On-farm prediction of red clover yields

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Abstract

Red clover (*Trifolium pratense* L.) grown at Taihape, New Zealand, was analysed to validate coefficients to predict biomass yield. The mean annual production of red clover over three years was 12,830±472 kg DM/ha/year, with the maximum mean growth rate of 112±7.21 kg DM/ha/day (spring). In non-limiting soil moisture conditions, red clover grew 7.44±0.31 kg DM/ha/°Cd up until the 11th of January and then at 2.67±0.47 kg DM/ha/°Cd. This pattern of production confirms previously results that show a reduction in growth rate for the mid-January-July period. This probably reflects increased partitioning of assimilate to red clover roots in response to a decreasing photoperiod. These coefficients are easily transferable to estimate red clover yield under non-limiting conditions for other locations. These could be integrated into feed budgeting software to assist on-farm decision-making. For years with a significant period of water deficit, a soil water budget is required coupled with the temperature-based coefficients to estimate yield and the potential loss of yield from summer dry conditions.

Keywords: thermal time, *Trifolium pratense,* on-farm, Taihape

Introduction

Pasture management systems in New Zealand have been built via a large body of work to support dairy and dry stock farms managing perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.*)* pastures (McCall and Bishop-Hurley 2003; Radcliffe 1981; Romera et al. 2009). Pasture growth rates have been integrated into climate-driven pasture growth models, that enable farm consultants to compare on-farm performance across a range of locations. These models support scenario testing and decision-making by predicting herbage mass seasonally and annually. However, there is limited modelled data available to guide sheep and beef farmers in more extensive, often more variable environments, and particularly when they are using other forage species.

For some of these other species, progress has been made. For example, simple temperature-based models have been developed to predict lucerne (*Medicago sativa* L.) yield potential under New Zealand conditions, which can inform best-practice management guidelines (Moot et al. 2022). Similarly, cocksfoot (*Dactylis glomerata* L.) growth responses to water and nitrogen availability have been quantified based on temperature adjusted coefficients for yield estimation (Mills Moot and McKenzie 2006). Recently Keenan et al. (2023), produced a set of coefficients that relate red clover production to mean air temperature under irrigated conditions. Several of these datasets were used to provide a framework for extending predictive capability to other economically important forage species within sheep and beef systems.

In each of these cases, the assumption is that pasture growth is directly influenced by the main environmental factors of temperature, soil moisture, and nitrogen fertility (Mills et al. 2006). The hypothesis is that these factors can be incorporated into simple empirical models to design on-farm systems, allowing farmers to make informed decisions about whole-farm production and reduce the risk associated with using these forages.

In their study, Moot et al. (2022) used irrigated crops and assumed nutrient supply was not limiting due to biological nitrogen fixation in lucerne. The same assumption was made for red clover (*T. pratense* L.) by Keenan et al. (2023) and is assumed in the present study.

However, in addition to temperature, a water deficit will disrupt the linear growth in the temperature relationship and this is particularly relevant on-farm when irrigation is unavailable. Mills et al. (2006) showed that unirrigated and irrigated pastures with similar nitrogen inputs had equivalent growth rates before and after the period of water deficit. Accounting for the impact of a soil moisture deficit is necessary to estimate red clover growth rates in response to temperature. Therefore, this analysis included a simple soil water budget to demonstrate how this could be applied on-farm.

Once the temperature adjusted growth rate is known, additional parameters such as assimilate partitioning to flowers or roots can be incorporated for more detailed yield estimation, but this was not the purpose of the current study. Thus, the aim of this study was to assess whether the previously generated temperature adjusted red clover growth rates (Keenan et al. 2023) were consistent with those generated from a commercial farm situation.

Specifically, we sought to determine whether the

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Table 1 Harvest and grazing parameters for red clover at Rihia Land Company, Taihape

Season	Regrowth	Start date	Grazing date	Regrowth days
2020/21	1	25/10/2020	14/12/2020	50
	2	15/12/2020	25/01/2021	41
	3	26/01/2021	22/02/2021	27
	4	23/02/2021	21/03/2021	26
	5	22/03/2021	9/04/2021	18
	6	10/04/2021	10/05/2021	30
	7	11/05/2021	29/06/2021	49
	8	30/06/2021	11/08/2021	42
2021/22	1	12/08/2021	3/10/2021	52
	2	4/10/2021	2/11/2021	29
	3	3/11/2021	4/12/2021	31
	4	5/12/2021	1/01/2022	27
	5	2/01/2022	25/02/2022	54
	6	26/02/2022	6/04/2022	39
	7	7/04/2022	9/05/2022	32
	8	10/05/2022	2/07/2022	53
2022/23	1	3/07/2022	2/08/2022	30
	2	3/08/2022	27/09/2022	55
	3	1/10/2022	31/10/2022	30
	4	1/11/2022	25/11/2022	24
	5	23/11/2022	20/12/2022	27
	6	21/12/2022	26/01/2023	36
	7	27/01/2023	22/02/2023	26
	8	23/02/2023	4/04/2023	40
	9	5/04/2023	20/05/2023	45
	10	21/05/2023	30/06/2023	40

relationship between accumulated yield and thermal time was linear and whether this relationship was consistent across years and seasons and environments. Our null hypothesis was that coefficients derived from linear yield regressions on thermal time would not differ with those previously reported. If accepted, this would enable the use of a single growth coefficient to estimate red clover yield across environments.

Materials and Methods

An on-farm trial of “Grasslands Relish” red clover was established via direct drilling on 25 October 2020 sown at 14 kg/ha in a paddock that had previously been in a perennial ryegrass and white clover mixture. The paddock was on a commercial sheep and beef farm located east of Taihape (39^{o}76’S, 175^{o}91’E, 389 m.a.s.l) and was measured from establishment until the final observation on 30 June 2023. Specifically, red clover yield was accumulated and related to the accumulation of temperature as thermal time over the same period. This was used to quantify the temporal pattern of red clover production in an on-farm situation. Red clover composition of the sward was reviewed at each harvest through a visual assessment of two components: red clover and weed species.

Details of harvest dates for dry matter production, rotation information, days between harvest dates and a detailed field diary of management actions are summarised in Tables 1 and 2. This included agronomic information and was used to determine the grazing interval (days and thermal time) of regrowth.

Dry matter was harvested from three sections of the

Table 2 Field diary of management actions for red clover at Rihia Land Company, Taihape

Date	Activity
10/10/2020	Fertiliser application: AgLime 1000 kg/ha
25/10/2020	Sowing 14 kg/ha “Grasslands Relish”
25/10/2020	Fertiliser application: Cropmaster DAP 200 kg/ha
3/12/2020	Chemical application Preside 65 g/ha and Uptake oil 1 L/ha
28/05/2021	Chemical application Sequence 1 L/ha and Bonza 1 L/ha
25/11/2021	Fertiliser application: Cropmaster DAP 200 kg/ha
22/04/2022	Fertiliser application: Cropmaster DAP 200 kg/ha
20/03/2023	Fertiliser application: Cropmaster DAP 200 kg/ha

paddock with a single exclosure cage (0.5m^2) placed in each area to ensure herbage could be measured independently of farm operations (Table 1). Each time the paddock was due to be grazed we were alerted by text message, and a cut was taken within 24 hours of animals entering the paddock. Post-grazing an area was trimmed and the cage placed on the new area for subsequent measurement. The paddock was predominantly rotationally grazed by finishing lambs over the three years. The first harvest was delayed until 50 days after sowing to encourage red clover root development.

Fertiliser (Table 2) included 200 kg/ha Cropmaster 20^{TM} (18.8%N, 10%P, 12%S) and 1000 kg/ha AgLime (36% Ca; specification of 95% passing a 2.00 mm screen and 50% passing a 0.5 mm screen) applied pre-sowing. Post sowing (39 days) at two trifoliate leaves, 65 g/ha of Preside^{TM} (800 g/kg flumetsulam) and 1 L/ha of Uptake^{TM} oil (582 g/L paraffinic oil, 240 g/L alkoxylated alcohol non-ionic surfactants) were applied for post-emergent weed control (Table 2). At the end of Year 1, on the 28th May 2021 SequenceTM (240 g/L clethodim) herbicide was applied at 1 L/ha with 1 L/ha of Bonza (450 g/L Paraffinic oil) to control grass weeds at a 200 L/ha water rate.

Meteorological data

The closest meteorological station was 20+ km from the site and in a different climate environment, therefore NIWAs Virtual Climate Station Network (VCSN) was used. VCSN data include estimates of daily rainfall, potential evapotranspiration, air and vapour pressure, maximum and minimum air temperature, 10 cm earth temperature, relative humidity, solar radiation, wind speed and soil moisture on a regular (~5 km) grid covering New Zealand (11491 virtual climate station locations) (NIWA 2023a). Data was downloaded from the VCSN site (VCSN 30955, Network Number P198157, - Latitude 39.775, Longitude -39.775). Weather data were sourced from 1 July 2010 to 30 June 2023 to determine long-term means for the site.

Soil moisture

A soil moisture budget (Equation 1) was used to estimate the potential soil water deficit (PSWD). This required setting a lower limit of extraction depth for red clover. Brown and Moot (2004) demonstrated that red clover has extraction potential to 1.9 m. However, the soil specific data only provides water extraction to 1 m (Landcare Research 2022). The available water for the Taihape site (Gladstone_51a.1) based on soil-specific, readily available water extraction data (150 mm/1 m soil) (Landcare Research (2022) was extrapolated to 1.9 m at 150 mm/m to generate a red clover-specific water extraction, resulting in a total water extraction potential of 285 mm. However, authors suggest that when 50% of plant available water has been used, crops begin to show signs of physical stress (Jamieson et al.1984; Wilson et al. 1984), thus 143 mm has been used to assess when water stress from a deficit can be expected, which sets the ceiling for actual soil moisture deficit (ASMD).

Equation 1 $\text{PSWD} = \text{PSWD}_{i-1} + \text{Potential Evapotranspiration} - (\text{rainfall} + \text{irrigation})$

Where PSWD_{i-1} is the PSWD on the previous day, PSWD was set to zero at the start of each season (1st July) and was not allowed to exceed field capacity (i.e. zero), with excess water expected to have drained or run-off.

Mean daily potential evapotranspiration (EP) was calculated for the duration of the experiment from hourly weather data using Penman EP. The PSWD is not constrained by soil depth, nor water holding capacity. It provides a potential figure and allows assessment of the severity, and duration, of water stress within a growth season.

Thermal time

Daily thermal time (Tt) was calculated based on the method of Jones and Kiniry (1986). This uses a twostage model to interpolate thermal time of eight three-hourly periods using a sinusoidal curve fitted to daily minimum and maximum air temperatures. Cardinal temperatures for red clover were used as Tb=3°C, T_{opt} = 25 °C and T_{max}= 40 °C. No daily temperatures were recorded above T_{max} (Keenan et al. 2023).

Statistics

The yield and growth rate data were analysed by a one-way (replicate; anonymised) analysis of variance (ANOVA, Genstat v22; VSN International Ltd) to determine differences.

Linear and split-line regression analyses were then used to quantify the relationship between accumulated dry matter yield (kg/ha) and accumulated thermal time for each replicate. All regressions were fitted using a model/loss fitting procedure, which runs iterations with different coefficients, from a specified start point to reach coefficient values that best fit the relationship.

A split-line regression was then applied to determine if there was any quantitative change in the rate of accumulated dry matter yield with accumulated thermal time. This was also done on a replicate basis before ANOVA for both datasets. The coefficients analysed were any breakpoint (x and y values), Slope 1 and Slope 2 and their intercepts (x, y). Standard errors were calculated for each dataset. The time of any breakpoint was also analysed to determine whether changes in the response were influenced by water stress. Means are reported with their respective standard error of the mean (SEM).

Results

Three years of data were analysed. In the establishment year, red clover yielded 12460±472 kg DM/ha (Figure 1). Red clover yielded 12280 kg DM/ha in the second year, and 13880±472 kg DM/ha in Year 3, with an indication of a difference between years ($P = 0.051$).

Mean daily growth rates of red clover showed the seasonal differences expected in a temperate climate. Regrowth periods ranged from 18 days in the autumn of 2021 to 54 days in the summer of 2022. Mean daily growth rate ranged from 8 kg DM/ha/day in July to a maximum of 112±7.21 kg DM/ha/d in the spring (October) of Year 3. Red clover content averaged 87.7%±0.80, 81.5%±1.10 and 88.9%±0.80 in Years 1, 2 and 3, respectively. Year 1 and Year 3 red clover content was significantly higher ($P<0.01$) than Year 2.

A soil moisture budget was calculated to determine whether crops were impacted by soil moisture stress. The crops were considered moisture stressed when plant available water dropped below 50% (143 mm for the Gladstone soil) (Brown and Moot 2004; Jamieson et al. 1984; Wilson et al. 1984). This occurred in Year 1 and Year 2 for this dataset (Figure 3).

Thermal time was analysed across 14 growth seasons (2010-2025) to assess inter-annual variability and potential trends in crop growth conditions. During the experimental period, the mean Tt was 2977°Cd±216.

There was a difference ($P=0.02$) among years for Slope 1 (Figure 4). Year 1 (6.21 kg DM/°Cd) and Year 3 (7.01 kg DM/°Cd) had a higher temperature adjusted growth rate than Year 2 (4.78 kg DM/°Cd).

For Year 2, three linear regressions were applied to the data with an extra period of low growth occurring between Slope 1 and Slope 2 (Figure 4). Year 2 experienced water stress over two distinct periods of the growth season, 15/1/2022 to 7/2/2022 (a period of 340°Cd Tt) and 11/3/2022 to 23/3/2022 (a period of 135°Cd Tt) (Figure 3). This reduced the number of harvests during that period, as there was insufficient red clover mass to harvest.

Split line regressions were possible for Years 1 and 2 with the breakpoint in the relationship giving separate equations for Slope 1 and Slope 2. Specifically, the temperature adjusted growth rate of Slope 1 and Slope 2 in Year 1 were 6.21±0.32 kg DM/ha/°Cd and 3.64 kg DM/ha/°Cd. In Year 2 Slope 1 was 4.78±0.45 kg DM/ha/°Cd, Dry Slope was 1.59±0.55 kg DM/ha/°Cd and Slope 2 was 4.12±0.31 kg DM/ha/°Cd. Year 3 had the highest Slope 1 of 7.02±0.36 kg DM/ha/°Cd and Slope 2 was 2.53±0.12 kg DM/ha/°Cd ($P=0.017$). Slope 1 growth rates were higher ($P=0.019$) for Year 1 and 3 compared with Year 2. Slope 2 growth rates were higher ($P=0.017$) for Year 1 and 2 than Year 3.

There was no difference ($P=0.10$) in the thermal time accumulation to the breakpoint for the three years being approximately 1685±155 °Cd. This breakpoint occurred on 23/01/2021, 16/01/2022 and 15/01/2023 for Years 1, 2 3, respectively. There was no difference ($P=0.09$) over the three years for dry matter accumulated to the breakpoint with the mean value occurring at 9980±380 kg DM/ha. There was no significant difference for intercepts of x ($P=0.32$) or y ($P=0.59$) (Table 3).

Discussion

The current evaluation aimed to analyse data to determine if readily transferable coefficients could be calculated for red clover monocultures based on temperature, accumulated as thermal time, to create a standardised growth rate response to temperature accumulation. The focus was on the growth rate response to temperature accumulation to determine if a single value was appropriate or there was a need for a partitioning coefficient, as previously found by Keenan et al. (2023).

Year 3 at Rihia Land Company experienced growth rates of 7.02±0.36 kg DM/ha/°Cd up to the breakpoint in the third week in January, then growth slowed to 2.53±0.12 kg DM/ha/°Cd (Figure 5). These results are

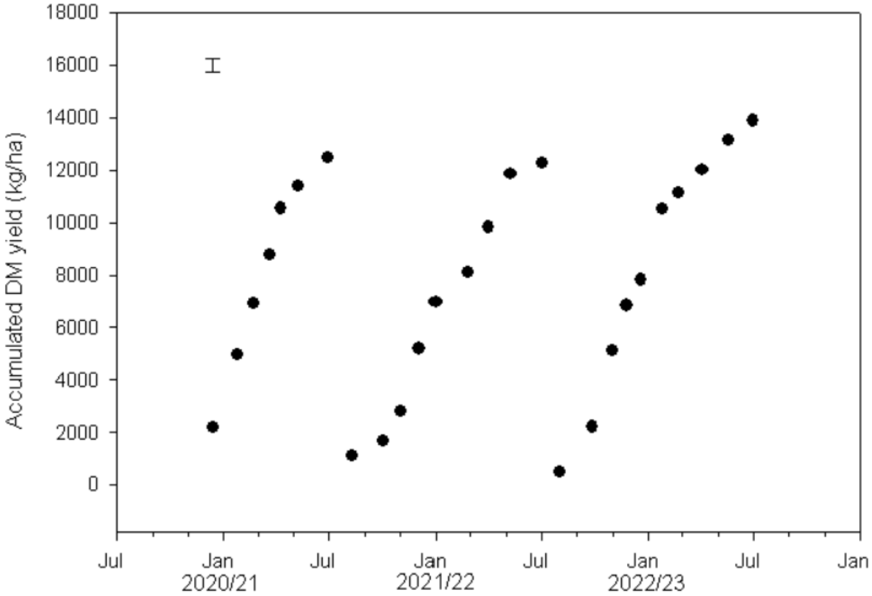

Figure 1 Dry matter (DM) yield for red clover grown over three years at Rihia Land Company, Taihape, New Zealand. Error bars represent the standard error of the mean for each growth season.

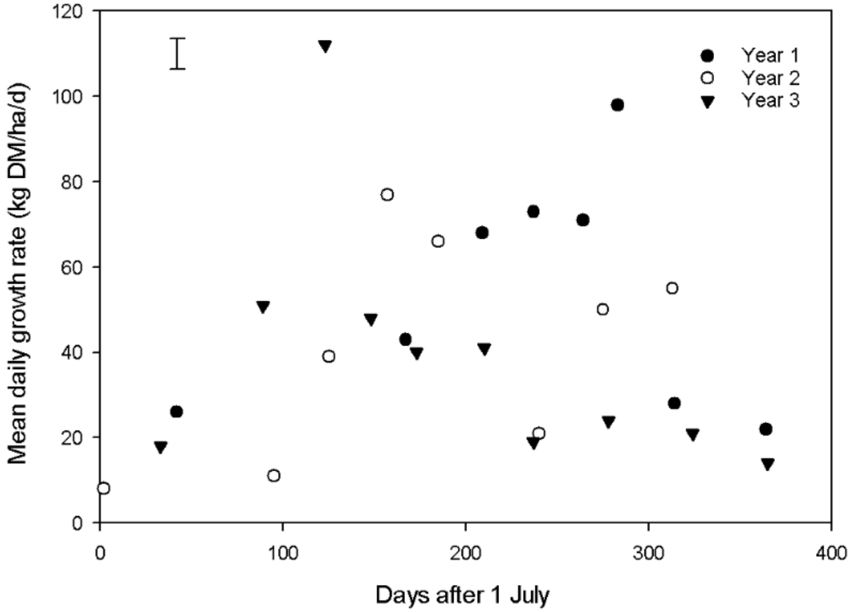

Figure 2 Mean daily growth rate of red clover grown at Rihia Land Company, Taihape, New Zealand. Error bars represent the standard error.

consistent with what was observed in Keenan et al. (2023) whereby red clover grew at a rate of 7.44±0.31 kg DM/ha/°Cd up until the 11th January and then observed a lower growth rate of 2.67±0.47 kg DM/ha/°Cd. These two datasets provide justification for applying a single coefficient to the two distinct periods for red clover under non-limiting conditions.

Year 3 did not observe moisture stress (Figure 3) which gives confidence to the yield assessment parameters provided by Keenan et al. (2023); Mills et

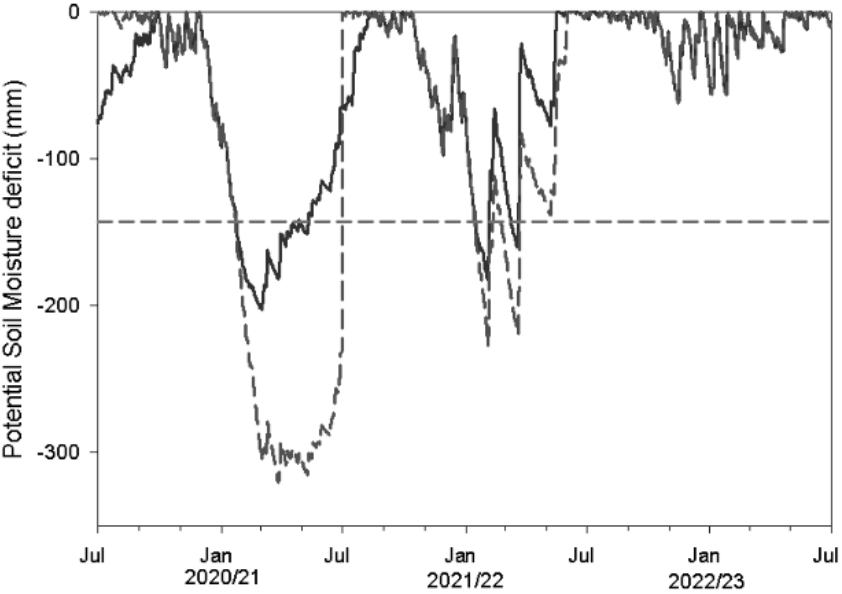

Figure 3 Actual and potential soil moisture deficits at Rihia Land Company, Taihape, New Zealand. from 1 July 2020 to 30 June 2023 based on meterological data from the VCSN, 50% PAW 143 mm (grey dash line), ASMD mm s(black line), PSMD mm (long dash).

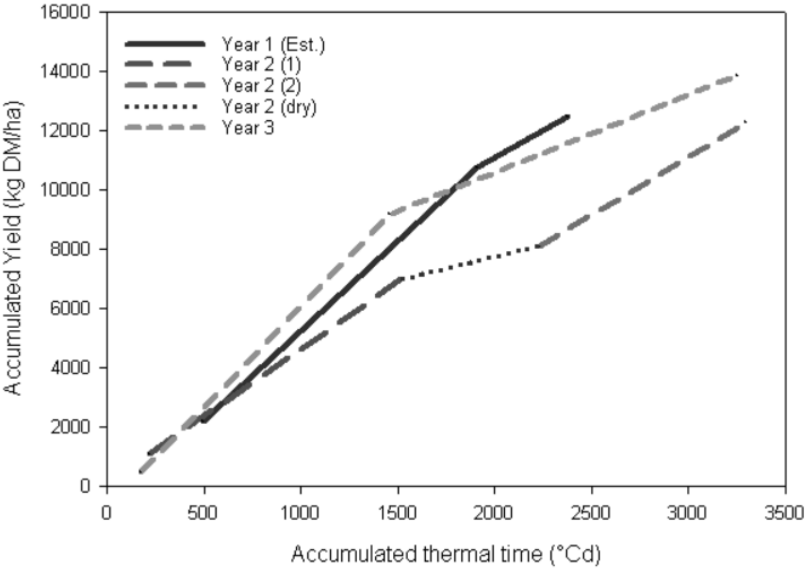

Figure 4 Accumulated dry matter (DM) yield against accumulated thermal time over three years for red clover crops grown Rihia Land Company, Taihape, New Zealand. Split line regressions of the mean of each treatment are shown and their coefficients summarised in Table 3.

al. (2006); Moot et al. (2022); Romera et al. (2009). The implication is that the thermal time is the variable and changes with locations but can be estimated at the farm level using publicly available information (NIWA 2023b). Thus, a farmer could then utilise the coefficient of 7.23 kg DM/ha/°Cd till mid-January, then 2.60 kg DM/ha/°Cd for the remainder of the season to estimate expected red clover yield across any location.

Analysis of Year 1 (establishment) data showed a linear response of yield to thermal time (Figure 5), which showed the crop grew at 6.21±0.32 kg DM/ha/°Cd for most of the growth season, until 1910°Cd, where a lower period of growth was observed, 3.64 kg DM/ha/°Cd. A single value was inappropriate for this

Table 3 Parameters of split line regressions fitted to the relationship between accumulated dry matter yield and accumulated thermal time for red clover. Standard errors of the slopes and intercepts are reported in parentheses, and coefficients of determination (R2) are shown.

Year	Slope	Equation
1	1	-1095(±420) + 6.21(±0.32)x $R^2 = 0.97$
1	2	3950(±310) + 3.64(±0.22)x $R^2 = 0.95$
2	1	-48(±250) + 4.78(±0.45)x $R^2 = 0.96$
2	2	5150(±270) + 1.59(±0.55)x $R^2 = 0.94$
2	3	-1240(±520) + 4.12(±0.22)x $R^2 = 0.95$
3	1	-877(±450) + 7.02(±0.32)x $R^2 = 0.98$
3	2	6850(±670) + 2.53(±0.31)x $R^2 = 0.97$

dataset; the breakpoint analysis was used following the loss fitting procedure, after analysis of the linear regressions.

Year 1 red clover did not support the null hypothesis, as it was exposed to a period of moisture stress from 21/1/2021 to 11/5/2021 (1112°Cd). This occurred around the time of the breakpoint, so it is uncertain whether moisture stress or partitioning impacted red clover growth. Comparisons in the literature were not possible, because this was an establishment crop. It has been suggested that during establishment, perennial legumes prioritise carbohydrates to contribute to their root system rather than canopy expansion (Moot et al. 2000; Moot et al. 2022; Ta et al. 2016), which could account for the changes in growth rates. However, below-ground measurements were not conducted as part of this research.

Year 2 red clover yield was the lowest for the experimental period, 12280±472 kg DM/ha/year. In this year the summer dry conditions meant allowance had to be made for the lack of soil moisture. This was experienced on the farm from 15th January 2022 to 7th February 2022, and again from 11th March 2022 to 23rd March 2022, which meant the equivalent of 475°Cd were lost as calculated from the deficit period using the soil moisture budget (Figure 3). In the field, harvests did not occur for 54 days due to limited growth during January/February (713°Cd). As a result, Slope 1 and Slope 2 growth rates were 4.78±0.45 kg DM/ha/°Cd and 4.12±0.31 kg DM/ha/°Cd, respectively. This higher rate of growth in Slope 2 in this second year may reflect some compensatory growth after the summer dry period but this remains to be validated.

As a result of the summer dry conditions experienced in the 2021/2022 season, the yield loss was estimated to be ~3170 kg DM/ha/year (713°Cd at a mean growth rate of 4.45 kg DM/°Cd), which would equate to a yield potential of 15450 kg DM/ha/year. This year also coincided with the lowest red clover composition in the sward, 81.5%, which meant~2,500 kg DM/ha/year was also lost. Thus, the estimated potential annual yield would be ~18000 kg DM/ha/year which is consistent with what was achieved under non-limiting conditions at Lincoln, in 2016/17 (Keenan et al. 2023).

The reduction in growth rate response to temperature accumulation after the break point in mid-January of all three years reflects a change in partitioning of assimilate to red clover roots in response to a decreasing photoperiod. This physiological trigger has previously been shown to change the partitioning priority from shoot to root in lucerne (Moot et al. 2003) and red clover after the second week of January (Keenan et al. 2023).

A challenge for soil water budgets is determining at what level of stress soil moisture impacts pasture growth. For this study an initial soil water deficit of 214 mm was used (75% of plant available water) based on root extraction to 1.9 m (Brown 2004) and a water holding capacity of 150 mm/m. However, using this value showed no soil moisture stress, which was not consistent with the field observations of low growth from 1st January to 15th February in the second year. Therefore a value of water stress restricting growth at 50% was considered more appropriate and utilised in the soil water budget.

Over the three years of measurement, red clover mean daily growth rates showed a typical temperate seasonal pattern of pasture production, with highest grown rates in peak spring (112±7.21 kg DM/ha/day) before declining to 14±7.21 kg DM/ha/day in winter (Figure 2). This temporal pattern of growth is expected for pastures in New Zealand and has been well documented for irrigated conditions (Radcliffe 1981) and these results are consistent with what was achieved in Keenan et al. (2023), whereby red clover growth rates increased from 8.05±1.17 kg DM/ha/d in June to a maximum of 125±5.25 kg DM/ha/d in early January. The lower range in this North Island environment was expected due to Taihape experiencing higher annual rainfall with even distribution, but cooler summer temperatures, and frequent cloud cover due to its elevation and inland location, compared with the warmer drier summer Lincoln environment. (NIWA 2023b). However, these abiotic differences were captured by the temperature adjusted growth rates and soil water budget.

Therefore, these parameters provide the basis for a yield of red clover to be estimated based on readily available air temperature data, in a farm situation. The values for Slope 1 and Slope 2 have been consistent across multiple seasons and locations which suggest they could be utilised to guide decision making on-farm Specifically for Years 1-3 of a red clover monoculture a

Slope 1 in line with the previous reports (Keenan et al. 2023) can be applied until the third week of January and Slope 2 from that point onwards. The accumulation of thermal time seems reasonable using a base temperature of 3°C.

Conclusions

Introducing short-lived perennial species into hill and high-country farms throughout New Zealand is often limited by a lack of knowledge of how much they can grow in a particular location. Therefore, the analyses in this paper provided transferable coefficients that can be used to estimate red clover growth with the accumulation of temperature as thermal time. In non-limiting soil moisture situations, red clover growth rate was linearly related to temperature; 7.23 kg DM/ha/°Cd till mid-January, then 2.60 kg DM/ha/°Cd. Based on these data, predictions can be made for red clover for other locations based on local temperature data and a soil water budget to assess the impact of summer dry periods. The coefficients remain to be validated by analysis of other datasets from other locations but offer a practical guide for yield estimation.

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REFERENCES

Brown HE, Moot DJ. 2004. Quality and quantity of chicory, lucerne and red clover production under irrigation. *Proceedings of the New Zealand Grassland Association 66*: 257-264. doi:https://doi.org/10.33584/jnzg.2004.66.2542

French BK, Legg BJ. 1979. Rothamsted irrigation 1964-76. *Journal of Agricultural Science UK 92*: 15-37. https://doi.org/10.1017/S0021859600060469

Jamieson PD, Wilson DR, Hanson R. 1984. Analysis of responses of field peas to irrigation and sowing date. 2. Models of growth and water use. *Proceedings of the Agronomy Society of New Zealand 14*: 75-81.

Jones C, Kiniry J. 1986. *CERES-Maize: a simulation model of maize growth and development*. First Ed. Publ. Texas A and M University.

Keenan L, Mills A, Smith M, Brown H, McKenzie S, Moot D. 2023. Predicting yield of irrigated red clover (*Trifolium pratense* L.) pastures in response to temperature. *Journal of New Zealand Grasslands 85*: 217-226. https://doi.org/10.33584/jnzg.2023.85.3666

Landcare Research. 2022. S-map - New Zealand’s national digital soil map. Retrieved from https://smap.landcareresearch.co.nz/maps-and-tools/app/

McCall DG, Bishop-Hurley GJ. 2003. A pasture growth model for use in a whole-farm dairy production model. *Agricultural Systems 76*: 1183-1205. https://doi.org/10.1016/S0308-521X(02)00104-X

Mills A, Moot DJ, McKenzie BA. 2006. Cocksfoot pasture production in relation to environmental variables. *Proceedings of the New Zealand Grassland Association 68*: 89-94. https://doi.org/10.33584/jnzg.2006.68.2636

Moot DJ, Scott WR, Roy AM, Nicholls AC. 2000. Base temperature and thermal time requirements for germination and emergence of temperate pasture species. *New Zealand Journal of Agricultural Research 43*: 15-25. https://doi.org/10.1080/00288233.2000.9513404

Moot DJ, Yang X, Ta HT, Brown HE, Teixeira EI, Sim RE, Mills A. 2022. Simplified methods for on-farm prediction of yield potential of grazed lucerne crops in New Zealand. *New Zealand Journal of Agricultural Research 65*: 252-270. https://doi.org/10.1080/00288233.2021.1909078

NIWA. 2023a. Virtual Climate Station data and products. Retrieved from https://niwa.co.nz/climate/our-services/virtual-climate-stations

NIWA. 2023b. Virtual Climate Station Network data. Retrieved from https://niwa.co.nz/climate/our-services/virtual-climate-station

Radcliffe JE. 1981. *Climatic and aspect influences on pasture production in New Zealand.* (PhD). Lincoln College, University of Canterbury, Christchurch. https://researcharchive.lincoln.ac.nz/entities/publication/5a2e3a22-0faa-4e0a-b507-cf5e2b5cdde5

Romera AJ, McCall DG, Lee JM, Agnusdei MG. 2009. Improving the McCall herbage growth model. *New Zealand Journal of Agricultural Research 52*: 477-494. https://doi.org/10.1080/00288230909510529

Ta HT, Teixeira EI, Moot DJ. 2016. Impact of autumn (fall) dormancy rating on growth and development of seedling lucerne. *Journal of New Zealand Grasslands 78*: 169-176. https://doi.org/10.33584/jnzg.2016.78.501

Wilson DR, Jamieson PD, Hanson R. 1984. Analysis of responses of field peas to irrigation and sowing date. 1. Conventional methods. *Proceedings of the Agronomy Society of New Zealand 14*: 71-74.