The “root” to more soil carbon under pastures

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Abstract

Recent interest in building soil carbon in pastoral systems is driven by the imperative to mitigate greenhouse gas emissions. It has been proposed that increasing root growth via deep rooting plants is a means of increasing soil carbon storage. Data on root depth distribution and production from a number of New Zealand studies are summarised to examine whether variation in root profiles can be manipulated and exploited. Most of the variation in root mass under grazed grass-clover pastures occurs in the upper 100 mm of soil. Changes in pasture management, such as soil fertility, grazing intensity and pasture species composition have a limited effect on root mass below this depth layer, of the order ±10-30%. Greater mass and length of roots in deeper soil layers under grazed grass-clover pastures is associated with lower soil fertility, drought stress and less commonly sown pasture species. The relationship between root mass (particularly deeper-root mass) and soil carbon storage has yet to be clearly established.

Keywords: pasture species, root mass, soil carbon, soil fertility

Introduction

The New Zealand pastoral sector faces a strong imperative to reduce or mitigate its greenhouse gas (GHG) emissions, given that they make a substantial contribution to national emissions (Sweeney *et al.* 2011). Options for direct reductions of the major contributing gases, methane and nitrous oxide, are currently limited and/or undesirable (e.g. reduction in stocking rate, Clark 2009), and options for mitigation via purchase of offsets outside the sector (i.e., “carbon credit trading”) are likely to be prohibitively expensive. Another major strategy, indirect mitigation via storage of carbon (C) in vegetation and soils, represents an attractive approach, since there may be secondary benefits to the sector in terms of product diversity and soil quality. Mechanisms already exist to facilitate “carbon farming” in the pastoral sector via vegetation change (i.e. the permanent forest sink initiative, PFSI). However the soil C offset provisions in the Kyoto Protocol have not been activated by the New Zealand Government, as there remains substantial doubt as to whether New Zealand will stand to benefit by doing so.

Long-term storage of C in soils has been widely promoted as a means by which primary producers can use their land resource to contribute to GHG mitigation and gain a financial benefit while maintaining current land use. It is frequently reported that by virtue of the large pool of C in soils, incremental increases in soil C concentration can make a major contribution to large-scale C sequestration (Lal 2003). However, it has been suggested that the relatively high levels of C observed in New Zealand pastoral soils may make further increases difficult to achieve. This assertion assumes that soils have a maximum capacity to store C that is insensitive to changes in management (e.g. increasing C inputs). The concept of “soil C saturation” proposed by Hassink (1997) has become more widely accepted in the last decade largely through the work of Six *et al.* (2002) and subsequent collaborators. Research in New Zealand and overseas has indicated that this capacity is likely to be a function of soil texture, soil structure and clay mineralogy (Alvarez & Lavado 1998; Percival *et al.* 2000; Diekow *et al.* 2005), characteristics that are difficult to modify by management.

However, there is one opportunity arising from the concept of C saturation: these fundamental soil characteristics are a feature of the entire soil profile, yet the concentration of soil C commonly shows an exponential decline with depth. While the current international convention on soil C assessment takes into account only the top 300 mm of soil, there would appear to be substantial scope for storing C in the 100-300 mm depth zone, where soil C concentration is likely to be further from a saturation limit than in the 0-100 mm depth zone. The challenge then becomes how to manipulate the input of C to this lower depth. Increasing the root growth of plants, particularly via deep-rooting plants, has been proposed as a means of achieving this (Crush & Nichols 2010; Powlson *et al.* 2011). The purpose of this paper is to examine the potential for incorporating deep-rooting plants into pastoral systems, on the basis of the (fairly limited) data available on root profile patterns for pastures and pasture species in New Zealand studies.

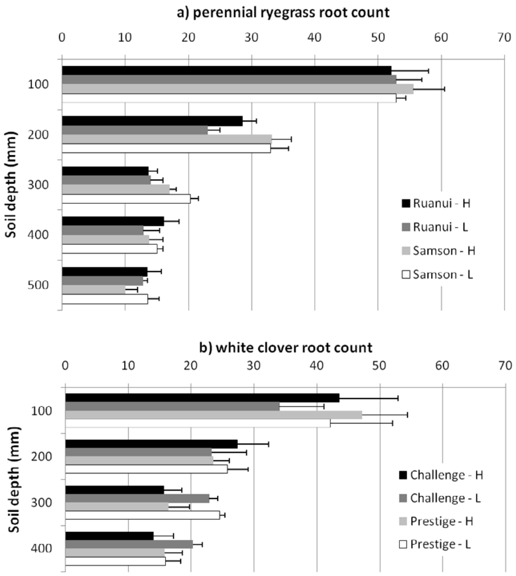

Figure 1 Root counts (per 100 mm of horizontal mini-rhizotron tube length) of a) two perennial ryegrass cultivars at five soil depths and b) two white clover cultivars at four soil depths, grown in constructed soil profiles at high (H) and low (L) P fertility. Bars represent SEM.

New Zealand root profile literature

Species differences

The earliest work on root profiles in New Zealand appears to be that of Jacques (1943), which examined the effect of P fertiliser incorporation on the root growth of perennial ryegrass (*Lolium perenne*), cocksfoot (*Dactylis glomerata*) and white clover (*Trifolium repens*) as well as grass/clover mixes. Root mass was measured in 300 mm increments in profiles 2.1 m deep and in 75 mm increments in the upper 300 mm of soil. Considerable differences between sward types in the proportion of root mass in the various layers were observed. The greatest root mass between 100-300 mm, as a percentage of root mass between 0-300 mm, was in the order perennial ryegrass (42%) > perennial ryegrass + white clover (40%) > cocksfoot (37%) > white clover (33%). Thus, variation between swards for total root mass in this layer was up to ±30% relative to the perennial ryegrass/white clover sward.

Substantial work on root profiles of pasture and crop species was also undertaken by Evans (1978) who demonstrated significant differences in the length of roots at 200-600 mm depth between species, noting c. 15% greater length for cocksfoot compared to ryegrass. His data showed large variation between 0-200 mm which obscured significant effects, but only small differences from 600-1400 mm, with the exception of the very deep-rooted lucerne (*Medicago sativa*).

Table 1 Root mass (kg DM m^{-3}) in three layers of the soil profile under four long-term P fertiliser treatments at Ballantrae Hill Country Research Station (letters denote significant differences within each depth layer, $p<0.05$).

Depth (mm)	H-H[1]	H-0	L-L	L-0
0-75	1.50 a	2.16 a	2.65 a	2.89 a
75-150	0.30 a	0.44 ab	0.49 b	0.54 b
150-300	0.25 a	0.26 a	0.38 a	0.41 a
Surface %	70	74	72	72

[1] treatment notation reflects fertiliser application regime from 1975-1980 then 1980-1995, H=high, 45 kg P $ha^{-1}y^{-1}$; L=low, 14 kg P $ha^{-1}y^{-1}$; 0=nil P.

McKenzie *et al.* (1990) compared root mass profiles to 800 mm depth for pure and mixed swards of lucerne, prairie grass (*Bromus willdenowii*), phalaris (*Phalaris aquatica*) and perennial ryegrass. Monocultures of lucerne and phalaris appeared to have greater root mass than perennial ryegrass, both in total and below 200 mm, and this was maintained in mixtures (no statistical analysis was noted).

Crush *et al.* (2005) have made detailed root mass profile measurements of several common temperate pasture species in 1 m long sand-filled root tubes. They concluded that with the exception of the very surface-rooting crested dogstail (*Cynosurus cristatus*) there was little difference in root mass profile shapes between species. In a more recent related study on N leaching in 500 mm deep lysimeters, Popay & Crush (2010) observed up to double the root mass between 100-200 mm and below 200 mm for phalaris, browntop (*Agrostis capillaris*) and cocksfoot compared to perennial ryegrass.

Management effects

In the study of Jacques (1943), root mass measurements in the 0-300 mm zone (where 80% of root mass was found) showed that the greatest percentage of root mass below 100 mm occurred when no fertiliser was added (for grasses) or where it was incorporated at 150 mm (for clover), suggesting that surface fertiliser additions reduced the allocation of resources to deeper root exploration and growth. Variation in total root mass between treatments was ±20% compared to surface applied fertiliser.

Matthew *et al.* (1991) examined the root mass and length distribution between 0-600 mm depth under two grazing management treatments, lax and hard (corresponding to 1800 and 800 kg DM ha^{-1} grazing residuals respectively). While the more severe grazing led to reduced root growth and total root mass (-10%), there were no effects on root depth distribution, suggesting that the opportunity to manipulate root growth through grazing management is limited.

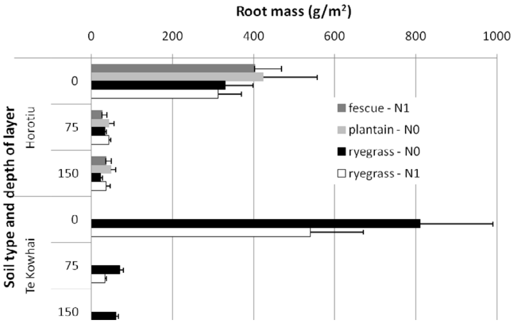

Figure 2 Root mass (g DM m-^{2}) in three soil layers from tall fescue-white clover (with N fertiliser), plantain (without N fertiliser) and perennial ryegrass-white clover (with and without N fertiliser) paddocks on two different soil types at Scott farm, Hamilton. Bars represent SED.

The root mass distribution from 0-600 mm depth under a grazed vs. ungrazed (i.e. fallowed from October –May) hill pasture differed only in the upper 50 mm in that it was c. 40% less in the fallowed pasture (Nie *et al.* 1997). Barker *et al.* (1988) found large differences in total root mass (0-800 mm depth) between sunny and shady aspects in low fertility hill country, but the only significant difference was at 150-200 mm depth, and the aspect difference was probably confounded by species composition and grazing management differences.

Root mass at two depths (0-80 and 80-160 mm) was measured at 6-8 week intervals over a year under two contrasting fertility treatments on a ryegrass/white clover pasture (Dodd & Mackay 2011). The site was a mown dairy pasture on a Marton silt loam in the Manawatu. The treatments were moderate fertility (Olsen P 22 µg/ml, no added N) and high fertility (Olsen P 49 µg/ml, 400 kg N ha^{-1}y^{-1} added). While the moderate fertility treatment had significantly higher root mass in the upper depth at two measurements (28 and 23% greater in September and November respectively), there was no difference in root mass at any time in the lower depth. Thus the overall root mass advantage at moderate fertility was 10%.

New Zealand unpublished root profile patterns

Root mass measurements to 300 mm soil depth were made on four long-term P fertiliser treatment farmlets at the Ballantrae Hill Country Research Station. The farmlets had a history of different combinations of fertiliser input rate between 1975-1980 then 1980-1995. They were H-H, H-0, L-L and L-0, where H=high, 45 kg P ha^{-1}y^{-1}; L=low, 14 kg P ha^{-1}y^{-1}; 0=nil P. Three sites in each of eight paddocks of each farmlet were sampled in late winter 1994. Roots were mechanically washed from soil and dry mass determined. Under these browntop-dominated pastures, the greatest overall root mass, and root mass at 75-150 mm depth, occurred under a low P fertility regime (Table 1). Root mass differences in the top 75 mm were obscured by high variance, and differences were small and non-significant in the lower 150-300 mm. Estimates of the surface root percentage (proportion of total root mass from 0-300 mm in the upper 100 mm) varied little, ranging between 70-74% (Table 1).

The depth distribution of root counts in two cultivars of perennial ryegrass and white clover was examined in a mini-rhizotron study conducted in reconstructed soil profiles during 2000-2001. The soil profiles had differing P fertility levels (Olsen P of 10 and 24 mg/kg for low and high fertility respectively) created by adding P fertiliser to low fertility hill country topsoil. Root counts were measured at 100, 200, 300, 400 and 500 mm depths as the number of roots intersecting the apex line of a horizontal clear tube in 100 mm tube length sections. The data indicated no differences between the two ryegrass cultivars 'Ruanui' and 'Samson' at either high or low P fertility (Fig. 1a). However, for the two clover cultivars ('Challenge' and 'Prestige') root counts were higher at the 300 mm depth in a low P fertility soil (Fig. 1b), reflecting the high soil P levels required by white clover for optimum growth (Jackman & Mouat 1972).

The depth distribution of root mass to 500 mm under 17 dairy pastures in three districts of the North Island (Waikato, Taranaki and Horowhenua) was measured during 2006. In each paddock four sites were sampled

Table 2 Results of a 26-year daily time step simulation of the model in Fig. 3, initialised with root production and soil carbon data from Dodd & Mackay (2011) and including an increase in root production at year 14 sufficient to increase root mass by 20%.

Depth (mm)	0-100		100-200	
Period (years)	0-13	14-26	0-13	14-26
Root production (kg C ha^{-1} d^{-1})	8	9.6	1.5	1.8
Root carbon (kg C ha^{-1})	533	640	100	120
Shoot + dung input (kg C ha^{-1} d^{-1})	23	23	0	0
Soil carbon (kg C ha^{-1})	23846	25075	1156	1384

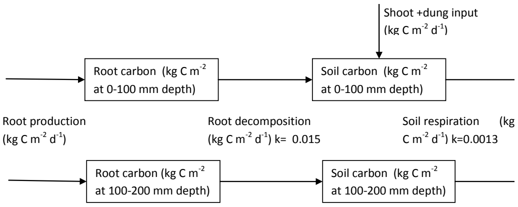

Figure 3 A simple dynamic model of root and soil organic carbon stocks in upper and lower soil layers. Root production and shoot + dung input rates are represented as constant daily fluxes (see Table 2). Root decomposition and soil respiration rates are represented as first order decay functions where k is the rate constant.

with 60 mm diameter cores. Additional data collected from each site included soil order, soil Olsen P, annual N input, annual P input, stocking rate, ryegrass and clover content from four harvested pasture quadrats and earthworm biomass from four 250 mm soil cubes. General linear model analyses of root mass and depth distribution indicated that the only significant factors for root mass in the upper 100 mm were clover content and earthworm mass. The surface root percentage ranged from 86-91%.

Root mass measurements were recently made at three depths (0-75, 75-150 and 150-300 mm) in a range of paddocks at the DairyNZ Scott Farm near Hamilton to examine the potential effects of soil type, species and N fertiliser regime. Six paddocks were sampled, including perennial ryegrass-white clover swards with and without N fertiliser, a tall fescue-white clover sward with N fertiliser and a plantain sward without N fertiliser on an allophanic soil (Horotiu silt loam); and perennial ryegrass-white clover swards with and without N fertiliser on a non-allophanic soil (Te Kowhai silt loam). Five 50 mm diameter soil cores were taken within each paddock, the roots washed out by hand and dried for 48 hr at 60ºC to determine dry mass. The data indicated no differences between pasture types on the Horotiu soil, but significantly greater root mass between 0 and 75 mm on the Te Kowhai soil (Fig. 2). On the Te Kowhai soil, root mass under ryegrass pastures was significantly greater at lower depths without added N (soil type/N fertiliser interaction, P=0.02). The surface root percentage ranged from 84-92%.

Discussion

The most consistent observation from a number of studies was the dominant role of the "conventional topsoil" layer (0-100 mm depth) in determining the amount and variability of root mass under pasture. For the dairy soils data presented here, generally >80% of roots were found in this zone regardless of species, soil type or management. The associated large variability in root mass in this layer (CVs of 30-80% in the data presented here) appeared to obscure potential differences between species and management effects. This highlights the need for sufficient samples to account for the variability in root mass data that probably results from small scale spatial variability (e.g. between-plant differences in root profiles; Crush & Nichols 2010) and the small areal extent of individual samples. However, the predominance of roots in the 0-100 mm layer does imply that it is in this part of the soil profile where the largest quantitative gains in root mass can be made by manipulation of either currently available species or soil characteristics. It may be that the best way to increase soil C via increases in root mass (if the link is demonstrated) is simply to increase total root mass by increasing topsoil root mass.

The concentration of root mass in the upper soil layer is generally attributed to the positive feedback of nutrient cycling processes also being focused in the upper soil layer. Since a primary function of roots is nutrient uptake, roots proliferate where nutrients are concentrated at the soil surface via fertiliser, dung deposition and tissue decomposition processes. The work of Jacques (1943) seems to bear this out by showing deeper rooting patterns with deeper placement of fertiliser. The consistent observations of higher root mass at depth under lower soil fertility conditions (N or P: Table 1, Fig 1b, Fig. 2) also support the notion of a tight coupling between nutrient concentration and root distribution through the profile. Lowering soil fertility overall would not be regarded as a practical means of shifting the root profile distribution downward, because of undesirable productivity losses. However, ways to redistribute nutrients more evenly through the profile could usefully be explored.

There is good evidence of differences between species in root profile distribution from the limited number of New Zealand studies (Crush *et al.* 2005; Evans 1978; Jacques 1943). However, these studies appear to be insufficient in number or scope to draw any specific conclusions about which species show greater root mass at depths below the topsoil. When these few studies are combined with international research (Craine *et al.* 2002; Garwood & Sinclair 1979; Nie *et al.* 2008; Shaffer *et al.* 1994; Skinner & Comas 2010), species such as tall fescue (*Festuca arundinacea*), prairie grass and phalaris do emerge as potential candidates for increasing root mass below 100 mm, but this remains to be verified under grazed field conditions. The data from Scott farm (Fig. 2) indicated a slightly but non-significantly greater root mass in the top 75 mm only for a tall fescue pasture compared to ryegrass.

Interestingly, grass species such as tall fescue, prairie grass and phalaris are also the ones typically advocated for drought-prone regions. Their ability to perform under such conditions is at least partly attributable to rooting depth (i.e. the greater volume of soil explored; Garwood & Sinclair 1979). Drought stress increases the proportion of root biomass in deeper soil layers among many grasses, including perennial ryegrass (Wedderburn *et al.* 2010), but not legumes or forbs (Skinner & Comas 2010). The pattern of shallow-root dominance is more pronounced in mesic environments where there is less selective pressure for the production of deep roots to access soil moisture. As with the soil fertility effects noted above, lower soil moisture would not be regarded as a practical means of shifting the root profile distribution downward, because of undesirable productivity losses. However, it is not necessarily the case that the opposite (increasing soil moisture by irrigation) leads to superficial root systems. In the study of Garwood & Sinclair (1979) there was some evidence that root length of perennial ryegrass and cocksfoot increased between 200-300 mm under irrigation.

While the bulk of available root profile data is focused on between-species differences, a further development more recently being explored is genotype differences within species. Root mass has been shown to be heritable in perennial ryegrass at levels that will allow breeding for larger root systems (Crush *et al.* 2006), and progress is now being made towards changing the shape of root systems towards deeper rooting patterns (Crush *et al.* 2010).

An important consideration when examining means of increasing root biomass in deeper soil layers is the source of carbon to build these tissues. Without an increase in photosynthetic C assimilation, C allocated to deep roots must be redirected either from shoot production (which is undesirable from the point of view of forage production and in itself will reduce photosynthetic capacity) or from shallow roots.

Finally, the nature of the relationship between root biomass and soil C throughout soil profiles is a vital component in addressing the feasibility of building soil C through a focus on deeper-rooted pastures. Most work to date on this question has focused on the whole soil profile rather than deeper soil layers. Northern hemisphere studies have linked root mass and production with soil C sequestration (Adair *et al.* 2009; Steinbeiss *et al.* 2008). However, the magnitude of root mass changes that might be achieved should be put in context.

The magnitude of the changes in root mass with various combinations of species and management indicated by the data presented here is of the order of up to 10-30%. It is possible to construct a simple dynamic model to illustrate the potential contributon of this increase to soil C sequestration (Fig. 3). The model includes root and soil organic carbon stocks in upper and lower soil layers. Root production and shoot + dung input rates are represented as constant daily fluxes (see Table 2). Root decomposition and soil respiration rates are represented as first order decay functions where the flux rate is a constant (k) multiplied by the source stock, as in most complex soil C models (e.g. Parton *et al.* 1988). By initialising this model with root production and soil C data using a typical pasture system such as measured in Dodd & Mackay (2011), the effect of root mass increases in two soil layers can be demonstrated (Table 2). The results show that a 20% increase in root mass in the lower soil layer (100-200 mm depth) leads to a 20% increase in soil carbon after 13 years, but due to the lower soil C stock in this layer that increase amounts to 228 kg C ha^{-1}. By comparison, a 20% increase in root mass in the upper soil layer (0-100 mm depth) leads to only a 5% increase after 13 years, because root decomposition is not the only C input to this layer. However the C stock this represents is much greater, at 1229 kg C ha^{-1}. The concept of soil C saturation (Hassink 1997; Six *et al.* 2002) thus has important implications for whether such theoretical increases can be achieved.

In summary, there does appear to be some scope for increasing the biomass of roots at greater depths under grazed pastures, through a combination of species selection, plant breeding and resource manipulation. The caveats are that the commercially available candidate species are those less commonly used in current pastoral systems and the resource manipulations run counter to current intensification practice. In addition, the impacts of changes in root biomass distribution in the soil must be examined in terms of C allocation in the plant and soil C dynamics. If it can be established that deeper-rooted pastures are a means to greater C sequestration, a rethink of optimal pasture management will be required.

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