAWC, plant-available water capacity.

[1] Argentine Pampas long-term calculation based on period 1983 to 2009.
[2] Terang long-term calculation based on period 1950 to 2010.
[3] Flynn and Yarram long-term calculation based on period 1889 to 2010.
[4] Elliot long-term calculation based on period 1961 to 2007.
[5] Cambridge long-term calculation based on period 1983 to 2013.
[6] Forth long-term calculation based on period 1980 to 2001.
[7] Cranbrook long-term calculation based on period 1989 to 1992.
[8] Soil Survey Staff, 2010. United States Department of Agriculture.

Table 2
Summary of forage Lucerne and annual ryegrass real datasets used for the calibration of the Agricultural Production Systems Simulator (APSIM).

Year	Location	D/I	Sowing date	Harvesting date									Crop management					Source/reference
													ISW (%)	Fert N (kg N ha^{-1})	SD (plants m^{-2})	RD (cm)	Cultivar	
Lucerne																		
2010	Pergamino	D	29-Mar	8-Oct	16-Nov	10-Dec							100	0	300	17.5	PRO INTA Luján	EEA-Pergamino INTA unpub. Data
2011	Pergamino			6-Jan	1-Feb	9-Mar	25-Apr	8-Jun	14-Sep	24-Oct	17-Nov	12-Dec						
2012	Pergamino			17-Jan	10-Feb	19-Mar	9-May	21-Jun	4-Oct									
2010	Rafaela	D	15-May	28-Sep	03-Nov	6-Dec							30	0	300	17.5	WL903	EEA-Rafaela INTA unpub. Data
2011	Rafaela			12-Jan	10-Feb	05-Mar	23-Apr	04-Jun	14-Sep	31-Oct	26-Nov	20-Dec						
2012	Rafaela			30-Jan	29-Mar	15-May												
2010	T Lauquen	D	19-Apr	15-Nov	13-Dec								100	0	250	17.5	Super Monarca	AER-T. Lauquen INTA unpub. Data
2011	T Lauquen			12-Jan	14-Feb	16-Mar	6-May	12-Jul	14-Sep	25-Oct	23-Nov	21-Dec						
2012	T Lauquen			2-Feb	26-Mar	26-Apr												
2012	Balcarce	D	18-Oct										92	0	300	20	WL611	J.J. Ojeda, unpub. Data
2013	Balcarce			9-Jan	7-Feb	13-Mar	17-Apr	5-May	16-Sep	28-Oct	26-Nov	27-Dec						
2014	Balcarce			28-Jan	24-Feb	16-Apr												
2007	Elliot	D/I	17-Jan	27-Mar	30-May	06-Sep	26-Nov						100	0	200	15	WAG/WDG[a]	Pembleton et al., 2010a
2008	Elliot			8-Jan	10-Mar	03-Jun												
2006	Cambridge	D	31-Oct										0	0	150	15	WAG/WDG[a]	
2007	Cambridge			06-Feb	17-May	30-Sep	12-Dec											
2008	Cambridge			21-Jan	19-Mar	24-Jun												
1989	Forth	I	16-Feb	03-Nov	6-Dec								50		200	15	WAG/WDG[a]	Pembleton et al., 2010b
1990	Forth			16-Jan	26-Feb	08-May	1-Aug	31-Oct	12-Dec									
1991	Forth			14-Jan	19-Feb	18-Apr	03-Jun	13-Nov	16-Dec									
1992	Forth			21-Feb														
1989	Cranbrook	D	2-Jan	23-Oct	12-Dec								50		210	15	WAG/WDG[a]	
1990	Cranbrook			23-Jan	13-Mar	21-Jun	14-Nov	19-Dec										
1991	Cranbrook			21-Jan	12-Mar	26-Jun	10-Dec	04-Feb										
Annual ryegrass																		
2010	Pergamino	D	01-Mar	18-May	10-Jun	08-Jul	10-Aug	13-Sep	12-Oct				60	250	300	17.5	Barturbo	EEA-Pergamino INTA unpub. Data
2010	Pergamino	D	01-Mar	18-May	10-Jun	08-Jul	10-Aug	13-Sep					60	250	300	17.5	Barturbo	
2011	Pergamino	D	28-Feb	10-May	08-Jun	21-Jul	29-Aug	06-Oct					60	250	300	17.5	Caleufú PV INTA	
2011	Pergamino	D	28-Feb	10-May	08-Jun	29-Aug	06-Oct						60	250	300	17.5	Caleufú PV INTA	
2012	Pergamino	D	28-Feb	30-May	10-Jul	23-Aug	21-Sep	12-Oct					60	250	300	17.5	Caleufú PV INTA	
2012	Pergamino	D	28-Feb	30-May	10-Jul	23-Aug	21-Sep						60	250	300	17.5	Caleufú PV INTA	
2010	G Villegas	D	08-Apr	22-Jun	18-Aug	07-Oct							15	150	365	17.5	Bill max	EEA-Gral. Villegas INTA unpub. Data
2010	G Villegas	D	08-Apr	19-Sep									100	150	400	17.5	Bill max	
2011	G Villegas	D	15-Apr	02-Sep	17-Oct								25	150	448	17.5	Bill max	
2011	G Villegas	D	15-Apr	28-Oct									62	150	400	17.5	Bill max	
2005	Terang	D	7-Apr	27-Jun	12-Aug	03-Nov							0	66	300	15	Progrow	Jacobs et al., 2009a
2005	Terang	D	7-Apr	27-Jun	03-Nov								0	106	261	15	Progrow	
2005	Terang	D	7-Apr	03-Nov									0	106	286	15	Progrow	
2006	Terang	D	6-Apr	16-Jun	4-Aug	30-Oct							0	128	550	10	Progrow	
2006	Terang	D	6-Apr	4-Aug	30-Oct								0	168	550	10	Progrow	
2009	Flynn	D	20-May	17-Aug	10-Nov								10	11	100	15	Winter Star II	Mickan and O'Brien 2010, 2011
2010	Flynn	D	14-Apr	06-Jul	09-Sep	11-Oct							100	64	250	10	Winter Star II	
2010	Flynn	D	14-Apr	11-Oct									100	64	250	10	Winter Star II	
2009	Yarram	D	22-May	19-Aug	26-Oct								0	18	200	10	Winter Star II	

D/I, dryland (D) or irrigated (I); ISW, Initial soil water previous sowing as percent of total plant-available water capacity; Fert N, fertilizer nitrogen applied; SD, Sowing density; RD, Row distance; T. Lauquen, Trenque Lauquen; G Villegas, General Villegas.

[a] The average of DM yield was used for winter active genotypes (WAG) and winter dormant genotypes (WDG).

2010; Errecart et al., 2014), based on the critical N concentration of reference (Justes et al., 1994) was calculated in order to evaluate the forage N nutrition.

2.3.2. South-eastern Australia

Both Lucerne and annual ryegrass were represented for at least two growing seasons. Data relating to forage crop DM yield of annual ryegrass were collated from the dairy regions of Gippsland (Flynn and Yarram) and Western Victoria (Terang) (Fig. 1b) in two consecutive years (Table 2). Data of Lucerne DM yield were collated from four locations of Tasmania, Elliot, Cambridge, Cranbrook and Forth. The forage growth period for each location is described in Table 2. At Cambridge and Elliot, cultivars were DuPuits (winter activity rating of 3), Grasslands Kaituna (winter activity rating of 4.5), SARDI 7 (winter activity rating of 7) and SARDI 10 (winter activity rating of 10). The number of cultivars evaluated at Cranbrook and Forth was higher (39 and 36 cultivars respectively). This pool of genotypes was classified into two groups according to their degree of winter dormancy (Table 2). Australian data are composed of a pool of previously published experiments, plus published and unpublished field data of forage growth on commercial farms.

Before data analysis, it was confirmed from consultations with agronomists and scientists who collected the data that forage growth was not restricted by factors that APSIM, generally, is not capable of simulating (e.g. soil fertility limitations other than nitrogen, pest and disease incidence, water logging). All the field experiments were conducted in rainfed conditions, except in Elliot and Forth, where field experiments were also conducted with irrigation. A summary of the data included in the study is provided in Table 2.

2.4. APSIM model parameterization

All simulations were undertaken using APSIM (version 7.5) (Keating et al., 2003). The model configuration consisted of modules for Lucerne growth (APSIM *Lucerne*), annual ryegrass growth (APSIM *Weed*), soil N and C (APSIM *SoilN*), crops residue dynamics (APSIM *Surface Organic Matter*) and soil water (APSIM *SoilWat*). Therefore, the initial soil data (C and N) used in all locations was the same. The soil parameters were gathered from the Soil Institute of INTA and also INTA scientists for Argentine locations (Supplementary Table 1). At Australia the soil parameters were chosen from the available soils in APSIM that best reflected the soil types at each location. The soil water parameterization in both regions is presented (Supplementary Table 1).

Model output from each simulation was DM yield by individual harvests (kg DM ha^{-1}). In all simulations the harvesting rule were set to remove the biomass at height of 30 mm (harvest script, Tables 3 and 4).

2.4.1. Lucerne

Dry matter yield of Lucerne was simulated with the APSIM *Lucerne* module (Robertson et al., 2002). For calibration, the framework for the winter dormancy rule, described in Pembleton et al. (2011), was used. The genotypes of winter activity, rating from 3 to 5.5 and 6 to 10, were considered winter-dormant genotypes and winter-active genotypes, respectively. The temperature thresholds for entry and exit from dormancy were modified for Rafaela and Trenque Lauquen (Table 3). The new thresholds were defined with basis on the potential growth rate simulated for a long-term of 30 years (Fig. 2). Daily potential growth rate was calculated based on the thermal time calculation (Base temperature 2 °C) provided by the model in an XML format file. According to this analysis the mean simulated growth rate varies by location. This differential response in simulated Lucerne potential growth rate supports the change in temperature thresholds within winter dormancy rules. For all the simulations the photoperiod threshold written by Pembleton et al. (2011) were maintained (Table 3). For the calibration, all dataset was grouped into two parts, winter-dormant and winter-active genotypes. In the model cv. Grasslands Kaituna was selected to represent a winter-dormant genotype, and the cv. Sceptre was selected to represent a winter-active genotype.

Initial simulations indicated that the inclusion of a water table contribution to PAWC in the Rafaela location was required. This information was, subsequently, obtained from INTA Rafaela Research Station and the water table contribution was indirectly estimated for each interval between cuttings, considering values of Lucerne water use efficiency (Dardanelli and Collino, 2002) and the water use from the upper layers (which was supplied by rainfall). When the water table was present, the amount of forage water use resulted from the sum of water supplied by

Table 3
Manager script of the simulation to sowing, harvesting and control dormancy in Lucerne.

Sow on a fixed date script

```
if (today = date('[date]') then
[crop] sow plants = [density], sowing_depth = [depth], cultivar = [cultivar], row_spacing = [row_spacing], crop_class = [class]
endif
```

Harvest script[1]

```
if (today = date('[harvest_date_1]') then
Lucerne harvest plants = 250(/m2), height = 30 (mm), remove = 1
'[surfaceommodule]' tillage type = burn, f_incorp = 1 tillage_depth = 0
endif
```

Control dormancy script

Elliot[2] Photoperiod (range Julian days)	(range hours)	Tmean[3] (°C)	Trenque Lauquen Photoperiod (range Julian days)	(range hours)	Tmean[3] (°C)	Rafaela Photoperiod (range Julian days)	(range hours)	Tmean[3] (°C)	Crop_class	Crop response
>60 and <200	14.0 to 10.6 (10.3)[4]	<=15	>60 and <200	13.8 to 11.0 (10.7)[5]	<=23	>60 and <200	13.6 to 11.3 (11)[4]	<=23	regrowth	delay
		<=5			<=10			<=14	delayed	reduce
		<=5			<=8			<=11	reduced	dormancy
>200 or <60	10.6 to 14.0 (16.3)[5]	>5	>200 or <60	11.0 to 13.8 (15.6)[6]	>7	>200 or <60	11.3 to 13.6 (15.1)[5]	>12	dormant	reduce
		>10			>15			>17	reduced	delay
		>15			>23			>23	delayed	spring

[1] Corresponding to only one harvest date at Trenque Lauquen. This script should be repeated depending on number of harvesting dates.
[2] Scripts are written for Pembleton et al., 2011 with basis on a pool of winter active genotypes (winter activity rating of 7 to 10).
[3] Tmean = (minimum daily air temperature + maximum daily air temperature)/2.
[4] Minimum daylight hours in the considered period.
[5] Maximum daylight hours in the considered period.

Table 4
Manager script at the initialization, start of day and end of each day of the simulation to sowing, fertilization and harvesting in annual ryegrass.

Sow on a fixed date script	Fertilize on fixed date script	Harvest script[1]	End crop script
Initialization			
		summing = 0	
Start of day			

if (today = date('[date]') then
[crop] sow plants = [density], sowing_depth = [depth], cultivar = [cultivar], row_spacing = [row_spacing], crop_class = [class]
endif
	if (today = date('[fert_date]') then
	N_topsoil = $NO_3(1) + NH_4(1) + NO_3(2) + NH_4(2)$
	if (N_topsoil < [fert_criteria]) then[fertmodule]
	apply amount = [fert_amount] (kg/ha),
	depth = 50 (mm), type = [fert_type] ()
	endif
	endif
		if (today = date('[harvest_date_1]') then
		weed1 harvest plants = 200 (/m^2),
		height = 30 (mm), remove = 1
		'[surfaceommodule]' tillage type = burn,
		f_incorp = 1 tillage_depth = 0
		endif	

End of day			

			if (today = date('[date]')
			then
			[crop] end_crop
			endif

[1] Corresponding to only one harvest date at Pergamino. This script should be repeated depending on the number of harvesting dates.

the rainfall, and the capillary contribution from the water table (Dardanelli and Collino, 2002).

Management operations (cultivation, sowing, N fertilizer management, irrigation, harvesting) in the simulations mimicked those applied in the field. A complete description of sowing, harvesting and control dormancy scripts used in Lucerne simulations can see in Table 3.

2.4.2. Annual ryegrass

A sensitivity analysis enables the user to determine responses of key model outputs (e.g., harvestable biomass) to variations in selected parameters. Such an approach enables model users to investigate the relative importance of each parameter to biomass production in different production contexts. Hence, sensitivity analysis of module parameters was performed. For these simulations, phenology coefficients were decreased by 50% and increased by 100 and 200% from the baseline parameters to evaluate the possible impact of these changes on biomass production (Fig. 3a). In addition, the biomass change ratio in Pergamino was evaluated when Kc was decreased by 50% and increased by 50 and 100% from the baseline parameter (Fig. 3c). At the same time the transpiration model output (ep) for different Kc values (Fig. 4a1 and a2) and the extractable soil water (esw, Fig. 4b1 and b2) was evaluated for two sites giving a total of 73 simulations.

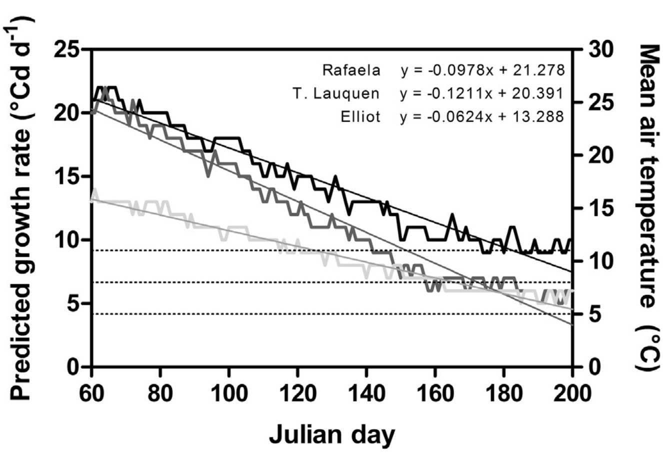

Fig. 2. Potential Lucerne growth rate predicted by APSIM *Lucerne* module (left y-axis) and mean air temperatures (right y-axis) between the Julian day 60 and 200 at Rafaela (——), Trenque Lauquen (——) and Elliot (——). Broken lines indicate the minimum thresholds of dormancy temperatures by location: 5 °C, 8 °C and 11 °C for Elliot, Trenque Lauquen and Rafaela, respectively. Solid lines indicate the linear regression for the potential growth rate predicted by location. The potential growth rate simulated and mean air temperatures shown were calculated with basis on a long-term period of 30 years.

To assess potential errors in soil datasets, a sensitivity analysis was undertaken for water extraction coefficient (KL) and root exploration factor (XF), pH, initial soil water, initial soil N, initial soil organic carbon and sowing depth in Pergamino (Fig. 3b) and maximum PAWC (Fig. 3d). In this analysis, simulations were undertaken using actual data of four different soils. The soil parameters air dry, LL, DUL and saturated volumetric water were increased and decreased by 20%, and thus PAWC of the soils were increased and decreased by 20% giving a total of 91 simulations. The parameters to which DM yield was most sensitive were identified by the use of comparative graphs (Fig. 3).

For annual ryegrass simulations, the cultivars used in the field were not available in the model, hence, the cultivar that best reflected the maturity/development type of the cultivars from those available in APSIM (Pembleton et al., 2013) was used (late flowering). Management operations (cultivars, sowing, N fertilizer management, irrigation, harvesting) in the simulations mimicked those applied in the field. Sowing rules, plant density, row spacing, cultivar, fertilizer and harvesting rules were the primary agronomic factors manipulated. A complete description of sowing, fertilization and harvesting scripts used in ryegrass simulations can be seen in Table 4.

Based on previous sensitivity analysis and an exhaustive review of the literature, the following modifications were done to the model parameters in order to improve simulation accuracy. First, the thermal time between sowing and emergence was determined by parameters; *shoot_lag* (15 °Cd) and *shoot_rate* (2 °Cd mm^{-1}), in an XML format file. The module changes the growth parameters according to the crop growth habit selected: winter grass, winter dicotyledonous, summer grass and perennial grass. Interestingly, *shoot_lag* and *shoot_rate* did not differ according to this classification. As noted by Monks et al. (2009), *shoot_lag* values in barley grass and perennial ryegrass were of 77 and 66 °Cd, respectively. Much lower values in the same experiment, of the order from 29 to 39 °Cd, were found for annual weed grasses. Other studies published by Moot et al. (2000) found that thermal times to 75% germination and to 50% of final emergence for Italian ryegrass were 90 and 145 °Cd, respectively. Similarly, Mohammed et al. (2013) found accumulated thermal time to 75% emergence of *Lolium multiflorum* in the order to 137 to 218 °Cd for different sowing dates in New Zealand. To address this, both parameters were measured in an Argentine cultivar of annual ryegrass for 75% germination and to 75% of final emergence (J.J. Ojeda, unpub. Data, Table 5). Based upon the previous analysis and on the basis that these parameters are genetically determined (Moot et al., 2000), the standard parameters of *shoot_lag* and *shoot_rate* were modified from 15 to 75 °Cd and from 2 to 4.6 °Cd mm^{-1}, respectively. Second, the standard parameters that define the node appearance rate (*y_node_app_rate*) and the value of leaf number per plant after harvest (*leaf_no_at_emerg*) were modified.

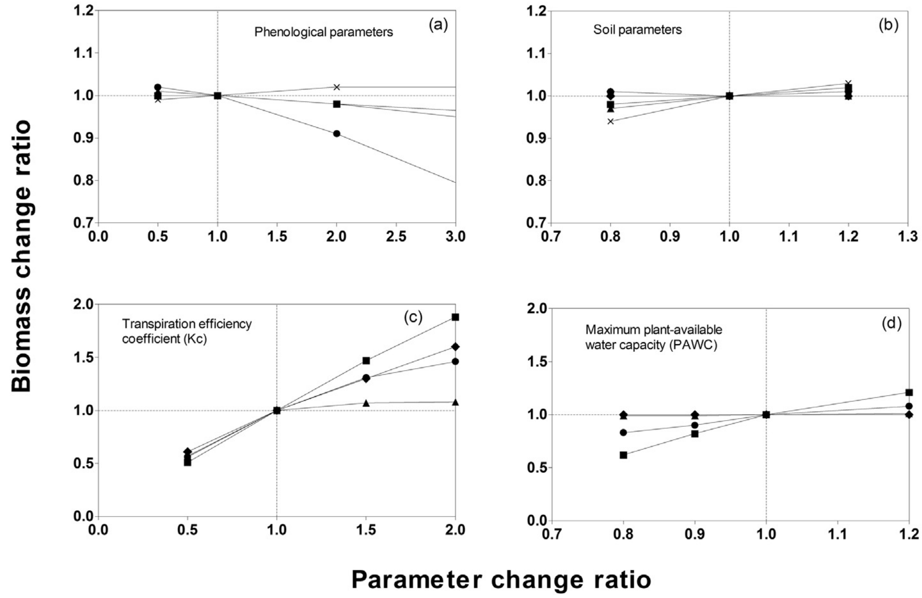

Fig. 3. Sensitivity analysis of APSIM *Weed* model parameters: Biomass change ratio v. (a) change ratio of phenological parameters for shoot growth starts (—■—), shoot elongation rate (—▲—), node appearance rate (—●—), leaf number at emergence (—X—) **(b)** soil parameter change ratio in Pergamino for sowing depth (—●—), water extraction coefficient, KL (—■—), root exploration factor, XF (—▲—), initial soil organic carbon (—▼—), initial soil N (—◆—), initial soil water (—X—) and pH (—+—) **(c)** transpiration efficiency coefficient (Kc) change ratio for Pergamino (—●—), General Villegas (—■—), Flynn (—▲—), and Terang (—◆—) **(d)** maximum plant-available water capacity (PAWC) change ratio for Pergamino (—●—), General Villegas (—■—), Flynn (—▲—), and Terang (—◆—). Broken line in x and y-axis indicates the baseline parameter and no changes in biomass production, respectively.

The fundamental basis of the *y_node_app_rate* modification were the experiments reported by Agnusdei (1999) for *Lolium multiflorum* in Argentine Humid Pampas and Lattanzi et al. (1997) for Italian ryegrass in Balcarce where shown values of this parameter were 140 and 138 °Cd, respectively. In addition, the sensitivity analysis of *y_node_app_rate* suggested that significantly influenced the predicted harvestable biomass (Fig. 3a). The *leaf_no_at_emerg* was modified, so that harvests coincided with the occurrence of 3 fully emerged leaves on plants (Fulkerson and Donaghy, 2001). Similarly to *shoot_lag* and *shoot_rate*, these parameters did not differ according to the crop growth habit selected. Third, a new use water efficiency parameter was required for the annual ryegrass growth with respect to the period from sowing to first harvest. Kc (Pa) was reduced for the juvenile and flower initiation stages from the standard value of 5 to 2.5 Pa, (Table 5). These changes were justified based on the sensitivity analysis (Fig. 3c) and studies of winter crops which have identified that the Kc can vary greatly within the same species (Kemanian et al., 2005).

2.5. Evaluation of model performance

Initially, model performance was visually assessed by comparing scatter plots of observed values against the y-axis vs. modelled values against the x-axis (Piñeiro et al., 2008). When multiple data points for the one observation were available, the range was included as error bars. The evaluation of model performance described in Tedeschi (2006) was used as the basis to statistically evaluate model performance. The parameters used were: Pearson's correlation coefficient

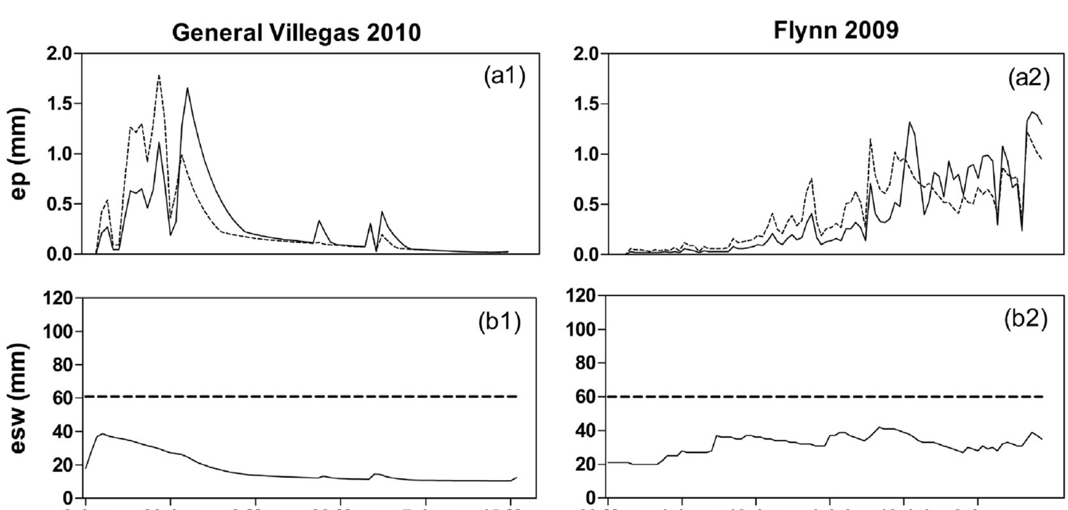

Fig. 4. Comparison between (a) transpiration model output (ep) for transpiration efficiency coefficient (Kc) baseline (—) and Kc baseline ×0.5 (— —) and (b) actual extractable soil water (esw) during the establishment period of annual ryegrass in General Villegas 2010 and Flynn 2009. Dashed line in graph (b1) and (b2) represent the 50% of plant-available water capacity (PAWC) of each location.

Table 5
Parameter settings in the simulations for the whole growth period (phenology) and for the implantation period (efficiency).

	Parameter	Original weed module	Modified weed module
Phenology	Shoot growth starts[1]	15	75[6]
	Shoot elongation rate[2]	2	4.6[6]
	Node appearance rate[3]	95	140
	Leaf number at emergence[4]	2	1.5
Efficiency	Transpiration efficiency coefficient[5]	0.005	0.0025

[1] *shoot _lag*, denotes time lag before linear coleoptile growth starts (°Cd).
[2] *shoot_rate*, denotes shoot elongation rate from germination to emergence (°Cd·mm^{-1}).
[3] *y_node_app_rate*, denotes node appearance rate per plant (°Cd).
[4] *leaf_no_at_emerg*, denotes expanded leaf number at emergence.
[5] *transp_eff_c*.
[6] Argentine cultivar Don Gianni. Los Prados.

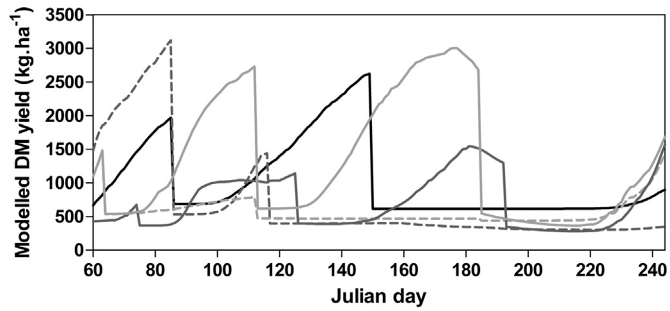

Fig. 5. Modelled biomass accumulated (kg ha^{-1}) by APSIM *Lucerne* module in autumn-winter period using the winter dormancy rules written by Pembleton et al. (2011) at Elliot (—), Trenque Lauquen (—) and Rafaela (—). Broken lines indicate modelled biomass accumulated (kg ha^{-1}) for Trenque Lauquen (- - -) and Rafaela (- - -) with temperature thresholds modified within winter dormancy rules.

and coefficient of determination (r and R^2, respectively, which represent the proportion of the total variance in the observed data that can be explained by the model); mean bias (the difference between observed and predicted mean, ideally 0); mean prediction error (MPE, a measure of general model efficiency expressed as % of mean, whereby, the lower the value, the better); model efficiency, (MEF, the proportion of variation explained by the modelled value with a value of 1 indicating a perfect fit); variance ratio (v, ratio of the variance in observed data to the variance in the modelled data, ideally 1); bias correction factor (Cb, an indication of how much a fitted linear regression between observed and modelled values deviates from a line described by Y = X, ideally 1); and the concordance correlation coefficient (CCC, which is a simultaneous measure of accuracy and precision, with an ideal fit indicated by a value of 1). Accuracy was measured by the Cb proposed by Lawrence and Lin (1989), which indicates how far the regression line deviates from the concordance (Y = X) line. The CCC integrates both, precision (r) and accuracy (Cb) (Lawrence and Lin, 1989. The analysis for DM yield of both forages was calculated by individual harvest, biomass accumulated per year and data for each of the locations, separately, in order to test the accuracy of the simulations in different environments and over different time periods.

Deviations between observed and simulated values were calculated from the geometric means. Deviations were defined as differences between simulated and measured values, divided by measured values and expressed as percentage (Mitchell and Sheehy, 1997).

3. Results

3.1. Lucerne

Our long-term analysis of potential growth rates of Lucerne showed low accuracy of the APSIM *Lucerne* module for predicting the DM yield during the period of autumn–winter in Rafaela and Trenque Lauquen using the winter dormancy rules generated by Pembleton et al. (2011) (Fig. 5). The mean growth rate simulated varied by location, being the growth rates simulated in Rafaela higher than Trenque Lauquen and higher here than in Elliot (Fig. 2).

Lucerne DM yield of individual harvests were simulated adequately, as evidenced by the values of 0.59, 0.77 and 0.77 obtained for the R^2, correlation coefficient and CCC, respectively (Table 6). A visual evaluation of model performance is given in Fig. 6a. Very good model prediction was found for accumulated yield (Fig. 6b). This was confirmed by the statistics parameters of 0.87, 0.93 and 0.92 for the R^2, correlation coefficient and CCC, respectively (Table 6). The observed Lucerne DM yield ranged from 763 kg DM ha^{-1} in Cambridge to 3838 kg DM ha^{-1} in Forth. However, the range of DM yield simulated was at 30% less than observed, ranging between 1238 kg DM ha^{-1} in Trenque Lauquen to 3393 kg DM ha^{-1} in Forth. The Argentine locations with better DM yield predictions were Rafaela, Balcarce and Trenque Lauquen. In contrast, in Pergamino the Lucerne DM yield was poorly simulated by the model (Table 6), due to overprediction in all of the years. Regarding this prediction and given that biomass N concentration data for this location were available (Table 7), the NNI was calculated for 16 consecutive harvests for the periods 2010 and 2012. The average NNI was 0.76, at 24% below the NNI optimum. This analysis demonstrated a nitrogen deficient condition for Lucerne in Pergamino for all growth periods. The comparison between Rafaela location, with and without water table contribution, identified that the incorporation of this water source improved model performance in predicting Lucerne DM yield, as highlighted by the improvements in the R^2 value, r, mean bias, MPE, MEF, and CCC (Fig. 7, Table 6).

In south-eastern Australia, the model predicted DM yield adequately in Cranbrook and Forth, but poorly predicted the DM yields at Cambridge and Elliot, under both rainfed and irrigated conditions. Fig. 8 shows an appropriate similarity between observed and modelled DM yields in selected locations during Lucerne season growth from sowing using winter-dormant and winter-active genotypes. The performance of the model in predicting crop DM yield shown in Figs. 5 and 7 was confirmed by the summary statistics (Table 6). There were no discernible groupings, based on winter activities and crop age. Similarly, no differences were found between observed and modelled DM yield between seasons, as was evidenced for selected locations, in Fig. 8.

3.2. Annual ryegrass

The model without modification demonstrated a poor ability to simulate annual ryegrass DM yield with the full data set of individual harvests, with values of 0.46, 0.68 and 0.67 for the R^2, correlation coefficient and CCC, respectively (Table 8). From 15 DM yield observations of the first harvest (8 from the Argentine Pampas and 7 from south-eastern Australia) 14 overestimated annual ryegrass DM yield (Fig. 9a), using the APSIM *Weed* module without the modifications performed in this paper. Our simulations estimated values of accumulated herbage in the first harvest of the order of 6000 kg DM ha^{-1} in Pergamino, 5000 kg DM ha^{-1} in General Villegas and 4000 kg DM ha^{-1} in Terang and Flynn (Fig. 9a). In year 2010 at Flynn, during the period from sowing to first harvesting (1000 °Cd), the deviation between observed and modelled values were 773%. The model, generally, both over- and underpredicted DM yield for annual ryegrass in the period from sowing to first harvest and when the crop was already established, respectively (Figs. 8a and 10a).

The sensitivity analysis carried out for the establishment period of annual ryegrass showed (i) low sensitivity of the model when soil parameters were modified, the changes in biomass production being no greater than 6% (Fig. 3b), (ii) biomass production reduction in Argentine locations when PAWC was decreased (Fig. 3d), (iii) sensitivity of biomass production when phenological parameters were modified. The main change in biomass (less than 20%) occurred when

Table 6
Summary statistics indicating the performance of the Agricultural Production Systems Simulator (APSIM) in predicting the DM yield (kg ha^{-1}) of Lucerne in the Argentine Pampas and south-eastern Australia.

	Balcarce	Rafaela		T. Lauquen	Pergamino	Cranbrook	Forth	Cambridge	Elliot		Total	
		WOWTC	WWTC						D	I	H	Y
No. of observations	12	15	15	13	18	24	30	12	12	14	154	39
Mean (actual)	2557	2137	2137	1456	1292	2862	3838	763	1771	2484	2357	9456
Mean (simulated)	2391	1464	1938	1238	1903	2882	3393	1501	2210	1960	2361	9323
Std. Dev (actual)	1037	805	805	485	489	1055	1296	351	948	1048	1345	6727
Std. Dev (simulated)	1193	853	987	755	849	940	1186	1176	1254	1073	1244	6002
R^2	0.68	0.49	0.66	0.62	0.26	0.68	0.69	0.68	0.01	0.44	0.59	0.87
Pearson correlation coefficient (r)	0.82	0.70	0.81	0.79	0.51	0.83	0.83	0.82	0.10	0.67	0.77	0.93
Mean bias	166	673	199	219	−612	−20	445	−738	−439	524	−3	133
Mean prediction error (MPE)	0.26	0.43	0.28	0.35	0.73	0.20	0.22	1.50	0.90	0.47	0.39	0.26
Modelling efficiency (MEF)	0.54	−0.40	0.43	−0.20	−2.90	0.68	0.56	−10.54	−2.04	−0.30	0.53	0.86
Variance ratio	0.87	0.94	0.82	0.64	0.58	1.12	1.09	0.30	0.76	0.98	1.08	1.12
Bias correction factor (Cb)	0.99	1.00	0.98	0.91	0.86	0.99	1.00	0.55	0.96	1.00	1.00	0.99
Concordance correlation coefficient (CCC)	0.82	0.70	0.80	0.71	0.44	0.82	0.83	0.45	0.09	0.67	0.77	0.92

WOWTC, without water table contribution; WWTC, with water table contribution; D, dryland; I, irrigated; H, dry matter yield by individual harvest; Y, accumulated dry matter yield per year.

y_node_app_rate was increased by 200% (Fig. 3a) and (iv) the high sensitivity of the model in all locations when Kc was modified. For example, a reduction of 50% in this parameter generated a similar reduction in biomass production (Fig. 3c) without significant changes in ep (Fig. 4a1 and a2). When phenology parameters (Figs. 9b and 10b) and Kc (Fig. 9c) modifications were introduced into the *Weed* module (Table 6), the prediction of DM yield of both periods (establishment and regrowth) was improved relative to the initial situation. This was reflected in the performance parameters of the model (Table 8). However, DM yield was well simulated, as the crops developed only for the south-eastern Australian locations only (Fig. 10).

Prediction of DM yield for the whole growth period improved with the modified *Weed* module for all locations, except for Terang (Fig. 11). Summary statistics comparing observed and modelled accumulated DM yield analysis, before and after model modifications, demonstrated the improvement in the model predictions, as indicated by the R^2 (0.72 to 0.88) correlation coefficient (0.85 to 0.94) and CCC (0.77 to 0.90) (Fig. 12).

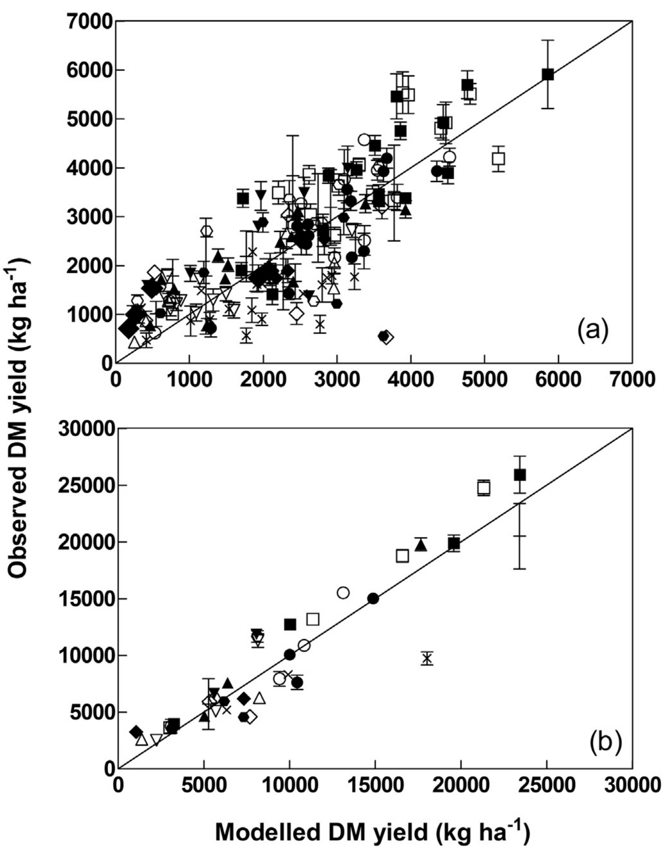

Fig. 6. Observed v. modelled DM yield (kg ha^{-1}) (a) for individual harvests and (b) accumulated per year of Lucerne winter-active genotypes in Rafaela (▲), Cranbrook (●), Forth (■), Cambridge (♦), Elliot dryland (●), Elliot irrigated (▼) and winter-dormant genotypes in Balcarce (+), Trenque Lauquen (▽), Pergamino (x), Cranbrook (○), Forth (□), Cambridge (△), Elliot dryland (◇) and Elliot irrigated (○). Diagonal lines represent 1: 1 fit (i.e. y = x). Capped vertical bars represent the range in observed values where such data were available.

4. Discussion

The main objective of this study was to evaluate the ability of APSIM to simulate the growth and DM yields of Lucerne and annual ryegrass (using the *Weed* module) in several locations of Argentina, as well as to compare model performance when simulating those crops in south-eastern Australia. This study was based on a detailed calibration of the model with actual parameters recorded at field trials. However, the model will require validation with independent data in further studies.

Lucerne DM yield was simulated with reasonable accuracy in most locations except Pergamino, Cambridge and Elliot. Results showed that the *Weed* module of APSIM has poor accuracy for simulating growth patterns and yields of annual ryegrass DM yield before the

Table 7
Observed data from Lucerne plant nitrogen concentration grown in Pergamino. Nc, critical N concentration; No, observed N concentration.

Harvest date	Nc	No
	(g N kg DM^{-1})	
8-Oct.-10	36.8	32.3
16-Nov.-10	39.8	26.6
10-Dec.-10	41.7	30.1
6-Jan.-11	41.7	25.2
1-Feb.-11	41.2	30.5
9-Mar.-11	40.0	30.5
25-Apr.-11	41.7	32.1
8-Jun.-11	41.7	33.8
14-Sep.-11	41.7	31.0
24-Oct.-11	41.2	34.2
17-Nov.-11	41.7	32.2
12-Dec.-11	41.7	28.2
17-Jan.-12	41.7	28.8
10-Feb.-12	41.7	36.0
19-Mar.-12	40.1	32.8
9-May-12	41.1	32.3

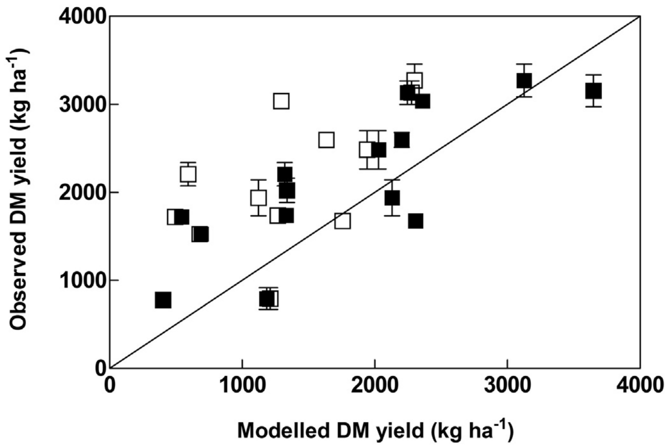

Fig. 7. Observed v. modelled DM yield for individual harvests (kg ha^{-1}) of Lucerne in Rafaela without water table contribution (□) and with water table contribution (■).Diagonal lines represent 1: 1 fit (i.e. y = x). Capped vertical bars represent the range in observed values where such data were available.

first harvest with the full data set. However, when phenology parameters and Kc modifications were introduced into the *Weed* module, the prediction of DM yield by individual harvest was improved.

4.1. Lucerne

This study has demonstrated that it is possible to simulate Lucerne DM yield adequately using the APSIM *Lucerne* module. This result is not surprising as this module has been extensively tested and evaluated in many environments for their ability to predict total DM yield (Robertson et al., 2002; Dolling et al., 2005; Chen et al., 2008; Pembleton et al., 2011; Moot et al., 2015). However, there were locations, such as Pergamino, Cambridge and Elliot which were rainfed and irrigated, where the model tended to over predict Lucerne DM yield. This overestimation was not unexpected, as the model accounts for neither soil fertility limitation other than N, nor any influences of pest and disease pressure on plants. Therefore, the APSIM *Lucerne* module is a predictor of potential maximum yield (Pembleton et al., 2011).

In all locations, the DM yield simulated was improved in respect to data published by Pembleton et al. (2011) for Tasmania. Although winter activity rules published by Pembleton et al. (2011) improved prediction of DM yield in winter, it was necessary to modify these rules for Trenque Lauquen and Rafaela using local long-term data for temperature. Nonetheless, the creation of winter activity rules by Pembleton et al. (2011) was based on the combination of the cultivars DuPuits and Grasslands Kaituna data, to give a representation of a winter-dormant genotype, and the cultivars SARDI 7 and SARDI 10 data as a representation of a winter-active genotype. Our analysis of temperature thresholds within winter dormancy rules determined that future studies of modelling are needed to understand the potential growth response of Lucerne genotypes with similar winter activity under different environments.

Within Argentine locations, APSIM poorly simulated Lucerne DM yield at Pergamino. The overestimation was justified through a deficient nitrogen state of Lucerne in all growth cycles (Table 7). The cause of this deficiency could have been the water logging because APSIM is not currently able to simulate the complex dynamics of N in alternately flooded soil environments (Zhang et al., 2006) which decreases the capacity of fixed atmospheric nitrogen due to anaerobic soil conditions. Further, since maximal rates are obtained at supra-ambient oxygen partial pressure (Arrese-Igor et al., 1993) it has been suggested that nitrogen fixation could be limited by oxygen availability. Thereby, possible decreases in nitrogen fixation could have led to overpredictions of DM yield at Pergamino. At Cambridge, the DM yield overestimation occurred only in the first year of growth, contrasting with Dolling et al.

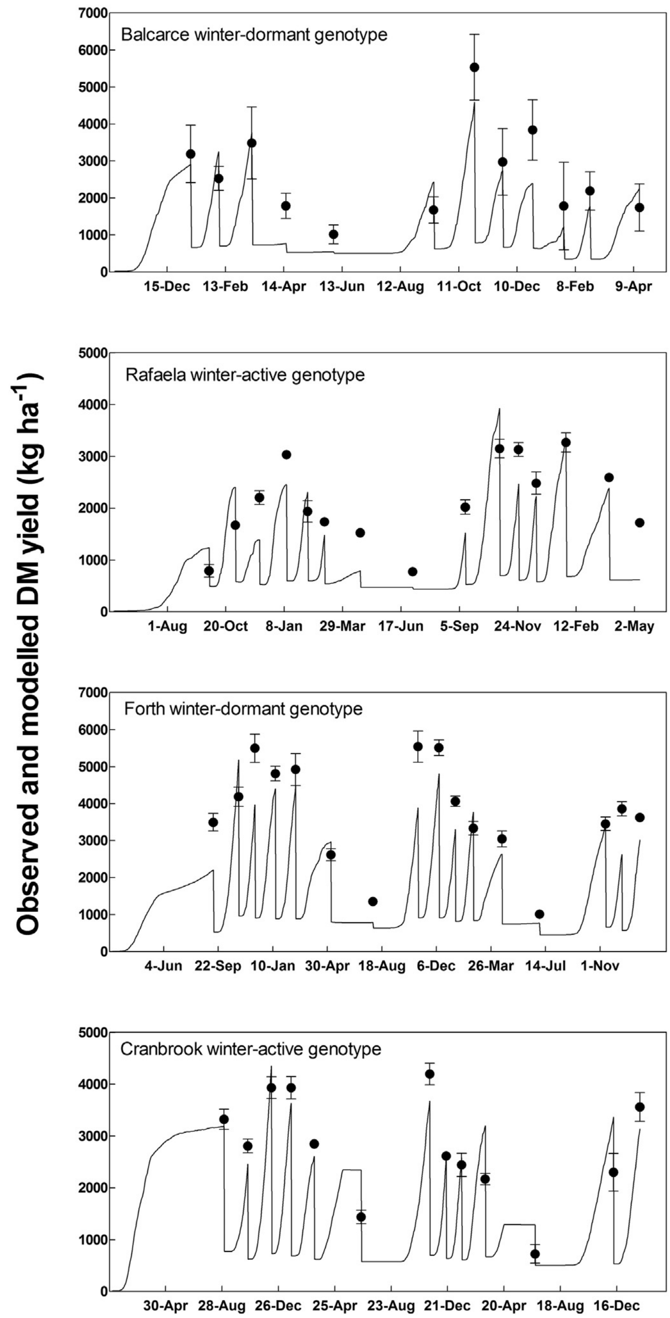

Fig. 8. Simulated (—) and observed (●) DM yield (kg ha^{-1}) of Lucerne in selected forage crops grown in the Argentine Pampas and south-eastern Australia. Capped vertical bars represent the range in observed values where such data were available.

(2005) report. In the second year of Lucerne, APSIM generally simulated DM yield well in this location of Australia. At Elliot, under both dry and irrigated situations, there was DM yield overestimation in the first and second years in a small number of harvests. The biomass yield for the majority of harvests at Elliot was underpredicted. Similar results were reported by Pembleton et al. (2011) for the same environmental conditions.

4.2. Annual ryegrass

Except for the period from sowing to first harvest, APSIM was capable of predicting DM yield of annual ryegrass in the Argentine Pampas and south-eastern Australia locations with reasonable accuracy. The accuracy of the model was similar to that obtained when predicting

Table 8
Summary statistics indicating the performance of the Agricultural Production Systems Simulator (APSIM) in predicting the DM yield (kg ha^{-1}) of annual ryegrass in the Argentine Pampas and south-eastern Australia.

	Sites					Individual harvests			Accumulated per year	
	Pergamino	Gral. Villegas	Terang	Flynn	Yarram	I	M1	M2	I	M2
No. of observations	29	5	10	5	2	51	51	51	15	15
Mean (actual)	1346	1512	6409	1834	–	2511	2511	2511	8536	8536
Mean (simulated)	1117	1779	5323	2612	–	2744	2406	2297	9328	7809
Std. Dev (actual)	613	1048	5733	1677	–	3271	3271	3271	5029	5029
Std. Dev (simulated)	682	1030	4523	1577	–	2826	2685	2710	3250	3800
R2	0.15	0.43	0.93	0.64	–	0.46	0.85	0.89	0.72	0.88
Pearson correlation coefficient (r)	0.38	0.66	0.96	0.80	–	0.68	0.92	0.94	0.85	0.94
Mean bias	228	−267	1086	−778	–	−233	105	214	−792	727
Mean prediction error (MPE)	0.55	0.54	0.32	0.66	–	0.98	0.52	0.46	0.34	0.24
Modelling efficiency (MEF)	−0.53	0.25	0.86	0.35	–	0.43	0.84	0.87	0.65	0.83
Variance ratio	0.90	1.02	1.27	1.06	–	1.16	1.22	1.21	1.55	1.32
Bias correction factor (Cb)	0.99	1.00	0.97	1.00	–	0.99	0.98	0.98	0.91	0.96
Concordance correlation coefficient (CCC)	0.38	0.66	0.94	0.80	–	0.67	0.90	0.93	0.77	0.90

I, initial weed module; M1, weed module modified by phenology; M2, weed module modified by phenology and Kc.

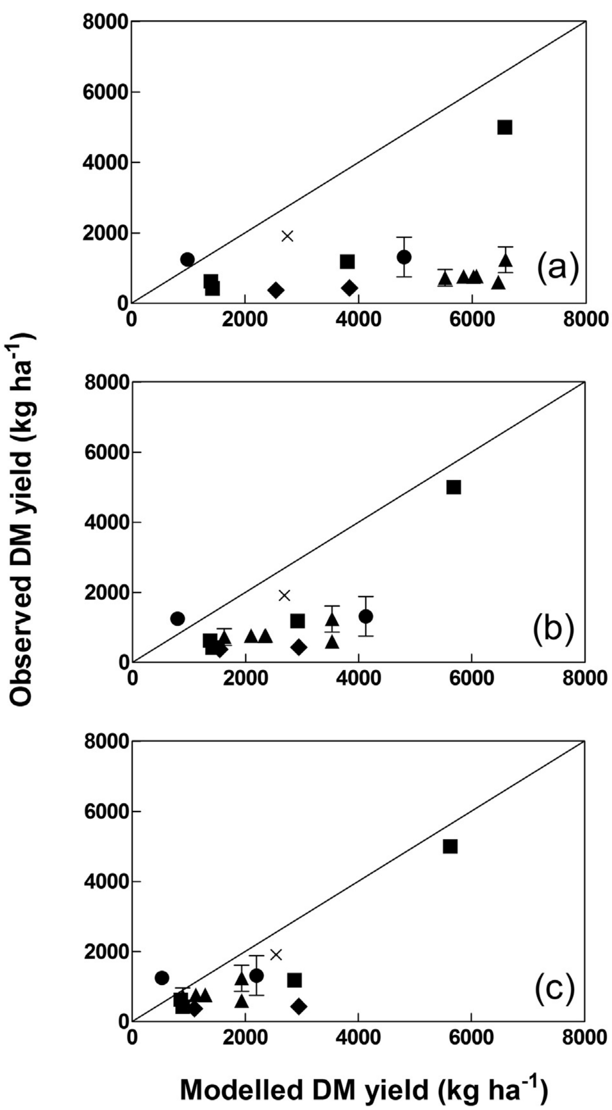

Fig. 9. Observed v. modelled DM yield (kg ha^{-1}) of individual harvests for established annual ryegrass in the implantation period (first harvest) simulated with (a) the original weed module, (b) the modified weed module by phenology, and (c) the modified weed module by phenology and Kc in Pergamino (▲), General Villegas (●), Terang (■), Flynn (♦) and Yarram (x). Diagonal lines represent 1: 1 fit (i.e. y = x). Capped vertical bars represent the range in observed values where such data were available.

annual ryegrass growth in the southern part of New South Wales (Deen et al., 2003) and south-eastern Australia (Pembleton et al., 2013).

Accurate phenology simulation of annual ryegrass is important, because the biomass accumulation in APSIM is defined directly by the RUE and TE parameters both fixed by each phenological state. In this context, and based on our previous sensitivity analysis, the parameters *shoot_lag* and *shoot_rate* were adjusted according to the growth habit of Italian ryegrass (Moot et al., 2000; Mohammed et al., 2013). Two other phenological parameters that have direct influence on DM yield in the model are node appearance rate (*y_node_app_rate*) and the number of leaves per plant after emergence and harvest (*leaf_no_at_emerg*). The node appearance rate was modified on basis of previous local experience with *Lolium multiflorum* (Agnusdei, 1999) and Italian ryegrass (Lattanzi et al., 1997) (Table 5). Similarly, the *leaf_no_at_emerg* parameter was modified so that harvests coincided with the occurrence of 3 fully emerged leaves on plants (Fulkerson and Donaghy, 2001). In order to achieve this management, the parameter was reduced by 0.5 leaf (Table 5). There are no previous reports of modifications of the phenology and Kc parameters of the APSIM *Weed* module. However, where changes were made to these parameters in other APSIM modules (e.g. Lucerne), they have improved the phenology (Moot et al., 2000) and DM yield predictions (Dolling et al., 2005; Brown et al., 2006; Chen et al., 2008). Kc in the APSIM *Weed* module has been specified by phenology stages. This module does not explicitly deal with the seasonal variation of parameters of water efficiency that are aforementioned.

The APSIM *Weed* module was limited in its ability to appropriately simulate the growth dynamics of annual ryegrass under the agro-ecological conditions of Pergamino and General Villegas in the Argentine Pampas, when the crop was regularly harvested throughout the growing period. The greatest deviance was observed in the first harvest yield in the period of crop establishment (Fig. 9a). Deen et al. (2003) also reported deviations between observed and estimated biomass data of the weed ecotype of annual ryegrass, simulated with APSIM at early stages of growth, that were frequently in excess of 100%. However, our simulations estimated biologically atypical values of accumulated herbage, of the order of 6000 kg DM ha^{-1}. Conversely, accurate performance of the APSIM *Weed* module for simulating annual ryegrass grown for forage was reported by Pembleton et al. (2013). The origin of these inconsistencies at first harvest might be related to the parameters used for the calculation of biomass production. As stated previously, the *Weed* module refers to the APSIM model Plant and calculates two estimates of the daily biomass production each day: one limited by the available water for transpiration (delta dry matter transpiration = SWS ∗ TE), and the other by the radiant energy. The TE is derived from the vapour pressure deficit (VPD) estimated from mean daily temperatures (Tanner and Sinclair, 1983), and a Kc that is held constant in the

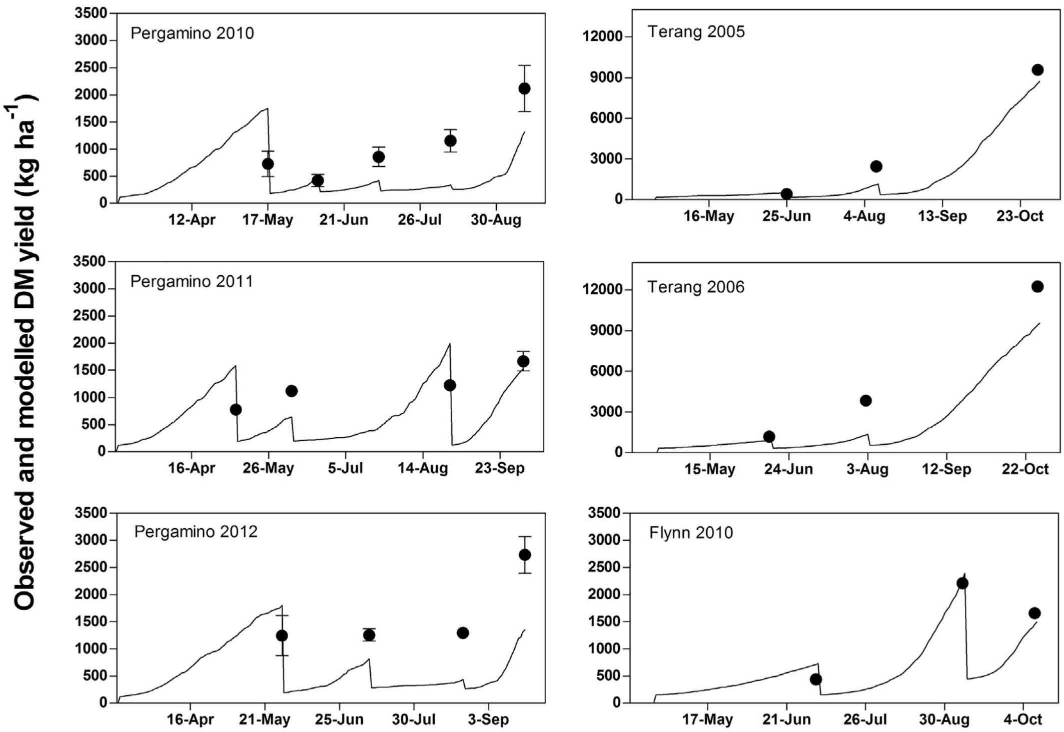

Fig. 10. Simulated (—) and observed (●) DM yield (kg ha^{-1}) of annual ryegrass with modified weed module by phenology parameters and Kc in selected forage crops grown in the Argentine Pampas and south-eastern Australia. Capped vertical bars represent the range in observed values where such data were available.

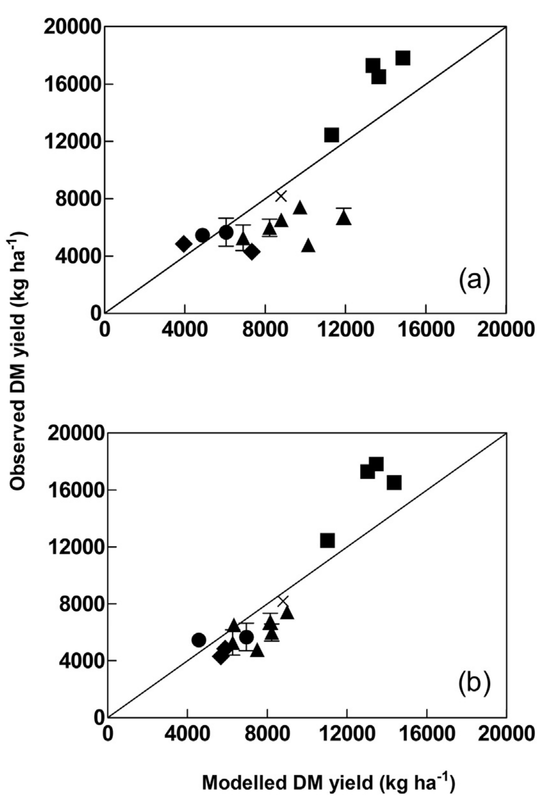

Fig. 11. Observed v. modelled DM yield (kg ha^{-1}) accumulated for the whole growth period for annual ryegrass simulated with (a) the original weed module and (b) the modified weed module by phenology in Pergamino (▲), General Villegas (●), Terang (■), Flynn (♦) and Yarram (x). Diagonal lines represent 1: 1 fit (i.e. y = x). Capped vertical bars represent the range in observed values where such data were available.

model. However, studies in winter crops have found that the Kc can vary greatly within the same species. For example, Kemanian et al. (2005) reported ranges from 3.2 to 7.0 and 2.8 to 6.7 Pa for a wide range of barley

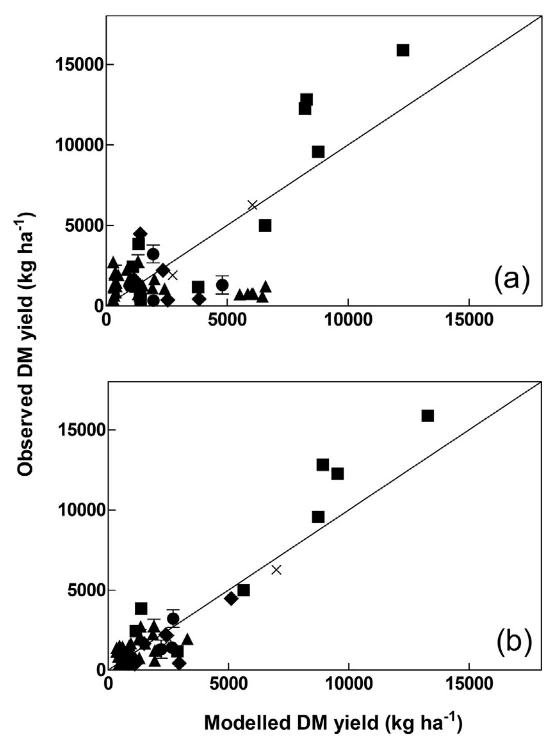

Fig. 12. Observed v. modelled DM yield (kg ha^{-1}) of individual harvests for established annual ryegrass (harvest two onwards) simulated with (a) the original weed module and (b) the weed module modified by phenology in Pergamino (♦), General Villegas (●), Terang (■), Flynn (♦) and Yarram (x). Diagonal lines represent 1: 1 fit (i.e. y = x). Capped vertical bars represent the range in observed values where such data were available.

and wheat cultivars, respectively. Hence, one possible reason of the yield overestimation of annual ryegrass, particularly at first harvest observed in this study, could be due to the relatively high Kc that the *Weed* module uses in all the phases of the crop (5 Pa). For that reason, a recalculation of the default Kc provided in the module was performed as the quotient between the TE, supplied as outfiles from the model (*transp_eff_cf*), and the VPD calculated from the maximum and minimum temperatures (Tanner and Sinclair, 1983). Interestingly, the corrected Kc dropped by about 50% (2.5 Pa) and, hence, also the DM yield estimated for the first harvest dropped (Fig. 3c) without significant changes in ep (Fig. 4a1 and a2). The esw values below 50% of PAWC during the establishment period (Fig. 4b1 and b2) meant that the annual ryegrass was not able to achieve high transpiration rates (Allen et al., 1998). On the other hand, the effect of PAWC reduction on biomass production was not considered because the changes in LL and DUL parameters modify the PAWC for the complete growth period (not only in establishment period) and that the resultant overall change in DM yield would be different depending on soil type (Fig. 3d).

While the overestimation of the observed data was partially corrected with this amendment, the deviation fitted in the range reported by Deen et al. (2003) still persisted. As mentioned initially, the discrepancy discussed in the previous paragraph was not evident in the simulations reported by Pembleton et al. (2013) for Terang, Flynn and Yarram in south-eastern Australia. However, when we analysed only the data of the period between sowing to first harvest, we found deviations between observed and estimated biomass data, for example, in year 2010 in Flynn (Fig. 9a). Also, there was a high growth in the same period of the order of 5000 kg DM ha^{-1} in year 2006 in Terang, similar to that in the Argentine Pampas. The plant available water capacity and the initial water in Terang were 151 and 0 mm, respectively. However, the rainfall in the same period was 225 mm. This corroborated that the high simulated growth of the *Weed* module in the implantation period depended, largely, on the initial water. These environmental differences suggest that the apparent accuracy of the model reported by Pembleton et al. (2013) could have been, to a certain extent, due to the fact that most data used for their simulations were with suboptimal water conditions. This latter point prevented the estimation of high biomass production rates and, hence, the expression of the model deficiency at early stages of growth.

The performance of the *Weed* module, in predicting crop DM yield reflects that this module has not been fully developed and extensively tested across a range of environments (Deen et al., 2003; Pembleton et al., 2013). The *Weed* module was not created in order to simulate annual ryegrass grown for forage rather than annual ryegrass as a weed in cereal cropping systems. Therefore, future studies of modelling will be needed to improve its use as forage crop.

5. Conclusions and future development requirements

This study reports on the ability of APSIM to model growth rate and DM yield of Lucerne grown in four distinct environments of the Argentine Pampas and four cool temperate environments of Tasmania and Victoria, Australia. Our study has shown that DM yield of Lucerne can be modelled by the APSIM *Lucerne* module with reasonable accuracy without any modifications. Although good results were obtained when the winter activity rules were incorporated under these environments, it was necessary to create new temperature thresholds within winter activities rules, for each location.

This study also showed that the original version of APSIM *Weed* module cannot be used to accurately simulate the growth and yield of rainfed annual ryegrass in a large range of geographic locations within Argentina and Australia for different years, soil characteristics and type of management. The greatest limitation was the overestimation of DM yield during the establishment period in both countries. This study has indicated that the model had greater accuracy in simulating annual ryegrass DM yield in south-eastern Australia than in Argentina. However, the model estimations were not accurate during the early stages in any of the two geographic locations analysed. The predictions of DM yield of annual ryegrass improved substantially when several key parameters (*shoot _lag*, *shoot_rate*, *leaf_no_at_emerg* and *transp_eff_c*) of the *Weed* module were modified. Our study contributes to the development of a module that has had fewer calibrations/validations and testing compared to the cereal crop modules in APSIM. However, future work on the APSIM *Weed* module is required in order to improve the DM yield prediction in annual ryegrass forage in early growth stages.

This study has shown that the APSIM model is a suitable candidate for the extension of forage crop research across multiple locations, years and management rules and could be a useful tool when investigating the interaction between different forage crops. However, as our study was based on data to both calibrate and evaluate the ability of APSIM to predict DM yields of Lucerne and ryegrass, further validations of the model with independent data are required.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.agsy.2015.12.005.

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