Modelling Phenological Development of Regrowth Lucerne (*Medicago sativa* L.) Using APSIMX

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Abstract
Predicting lucerne phenological development is important for optimising defoliation scheduling and other management events. This study provides a simple framework to quantify the phenological response of a semi-dormant (fall dormancy 5; FD5) lucerne to environmental factors. This response was used to create algorithms for the APSIMX model, which was verified using two different fall dormancy classes (dormant FD2 and non-dormant FD10). The framework includes lucerne node appearance, height, and flowering in response to temperature and photoperiod (Pp). An evaluation of methods for calculating thermal time (Tt) indicated that the "Moot model" to define cardinal temperature most accurately computed Tt. A Tb (base temperature) of 1˚C had the lowest CV% and highest P value. In the vegetative phase, the phyllochron increased from 23 to 45˚Cd/primary leaf as Pp decreased from 16 to 12.5 h; the "heightchron" and mean Pp displayed a poor polynomial relationship (R^2=0.44). In the reproductive phase, the phyllochron was consistent across Pp at 68˚Cd/primary leaf and the crop had a longer "heightchron" than in the vegetative stage. Tt to 50% bud initiation decreased as Pp increased. There was close agreement between predicted and observed values of node number and time to 50% bud initiation across genotypes.

Key Words
alfalfa, APSIMX, node number, height, flowering

Introduction
Crop models are useful tools for understanding agricultural systems and the interactions among their components, including soil, plants, environment, and management factor (Hodges 1990). Fall dormancy (FD) rating is an important classification for different lucerne (*Medicago sativa* L.) genotypes (Barnes et al. 1979). Predicting lucerne phenological development among different FD classes is important because crop development stage influences herbage quality and grazing management strategies. Primary drivers of phenological development are temperature and photoperiod (Pp). However, few studies have investigated modelling physiological development among different genotypes. The aim of this study was to quantify the response of semi-dormant lucerne (FD5) to these factors and create algorithms for the APSIMX model, then use the data from dormant (FD2) and non-dormant (FD10) genotypes to verify model performance.

Methods
Data source and experimental design
Data were assembled from a field experiment conducted from 2014 to 2018 at Lincoln University, Canterbury, New Zealand. Treatments were imposed as a complete randomized block design with four replications: three defoliation frequencies (every 28, 42 and 84 days) and three fall dormancy classes (FD2, FD5 and FD10). Reported data are from FD2, FD5 and FD10 under an 84 day cutting regime, over 4 growing years, each with 2-4 regrowth periods (Ta et al. 2017). The longest cutting interval was used to allow lucerne to express vegetative and reproductive development in each regrowth cycle.

Thermal time calculation and base temperature determination
The parameterization of phenological development involved calculating thermal time (Tt; ˚Cd) and selecting a suitable base temperature (Tb; ˚C) as a threshold temperature below which no development happens. For Tt calculations, the Moot model (Moot et al. 2001), the Fick framework (Fick and Onstad 1988), and the WE model (Wang and Engel 1998) were compared. For Tb determination, X-intercept, least variable and regression coefficient methods were compared.

Phenological measurements and calculations
At the beginning of each regrowth cycle, five shoots were marked on five plants in each plot (60 plants were measured) and node appearance, height and flowering were measured every 7-10 days. Nodes were counted

as sites of primary leaf attachment and height (mm) was measured on fully extended stems. Time of 50% bud initiation was recorded. Phyllochrons were defined as the thermal time interval between the appearance of successive primary stem nodes and calculated as the slope of Tt against node number in both the vegetative and reproductive phases. "Heightchron" in both vegetative and reproductive phases was defined as the thermal time requirement for an increase of one mm stem height and calculated as the slope of Tt against height.

Model simulation and validation
Data from the FD5 treatment were used to develop equations and parameters for the APSIMX-lucerne model. Once the APSIMX-lucerne phenology module was built, data from FD2 and FD10 treatments were to verify the model.

Statistical analyses
Regression analyses, analysis of variance (ANOVA) and Fisher's least significant difference (LSD) were determined with RStudio (R.3.4.0). For model evaluation, the following values were calculated: coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE) and relative root mean square error (R_RMSE). To quantify the causes of deviation, the error was segmented into components, including standard bias (SB), non-unit (NU) slope and lack of correlation (LC).

Results and Discussion

Thermal time accumulation
A statistical evaluation of methods for calculating Tt indicated that the Moot model to define cardinal temperature most accurately computed Tt. A Tb of 1 ˚C had the lowest CV% of 26% and highest P value of 0.86.

Node appearance
The relationship between node number and Tt was a positive linear response in both vegetative (R^2=0.96-0.99) and reproduction phases (R^2=0.93-0.99). In the vegetative phase, phyllochron decreased from 30 to 28˚Cd/primary leaf as Pp increased from 12 to 16 h in spring, and phyllochron increased from 28 to 45˚Cd/primary leaf as Pp decreased from 16 to 14 h in autumn. In the reproductive phase, the phyllochron was constant at 68˚Cd/primary leaf (Figure 1). For all treatments, the regressions of observed values compared with predicted values were not significantly different from the 1:1 line (Figure 2). R^2 is in range of 0.86 to 0.89, R_RSME and NSE values indicated good agreement between predicted and observed values (Figure 2). This finding suggests that the difference of node appearance among three FD classes was not significant; a phyllochron of FD5 can thus be used to model node appearance of other FD genotypes.

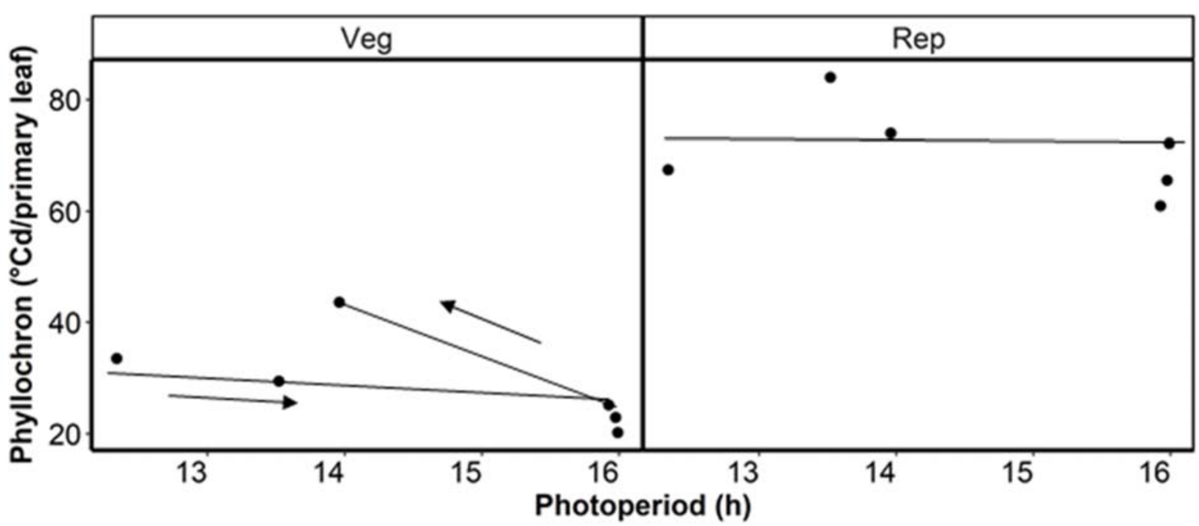

Figure 1. Phyllochron (˚Cd/primary leaf) against mean photoperiod (h) in both vegetative (Veg) and reproductive (Rep) phases for fall dormancy 5 (FD 5) from a field experiment conducted from 2014-2018 at Lincoln University, Canterbury, New Zealand. Lines represent linear regressions, and arrows indicate direction of photoperiod change.

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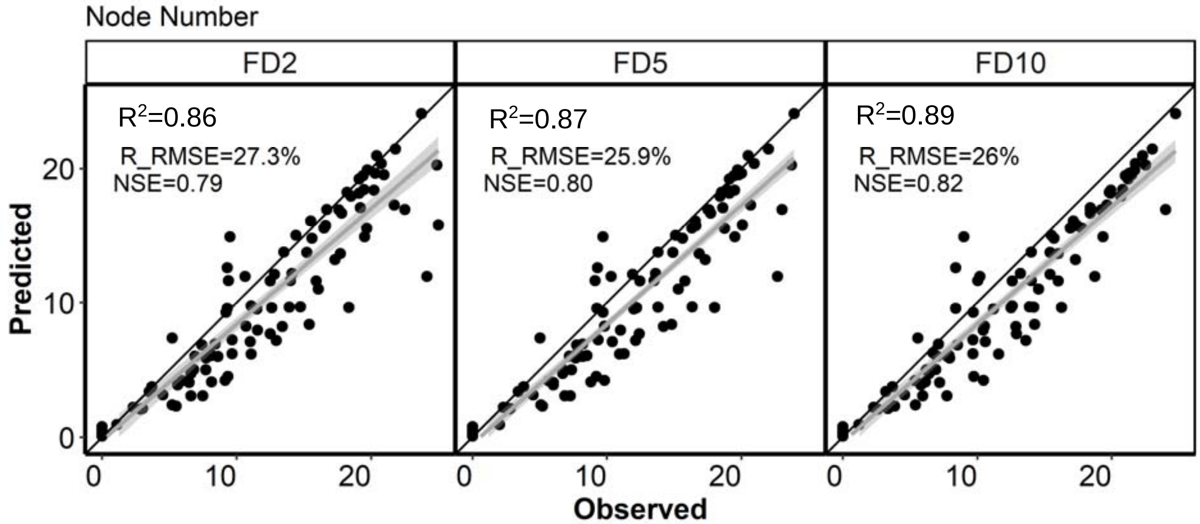

Figure 2. Predicted and observed values of lucerne node number for three dormancy classes (FD2, FD5 and FD10) from a field experiment conducted in 2014-2018 at Lincoln University, Canterbury, New Zealand (black dot). The grey lines represent linear regressions and shaded areas represent 95% confidence intervals. The black lines represent 1:1 lines.

Plant height

The relationship between height and accumulated Tt was a positive linear response in both the vegetative (R^2=0.81-0.99) and reproductive (R^2=0.70-0.97) phases. In the vegetative phase, the "heightchron" and mean Pp displayed a poor polynomial relationship (R^2=0.44) in which the "heightchron" decreased as Pp increased from 0.80 in 13 h to 0.69˚Cd/mm in 16 h. In the reproductive phase, the "heightchron" decreased as Pp increased from 2.2 to 1.8˚Cd/mm. The model adequately reflected the fast elongation rates in summer, but overestimated plant height in late winter and early spring (Figure 3). Overall, the regression of observed values compared with predicted values was not significantly different from the 1:1 line. However, the FD5 and FD10 classes had closer simulation results than FD2 class; the R_RMSE values were 21.9%, 20.9% and 30.7%. The regression lines were above the 1:1 line for FD2 and under the 1:1 line for FD10, which suggests that the model over-predicts the height of FD2 plants and under-predicts the height of FD10 plants (Figure 4). In the reproductive phase, the "heightchron" of FD2 was slightly higher than FD5 and FD10. The results suggest that separate functions are required to improve model accuracy for plant height across different FD classes

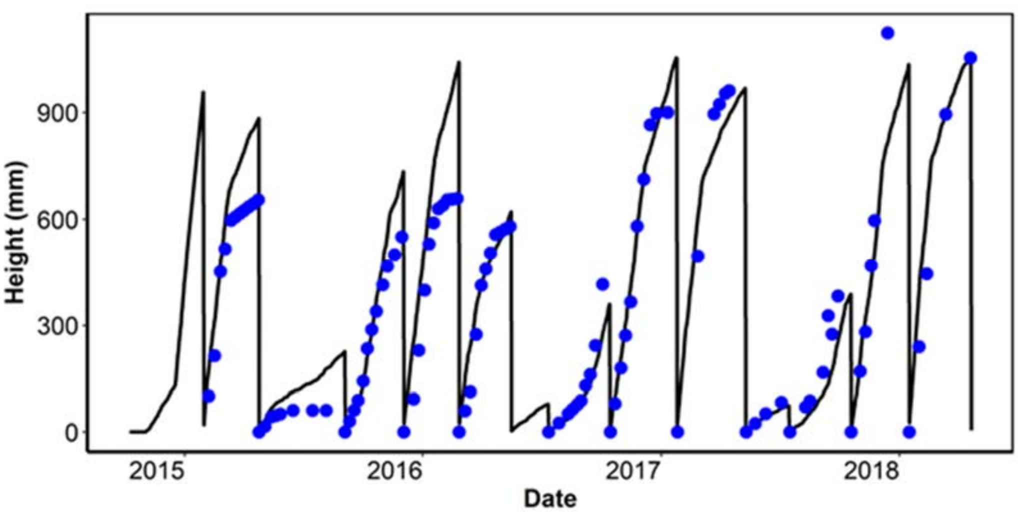

Figure 3. Predicted and observed values of plant height (mm) for fall dormancy 5 (FD5) from a field experiment conducted from 2014-2018 at Lincoln University, Canterbury, New Zealand. Lines are predicted values and blue dots are observed values.

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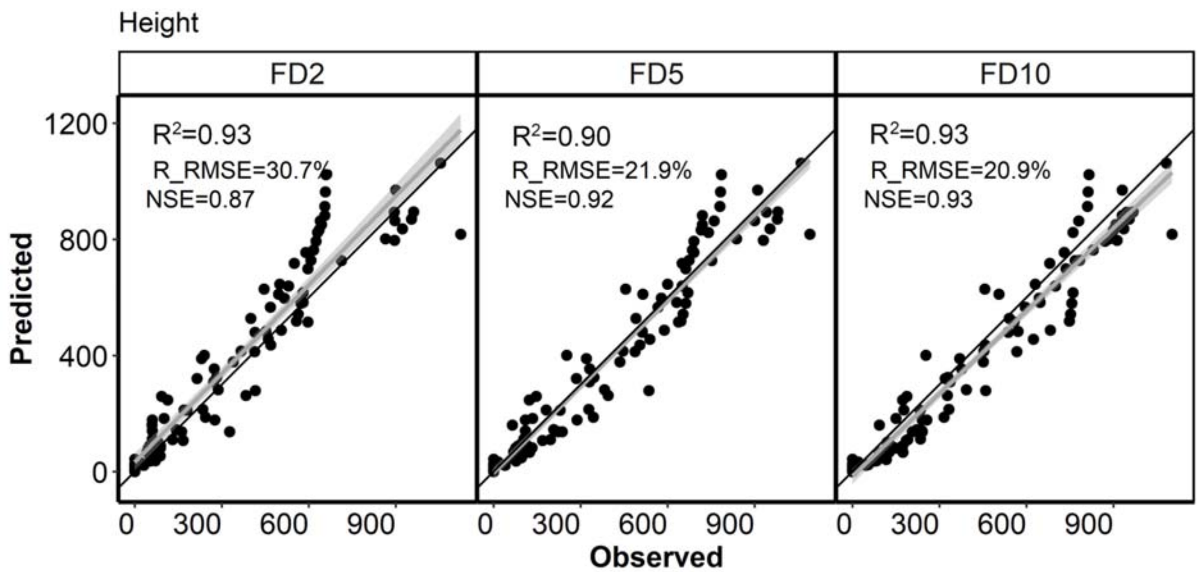

Figure 4. Predicted and observed values of lucerne plant height (mm) for three fall dormancy classes (FD2, FD5 and FD10) from a field experiment conducted in 2014-2018 at Lincoln University, Canterbury, New Zealand (black dot). The grey lines represent linear regressions and shaded areas represent 95% confidence intervals. The black lines represent 1:1 lines.

Flowering

Tt to 50% bud initiation decreased from 400 to 350˚Cd as Pp increased from 12.5 to 16 h. All genotypes had a highly significant agreement between predicted and observed values.

Conclusion

- The Moot model with a Tb of 1 ˚C was the most accurate approach for calculating Tt.
- The Phyllochron was only responsive to Pp in the vegetative phase. Greater Tt was required for leaf appearance in the reproductive phase.
- Functions of the phyllochron from FD5 were model node appearance of other FD genotypes.
- There was a poor polynomial relationship between "heightchron" and mean Pp in the vegetative phase; lucerne crops had a higher "heightchron" in the reproductive phase.
- The model over-predicted the height of FD2 plants and under-predicted the height of FD10 plants, so separate algorithms were needed.
- There was close agreement between predicted and observed values of node number and time to 50% bud initiation.

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