Development, growth and water extraction of seedling lucerne grown on two contrasting soil types

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Abstract
Dryland lucerne (*Medicago sativa* L.) was established at Lincoln University, New Zealand in two soils which differed in the plant available water content (PAWC). The high PAWC site is a silt loam soil with ~325 mm of water to 2.3 m. The low PAWC site had a very stony silt loam soil with only ~125 mm to 2.3 m. Both crops were sown on 10 October 2011 and established with 200 plants/m^2. The high PAWC site produced 2600 kg DM/ha shoot yield from sowing to 50% flowering compared with only 900 kg DM/ha at the low PAWC site. Both crops extracted water from the soil to a depth of ~1.2m, but the lucerne grown on the high PAWC soil extracted twice as much water to this depth. The water use efficiency (WUE) for both crops was 27.0 kg/DM/ha/mm of water used. The leaf appearance rate was 48 degree-days per node (T_b=1°C) and was unaffected by site. Leaf area expansion rates exhibited a strong relationship with accumulated thermal time (R^2>0.94). Leaf area on the high PAWC site increased exponentially at about at 0.004 m^2 leaf/m^2 soil per degree-day, compared to the low PAWC site which increased linearly at a rate of 0.0009 m^2 leaf/m^2 soil per degree-day. Soil moisture extraction patterns indicated an extraction front velocity of 13 mm/day at both sites. Differences in lucerne yield were therefore fully attributable to differences in water extraction to a depth of 1.2 m

Keywords
Alfalfa, leaf area index, lucerne, *Medicago sativa* L., water extraction, water use efficiency

Introduction
Dryland lucerne (*Medicago sativa* L.) growth is largely dependent on its ability to extract water from the soil profile. Soil type, more specifically plant available water has a marked effect on yield. For example Moot *et al*. (2008) reported annual lucerne yields 50% greater on a deep silt loam compared with that of a stony silt loam. The ability of a crop to extract water from the soil profile is dependent on characteristics of the plant roots (Jamieson and Ewert, 1999) and the soil profile (McLaren and Cameron, 1990). Brown (2004) showed an extraction front velocity of seedling lucerne grown on a high PAWC soil of 15 mm/day. In comparison Dolling *et al*. (2003) reported a rate of 1.7 mm/day for a deep sandy soil. Our aim was to investigate the influence of water supply on the ability of seedling lucerne to both capture and efficiently use water for growth. To do this lucerne was grown in similar climates, but on soils which differ in plant available water.

Methods
Experimental sites and crop management
Two identical experiments were conducted on soils which differed in their PAWC. The high PAWC site was in Iversen Field at Lincoln University (43 ° 38 ′S, 172 ° 28 ′E, 11 m.a.s.l). The soil is a Wakanui silt loam (*Udic Ustochrept*, USDA Soil Taxonomy) which typically has 2-3 m of fine textured material overlying gravels (Cox, 1978) and has a PAWC of about 325 mm to 2.3m (Brown, 2004). In contrast at Ashley Dene, Lincoln University's dryland sheep farm (30 m.a.s.l) 10 km south of the University, the soil is a Lismore stony silt loam (Udic Haplustept loamy skeletal) (Hewitt, 1998) with a shallow topsoil (0.2 m) that contains 30-40% stones overlaying coarse gravels. This results in a lower PAWC to 2.3m of about 125 mm (Moot *et al*., 2008).

Both sites were sown on 10 October 2011 with 'Stamina 5' lucerne coated seed at a rate of 16 kg/ha as a split plot randomised complete block design with four replicates. Topsoil samples (0-150 mm) collected prior to sowing showed a pH (H_2O extraction) range from 5.7 to 6.6; Olsen-extractable P from 23 to 27 mg/L; K (quicktest extraction) from 0.35 to 0.72 mg/L and sulphate-S 27 to 30 mg/kg. Mineral nitrogen (nitrate and ammonium) in the top 150 mm was 30 kg/ha and 80 kg/ha at the low and high PAWC sites respectively. Leaf and flower emergence were recorded weekly on 10 marked plants per plot. The seedling phase for lucerne was defined as completed when 50% of marked plants had an open flower.

Meteorological conditions
Temperature and rainfall were recorded at the low PAWC site, while at the high PAWC site records were taken 2 km away at Broadfields Meteorological Station (NIWA, National Institute of Water and Atmosphere Research, New Zealand). Rainfall for the measurement period was 180 mm at both sites. Potential evapotranspiration (P_{ET}) was also calculated from hourly weather data from Broadfields using the Penman P_{ET} method (French and Legg, 1979).

Dry matter production and leaf area index
Dry matter (DM) production was measured at 7 d intervals using a single 0.2 m quadrat, cut just above crown height. All DM samples were dried in a forced air oven (60°C) to constant weight. Leaf area index (LAI; leaf m^2/m^2 soil) was calculated using specific leaf weight (SLW; g DM/m^2 LAI) from a sub-sample of 20 shoots passed through a leaf area meter (LICOR 3100).

Thermal time
Daily thermal time (Tt, °Cd) was accumulated using a broken-stick threshold model where the base temperature (T_b) is zero, Tt is accumulated at a rate of 0.7 °Cd/°C up 15°C and then at a rate of 1.0 until 30°C (Moot *et al.*, 2001).

Soil water content
Volumetric soil water content was measured in 22 layers of the soil profile to a depth of 2.3m at 14 d intervals. The top layer (0-0.2m) was measured with TDR (Time Domain Reflectometry) and the remaining 21 layers were measured at their mid point with neutron probe (Troxler) calibrated for soil type. This intensity of measurement is required on these highly variable, alluvial outwash soils.

Water use
The water use (WU, mm per period) was calculated for each measurement period (Brown *et al.*, 2009);
Equation 1. $WU = P_R - (SWC_E - SWC_S)$
where P_R is the sum of rainfall for the same period, SWC_S and SWC_E represent the actual soil water content of the profile as measured above for the start and end of the period respectively.

Daily water use (WU_{daily}) was then calculated based on the fraction of WU compared with Penman potential evapotranspiration (P_{ET}) for the period and P_{ET} on each day ($P_{ET\ daily}$).
Equation 2. $WU_{daily} = (WU/P_{ET}) * P_{ET\ daily}$
Canopy cover (R/R_o) was calculated daily, extrapolated from the regression of LAI and thermal time for each site (Figure 1).
Equation 3. $R/R_o = 1\text{-}exp^{(-k*LAI)}$
K was assumed to be 0.75 (Khumalo, 2012) measured on seedling lucerne grown under similar conditions during the previous season. Soil evaporation (E_s) was calculated from the top 0.2 m layer which was assumed to be dependent on canopy cover;
Equation 4. $E_S = WU * (1-R/R_o)$

Statistical analysis
Statistical analyses were performed using GenStat 14th edition. SigmaPlot 12.0 was used in the regression analysis. Data is compared using standard error of means (SEM).

Results and discussion
Both crops reached 75% emergence on 16 October 2011 with final populations of 200 plants/m^2. The leaf appearance rate (phyllochron) was strongly related to temperature (R^2=0.99) and was 48 °Cd/node and unaffected by site (data not shown). This was a similar result to that of and Khumalo (2012) and Teixeira *et al.*(2011) who reported a phyllochron for early spring sown lucerne of 45 to 55 °Cd/node.

Final shoot yield at 50 % flowering was 2600 kg DM/ha at the high PAWC site but only 900 kg DM/ha at the low PAWC site. Final LAI was 2.18 and 0.76 for the high and low PAWC sites respectively (Figure 1). The leaf area expansion rates (LAER) showed a strong relationship (R^2>0.94) with accumulated thermal time. Leaf area index of the lucerne grown at the high PAWC site increased exponentially at about at 0.004

$m^2 m^2$ °Cd, compared to the low PAWC site which increased linearly at a rate of only 0.0009 $m^2 m^2$ °Cd. Canopy cover is a main driver of crop WU (Equation 3), and a reduction in leaf area is a mechanism to lessen the effects of water stress by reducing demand through both reduced growth (intercepted radiation) and transpiration (Hay and Walker, 1989). Brown (2004) showed that the LAI of dryland was only 10% of a fully irrigated crop under severe water stress. The lucerne therefore compensated for the lower PAWC by a reduced rate of leaf area development.

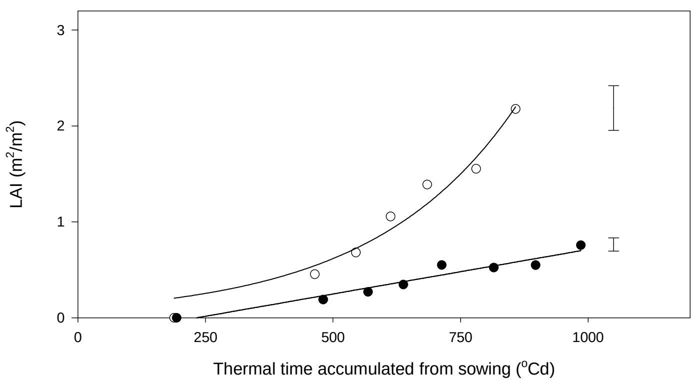

Figure 1. Leaf area index expansion in response to thermal time accumulation (Tt_b = 0°C) for 'Stamina 5' seedling lucerne to 50% flowering sown on 10 October 2011 at the high PAWC site (○) and the low PAWC site (●), Lincoln University, New Zealand. Bars represent one SEM of each replicate (*n*=4).
Note: Exponential regression (−○−) y = 0.105 *exp (0.004*x), R^2 = 0.96; linear regression (−●−) y = −0.217 + 0.0009x; R^2 = 0.94).

Both crops had a constant linear relationship (R^2 = 0.98) between accumulated shoot yield and WU with a WUE of 27.0 ± 1.06 kg DM/ha/mm (Figure 2). Crops differed in the amount of water used with lucerne at the high PAWC site using 90 mm compared with 34 mm at the low PAWC site. At the low PAWC site the crop therefore compensated by a reduced rate of growth and water use, but there was virtually no difference in WUE.
Both crops showed similar depths of water extraction of ~1.2 m, but differed in the amount extracted to this depth (Figure 3). Lucerne from the high PAWC site extracted 86 mm, nearly twice as much as the lucerne at the low PAWC site which extracted 45 mm to the same depth. Extrapolating soil water extraction to root growth indicates both crops showed similar extraction front velocity's (EFV) of about 13 mm per day. This result is consistent with that of Brown (2004) which who showed a seedling EFV of 15 mm grown under similar conditions, however the literature shows the EFV of lucerne is variable and a result of both soil and environmental factors (Dolling *et al.*, 2003).

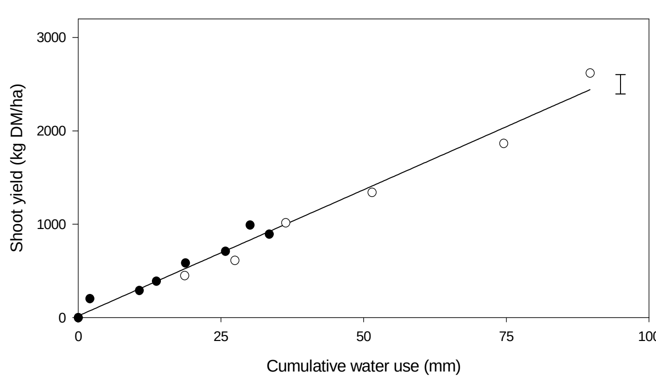

Figure 2. Accumulated shoot yield in relation to cumulative water use for Stamina 5' seedling lucerne to 50% flowering sown on 10 October 2011 at the high PAWC site (○) and the low PAWC site (●), Lincoln University, New Zealand. Bar represent one SEM of each replicate (*n*=4).
Note: Linear regression (−) y = 17.9 + 27.0 ± 1.06x, R^2 = 0.98.

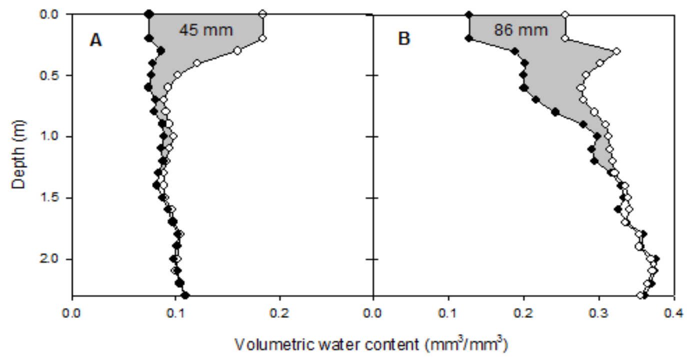

Figure 3. Upper (○) and lower (●) limits of water extraction for Stamina 5' seedling lucerne to 50% flowering sown 10 October 2011 at the low PAWC site (A) and the high PAWC site (B), Lincoln University, New Zealand.
Note: Shaded area and numbers represent soil water extraction from 10 October 2011 (○) to 11 January 2012 (□)

Conclusion

Water uptake explained most of the difference in lucerne growth. Limited plant available soil water reduced canopy expansion rates and light interception available for photosynthesis at the low PAWC site. At both sites the water use efficiency was 27 kg DM/ha/mm, and the extraction front velocity 13 mm/day. Quantifying the amount of plant available water extracted in a soil profile is critical for explaining yield differences for seedling lucerne crops. Differences in lucerne yield were therefore fully attributable to differences in water extraction to a depth of 1.2 m.

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