MODELLING GROWTH & QUALITY OF ALFALFA FOR LIVESTOCK

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ABSTRACT

Modelling alfalfa (lucerne) growth and development requires understanding of how the crop interacts with its environment. Over 20 years of field based research was used to calibrate the APSIM NextGen_Lucerne crop model. Phenological development was independent of grazing regime and fall dormancy (FD2, 5, 10) rating. The thermal time to flower buds visible for regrowth crops decreased linearly from 645 °Cd at a 10 h photoperiod (Pp) to 280 °Cd above a 14 h photoperiod. Buds visible to open flowers took a further 310 °Cd. The vegetative phyllochron was ~31°Cd in spring, but increased to 49 °Cd in fall. Post-buds visible the phyllochron increased to 69 °Cd. Plant height (heightchron; thermal time requirement for an increase of one mm stem height) pre-flowering showed an exponential decay as Pp increased from 4.2 °Cd/mm at 10 h to 0.6 °Cd/mm at 16.5 h for the FD5 genotype but this differed among FD classes. The critical Pp for stem extension, i.e. the day-length below which no stem elongation occurred was 11.1 h. Leaf area expansion rate (LAER) for FD5 decreased during a decreasing Pp from 0.018 $mm^2/mm^2/°Cd$ at 16.5 h to 0.008 $m^2/m^2/°Cd$ at 10 h. Different functions were required for FD2 and FD5 genotypes but a common extinction coefficient showed critical LAI was 3.65. Biomass accumulation was based on a temperature-dependent radiation use efficiency with partitioning and remobilisation to leaves, stems and roots changing with photoperiod and within regrowth cycles. This required functions to account for the seasonal pattern of root biomass partitioning and remobilization. The decrease in root biomass as photoperiod increased (mid-winter to mid-summer) was assumed as remobilization to shoots and carbon loss from maintenance respiration. As photoperiod decreased (mid-summer to mid-winter) root biomass increased as more carbon was partitioned below ground to replenish reserves.

Key Words: Fall dormancy, lucerne, *Medicago sativa* L.

INTRODUCTION

The east coast of New Zealand is typically summer dry with potential evapotranspiration exceeding rainfall for 3-5 months of the year (Salinger 2003). Alfalfa (lucerne; *Medicago sativa* L.) has always been grown in these regions, but it was predominantly conserved as hay with some direct grazing by weaned lambs. This meant it was relegated to <5% of the land area on a farm. It was seen as difficult to manage for direct grazed livestock because of its delayed spring growth. This didn't match lambing and calving times, when feed demand increases dramatically in these pasture-based farm systems. The management of alfalfa was based around the perceived need for the plant to reach 10% flowering before defoliation (Smith 1972; Sheaffer et al. 1988). From the late 1990s, a series of experiments were undertaken to challenge this guideline and examine whether a more flexible grazing regime could be developed. The subsequent 25 years of field experimentation has recently been used to calibrate the Agricultural Production Systems Simulator Next Generation (APSIM

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NextGen) for alfalfa. This paper outlines the field experimental results for regrowth (established) crops, their incorporation into the model and the consequences for on-farm management of grazed alfalfa. This paper focusses on results from the ‘Kaituna’ cultivar, which has a fall dormancy (FD) rating 5, which is the most commonly sown rating in temperate New Zealand. The final experiment of the series examined how an FD2 and FD10 genotype compared with FD5. Much of the experimental results and modelling work has been published, so this paper provides an overview of the main experimental results and modelling approaches applied for these crops grown without water stress.

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EXPERIMENTS

There were four main experiments used to develop relationships. All experiments were conducted at Lincoln University, Canterbury, New Zealand. Experiment 1 (E1) was conducted from 1997-2001 and compared the growth rates of alfalfa (FD5), chicory (*Cichorium intybus* L.) and red clover (*Trifolium pratense* L.) under irrigated (I) and rainfed (D) conditions (Brown 2004). Experiment 2 (E2) initially established irrigated and dryland alfalfa (FD5) sown at four dates (S1-S4) for two years. Experiment 3 (E3) was then imposed from 2000-2002, when four grazing regimes were introduced with the expectation that they would change the above and below ground biomass (Teixeira et al. 2007a; Teixeira et al. 2007b). The regimes included a 42±2 day (~300-600 °Cd) defoliation regime labelled Long|Long (LL) or a consistent 28±4 day (~200-400 °Cd) Short|Short (SS) rotation throughout the year. The remaining two treatments (SL and LS) followed the consistent regimes until mid-January (summer) when they were switched. Experiment 4 (E4) included the SS and LL regimes plus an extended 84±4 day regime (HH; ~530-1100 °Cd) and FD2, FD5 and FD10 genotypes (Ta 2018; Ta et al. 2020; Yang 2020; Hoppen et al. 2022).

All experiments had a common dataset collected, which included leaf appearance and flowering from marked plants. Fractional radiation interception was measured using a canopy analyser LAI-2000 or a Sunscan plant canopy analyser, both calibrated through regression analysis against destructive LAI measurements (Yang et al. 2022a). Biomass harvests of shoots were taken from 0.2 m^2 quadrats at regular (~two weekly) intervals throughout the growing season. At the end of the rotation roots were excavated from Experiments 3 and 4. Roots included crowns and taproots excavated down to 30 cm depth and represent the perennial biomass (referred to as root) compared with the shoot biomass (leaves, stems and flowers). These results enabled seasonal and within rotation biomass partitioning (to perennial organs) and remobilization (from perennial organs) to be separated. Post-harvest, crops were usually grazed in common with ewes and lambs or excess herbage was removed mechanically.

MODEL

The APSIM NextGen model uses the Plant Modelling Framework (PMF) (Brown et al. 2014) to capture crop responses to intercepted light, water and nutrient uptake on a daily basis. It also allows cultivar specific parameters to be considered to represent different genotypes (Brown et al. 2019). The model requires daily weather inputs that include, maximum and minimum air temperatures, total solar radiation, windspeed, and vapour pressure deficit. These were either measured onsite or were readily available from the Broadfields meteorological station, which is located 2 km north of the sites. The soil type for all experiments is an Udic Ustochrept described as fine silty, mixed, mesic (USDA taxonomy). Model outputs on a daily basis included alfalfa phenological stage, leaf area index (LAI), leaf, stem and root biomass. The simulation of phenological development requires a thermal time (Tt) function to drive progress through sequential pheno-phases and also develop canopy leaf area. A series of Tt functions were tested. A broken stick approach whereby the base temperature is 1 °C (Moot et al. 2001), provided the highest degree of accuracy compared with the more commonly used 5 °C derived from a continental climate (Fick et al. 1988),.

FIELD RESULTS AND IMPLICATIONS FOR MODEL DEVELOPMENT

Phenology

Experiment 1 quantified the linear change of “Tt requirement to flowering” of alfalfa to Pp, which is a characteristic of long day plants (Moot et al. 2003). In subsequent experiments, a function for “time to bud visible stage” was generated for modelling applications (Yang et al. 2021). This took the form of a broken stick function whereby Tt=1559-91.5*Pp when Pp <14 h and a constant Tt=278 °Cd at Pp $\geq$14 h ($R^2 = 0.67$). In practice, this gave a Tt requirement for 50% bud visible of 644 °Cd at a 10 h Pp and 278 °Cd at Pp greater than 14 h. The subsequent Tt requirement from “bud visible to open flowers” was constant at 310 °Cd. Node appearance (i.e. the inverse of the phyllochron) was also affected by Tt, but modified by Pp and plant phenophase. Vegetative nodes appeared consistently every ~31 °Cd under an increasing Pp, but increased from 35 to 49 °Cd as Pp declined from 16.5 to 10 h. For the very long periods of regrowth in HH crops, there were several regrowth rotations that had extended periods of flowering. This allowed a phyllochron value appropriate for the reproductive stage of ~61 °Cd to be estimated, which is approximately double the vegetative value. Stem extension has an impact on forage quality, with lignified stems of lower quality (Brown & Moot 2004). There were also field data that showed that node accumulation occurred before stem extension (Moot et al. 2003), so a function was developed to estimate crop height in response to thermal time (heightchron). For FD5 an exponential decay function was fitted (Yang et al. 2021) with a critical Pp of 11.1 h below which stem extension was minimal. This parameter was adjusted to account for the post-flowering phase in HH (84 day) crops and also differences in the FD2 and FD10 genotypes, based on results from Experiment 4.

Canopy development

This summary of results draws on the published data from Yang et al. (2022a). Leaf area expansion rate (LAER; mm/mm/°Cd) was used as a simple parameter to drive canopy expansion in response to temperature. This was calculated as the slope of the linear regression between LAI and Tt. The LAER changed with Pp consistently across different experiments. The LAER increased from 0.018 at 12 Pp to 0.022 at a 16.5 h Pp. In contrast, it declined linearly with Pp to a minimum of 0.008 at 10 h in fall. Complicating these LAER seasonal patterns, is the time taken to re-establish the canopy after each defoliation event. There are two scenarios in play; if basal buds are present (LAI>0) post-harvest then recovery from defoliation is rapid, but if they are absent then canopy removal stimulates basal-bud initiation and it takes longer to re-establish the canopy. For all crops, the x-axis intercept values from the linear regressions of LAI against Tt ranged from ~-50 to 200 °Cd. This suggests that some regrowth cycles required up to 200 ˚Cd to reach the calculated LAER, described as a lag phase of canopy expansion; whereas other regrowth cycles with longer periods between defoliation had basal buds present before defoliation occurred (x-axis intercept values $\leq$ 0 ˚Cd). This prompted faster canopy expansion post-defoliation. The x-axis represents the point at which LAER starts and so, if a single value was used, it can significantly under- or overestimate LAI over time. This leads to inaccuracies for estimating light interception and dry matter production. Therefore, a lag phase reduction factor (LRF) was required to account for the slower canopy expansion in the beginning of each regrowth cycle. This means that it took up to 200 °Cd for crops from the early regrowth stage to reach the maximum value of LAER for any given regrowth cycle. To do this, Tt since defoliation date increased from 0 to 200 °Cd, as the LRF increased from 0 to 1. In contrast, for the very long regrowth crops (HH treatment) that were left well into flowering before defoliation, basal buds were frequently present at harvest and were not removed during the harvest process. A basal bud function was developed to account for the initial leaf area post-defoliation (default = 0). An optimisation process, based on field observations of LAI development, was used to estimate a basal buds factor (BBF; % of LAER) with a value of 0.2 (20% of potential LAER) estimated. For the prolonged 84-day regrowth periods, canopy senescence was most apparent. Observed shoot biomass data (Figure 1) were used to fit and test a senescence function in APSIM NextGen, which improved model prediction of LAI and biomass for the HH treatment (Yang et al. 2022a).

Biomass accumulation, remobilisation and partitioning

For crops in Experiment 1, the growth rate of alfalfa increased linearly with temperature, but the rate was 20-30 kg DM/ha/d higher in an increasing than decreasing Pp (Moot et al. 2003). This prompted shoot and perennial organ (root+crown) biomass to be measured in Experiments 3 and 4 (Figure 2). Results showed a systematic seasonal pattern of root biomass decline in winter/spring, followed by an increase in mid-summer/autumn. This signal overrode changes within regrowth rotations and was apparent under different defoliation regimes (Moot et al. 2021). Thus, modelling shoot biomass required an accurate representation of these changes in perennial biomass, which are less relevant when modelling annual crops. Carbon assimilation in the APSIM NextGen model uses Radiation Use Efficiency (RUE) as a summary parameter, rather than photosynthesis and respiration. This simplification is appropriate for annual crops as the focus is on above ground biomass growth because root biomass curvilinearly increases across the vegetative stages. For alfalfa, to account for root biomass as a significant carbon sink, we used the concept of total radiation use efficiency (RUE_{total}). This includes biomass dynamics both above and below ground. Based on field data, RUE_{total} increased from negligible values at 8 °C to a maximum value of 1.6 g DM/MJ/m^2 at 18 °C, regardless of the fall dormancy rating of genotypes (Yang et al. 2022b). The study also includes a detailed investigation of the allocation of biomass among alfalfa organs. For example, leaf biomass demand was calculated from a simple linear function of LAI while stem dry matter was allocated to the organ based on an allometric power function in relation to shoot biomass.

The root biomass dynamic across seasons was characterised by a minimum in mid-summer and a maximum in late-fall, before it declined slowly over winter. The amount of root biomass lost in winter was used to estimate the rate of root turnover (i.e. respiration, translocation and senescence), which enabled a structural root component to be estimated as 2500±500 kg DM/ha. This was common to all genotypes based on the assumption that the structural component is not consumed by respiration. In contrast, the parameters for remobilization and partitioning were affected by both season of the year and fall dormancy class of genotypes. For example, FD2, FD5 and FD10 showed the same remobilization rate of 0.01/day across the year. However, the duration of the remobilization period was lower (200 °Cd) for FD2 compared with FD5 (250 °Cd) and FD10 (300 °Cd).

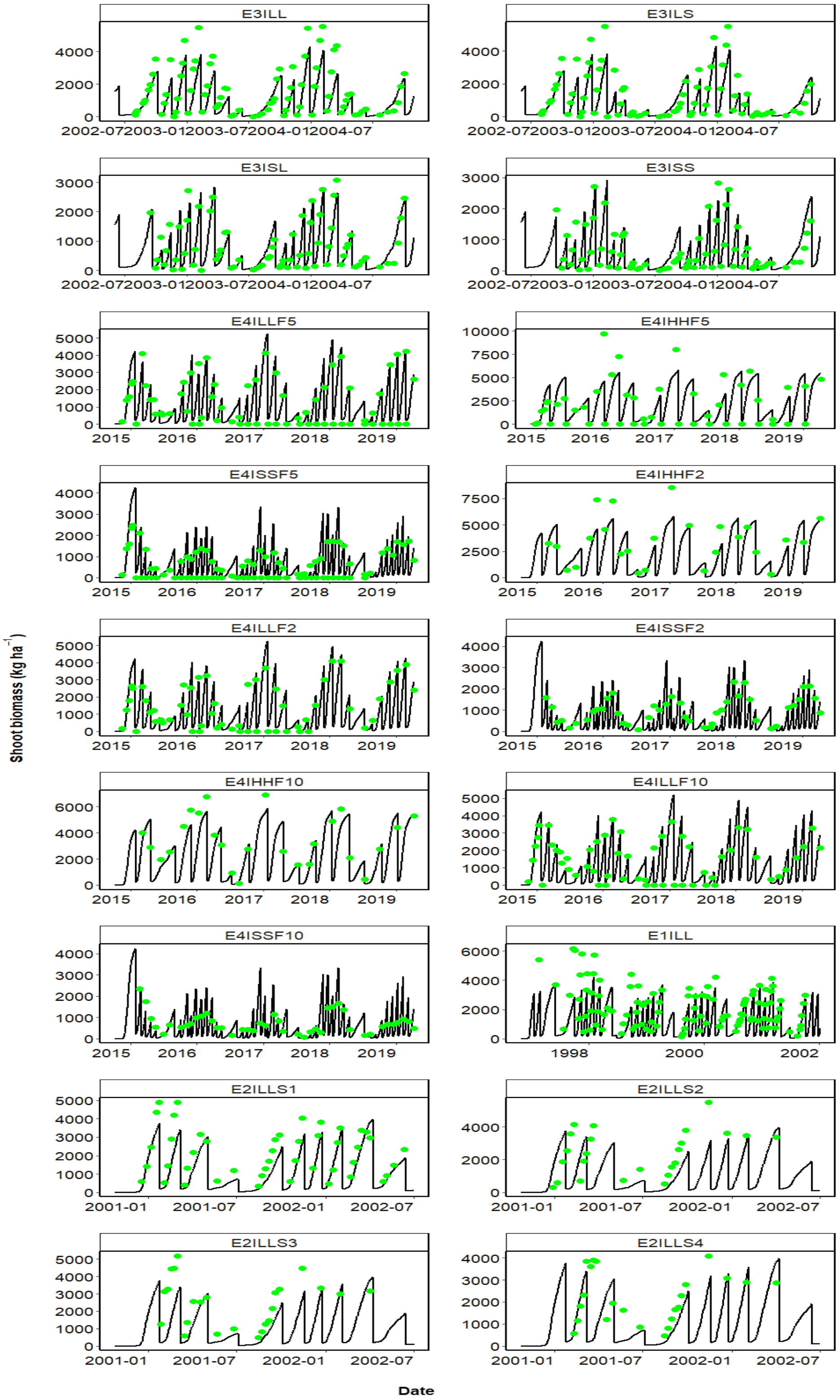

Figure 1. Time-series of predicted (—) and observed (●) shoot biomass. Datasets were from four irrigated (I) field experiments (E1-E4) with three defoliation treatments [HH (84 day), LL (42 day) and SS (28 day)] and two fall dormancy treatments (F5, F2 and F10) classes conducted in 2014-2019 at Iversen field, Lincoln University, Canterbury, New Zealand. F5 alone was sown for E1-E3. For E2 data for four different sowing dates (S1-S4) are shown.

N dynamics

For all treatments, alfalfa leaf N concentration ranged from 3.6% to 6.8% and decreased as leaf biomass increased, although this change was lower than for stem. Leaf N concentration was not affected by defoliation or genotype FD (data from Experiments 2 and 4). Stem N concentration ranged from ~1% to 6% and showed an allometric relationship with stem biomass. Root N showed a similar seasonal pattern as root biomass. To model these processes in the PMF, N supply was estimated as 2.5% of total biomass, whereas N demand was built from N concentration functions for each organ. To capture the seasonal pattern of root N, a N remobilization coefficient (% storage root N per day) was set at 2.0 for FD5 and 0.5 for FD2 and FD10) as Pp increased. However, from mid-summer to mid-winter when Pp decreased, an increase in taproot N concentration was driven by N partitioning to roots. Thus, the model was parameterized to have a maximal root N demand with no remobilization. As a result, the model had poor to fair prediction on leaf N, stem N and root N for all treatments. Applying the N module also improved shoot biomass predictions, especially for the 28 day defoliation treatment (SS).

DISCUSSION

The extensive experimental programme over a 25-year period has enabled the parametrization of the APSIM NextGen_Lucerne model. The experimental data highlighted several physiological aspects that need to be considered when modelling alfalfa which had major implications for on-farm management. Specifically, flowering was shown to be Pp dependent which implied that management decisions based solely on phenological stages were inappropriate. Improved management has encouraged greater use of alfalfa in New Zealand. Farmers are now encouraged to initiate spring grazing when the crop is 10-15 cm tall in spring and apply a rotational grazing system (Moot et al. 2016). Applications of the calibrated model indicated that a rotation length of about 350 °Cd (~ 10 main-stem nodes) is appropriate for New Zealand conditions. Similar management concepts have also been validated in an Argentinian beef grazing context (Berone et al. 2020). The analyses using APSIM-NextGen also highlighted the lack of difference in phenological development across genotypes with different fall dormancy classes in this temperate environment. Further model development requires testing of these responses with other genotypes and from other environments.

An implicit challenge when direct grazing alfalfa stands is that the herbage is usually removed over a long period (~3 to 10 days), depending on stocking rate. Thus, the time of basal bud emergence, which has implications for the development of leaf area in the following rotation, requires further investigation. To overcome the lack of experimental observations, the lag phase and a basal bud factor were developed in the current model. These functions need to be validated with field measurements and a mechanistic determination of basal bud initiation is required. Despite this, the model showed acceptable accuracy when estimating phenological development (Yang et al. 2021), leaf area expansion and canopy development (Yang et al. 2022a) and biomass partitioning (Yang et al. 2022b). A feature of the biomass modelling was the need to cope with seasonal biomass allocation differences, the effects of remobilisation within regrowth periods and differences among genotypes with different fall dormancy. An initial modelling approach to account for these dynamics considered changes in the length and rate of biomass remobilization. For instance, the FD10 genotypes remobilized taproot reserves for a longer period than FD2 and FD5 within each regrowth rotation. This may explain poor stand longevity of FD10 under intensive grazing (Harvey et al. 2014).

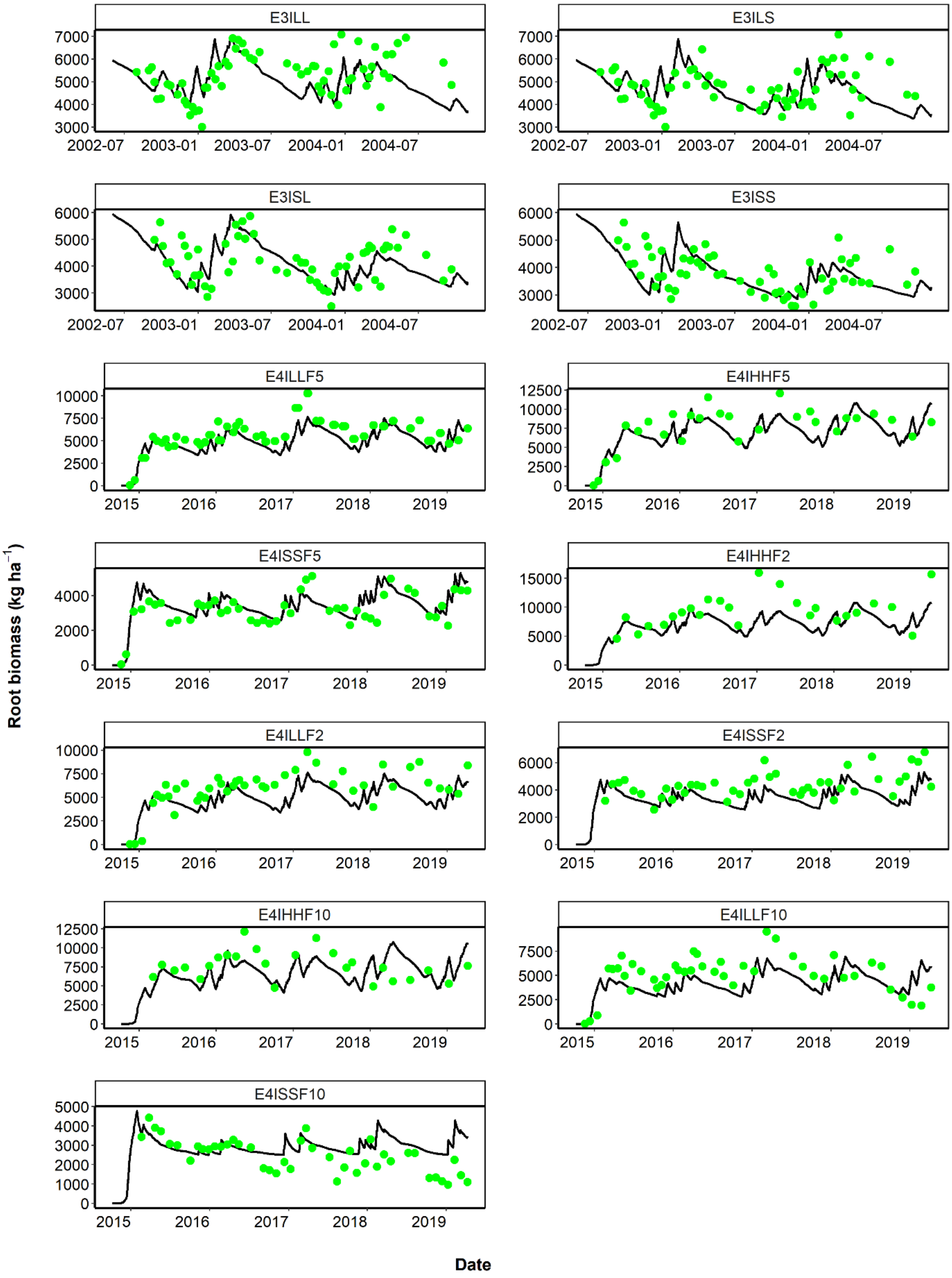

Figure 2. Time-series of predicted (—) and observed (●) root (taproots + crown) biomass. Datasets were from two irrigated (I) field experiments (E3 and E4) with multiple defoliation treatments [HH (84 day), LL (42 day), LS (42, 28 day), SL (28, 42 day), and SS (28 day)] for fall dormancy FD5 (E3 and E4) and FD2 and FD10 (E4) classes conducted in 2002-2019 at Iversen field, Lincoln University, Canterbury, New Zealand.

The combination of targeted field experimentation and biophysical modelling provided new insights that gave NZ farmers greater confidence to change on-farm management of alfalfa. For example, the previous management guideline to wait until 10% of flowering before grazing alfalfa is gone. It has been replaced by an emphasis on forage quality and utilization of the feed in spring when biomass and N remobilization from roots to shoots is enhancing spring growth rates. In autumn farmers are encouraged to let the crop flower to allow increased C and N partitioning to recharge root reserves, especially for an FD10 genotype.

SUMMARY

The APSIM NextGen_Lucerne model has been calibrated to capture alfalfa growth and development under non-limiting conditions, based on an extensive experimental programme. The model has been calibrated to represent field results but equally, in the absence of experimental data, model optimisation has proven effective to estimate model parameters. The combination of field research and modelling have unveiled new areas for future research and, importantly, underpinned changes in on-farm management for greater productivity, profitability and farm resilience, particularly in the summer dry regions of New Zealand.

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