INFLUENCE OF SIX CROP SPECIES ON AGGREGATE STABILITY AND SOME LABILE ORGANIC MATTER FRACTIONS

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Summary—The effect of the growth of barley, wheat, prairie grass, Italian ryegrass, white clover and lupin on the aggregate stability and related properties of a heavily cropped soil was investigated in a greenhouse experiment. For the non-leguminous crops, root mass and root length followed the order barley = wheat < prairie grass < Italian ryegrass. Less marked, but similar trends were found for microbial biomass C, cold and hot water-extractable carbohydrate content and aggregate stability. It was postulated that a higher root mass results in greater rhizodeposition of carbonaceous material and, therefore, a higher microbial biomass which in turn produces carbohydrate binding agents which increase aggregate stability. The hot water-extractable carbohydrate fraction was found to have a galactose plus mannose-to-arabinose plus xylose ratio of 2.1 confirming that it was predominantly of microbial origin. In comparison with the non-legumes, growth of white clover and lupin resulted in an unexpectedly high aggregate stability and to a lesser extent microbial biomass C content relative to their rather small root mass and length. Lupin, for example, had the highest aggregate stability of all the crops, while white clover had an aggregate stability similar to that of Italian ryegrass yet the two legumes had the lowest root length densities of all the crops studied. It was suggested that the rhizosphere microbial population of leguminous plants differed in some way to that of non-legumes (possibly due to the higher N content of rhizodeposited material) and that this contributed to the higher measured aggregate stability. A subsidiary experiment showed that fungal hyphal length in aggregates affected by lupin growth was four times that under wheat. There is a need for further research into aggregation in the rhizosphere of a wider range of legumes.

INTRODUCTION

The resistance of soil aggregates to the slaking and dispersive effects of water (aggregate stability) is important for maintaining a porous structure in arable soils. Mechanisms involved in the maintenance of stable soil aggregates include the strong bonding effects of humic polymers, the gluing and bonding effects of soil polysaccharides and the enmeshing effects of fine roots and fungal hyphae (Haynes and Beare, 1995).

Maintaining optimum soil conditions under continuous production of cereals or row crops is often difficult. Soil organic matter content is generally low and this can result in low soil biological activity and a decline in aggregate stability and soil physical condition. In order to develop cropping rotations that maintain or improve soil organic matter and soil structure, information regarding the specific effects that the growth of various crop plants have on these properties is required. However, such information is surprisingly sparse. Reid and Goss (1981) found that over a 6-wk period, root growth of perennial ryegrass and lucerne generally increased aggregate stability, while growth of maize, tomato and wheat decreased it. Dufey et al. (1986) found ryegrass increased stability but red clover had no significant effect. Tisdall and Oades (1979) attributed the greater effectiveness of ryegrass over white clover in improving aggregate stability to its much more extensive root system and the extensive vesicular–arbuscular (VA) mycorrhizal hyphae it supported. Stone and Buttery (1989) showed that of nine grasses and forages studied, those with the most extensive root systems resulted in the greatest improvement in aggregation. Similar results have been observed in the field (Perfect et al., 1990; Haynes and Francis, 1993).

Under field conditions, factors such as normal sowing rate of the crop (i.e. plant spacing) and seedling survival can confound the effect of crop growth on soil aggregation (Haynes and Francis, 1993). Our purpose was to investigate and compare the effects of growth of various crop species on
Table 1. Properties of the soils used in the study

<table>
<thead>
<tr>
<th>Property</th>
<th>Main experiment</th>
<th>Subsidiary experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic C (g kg$^{-1}$)</td>
<td>25</td>
<td>23</td>
</tr>
<tr>
<td>Total N (g kg$^{-1}$)</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Total carbohydrate (g C kg$^{-1}$)</td>
<td>3.1</td>
<td>2.6</td>
</tr>
<tr>
<td>Hot water-extractable carbohydrate (mg C kg$^{-1}$)</td>
<td>190</td>
<td>112</td>
</tr>
<tr>
<td>Microbial biomass C (mg g$^{-1}$)</td>
<td>380</td>
<td>295</td>
</tr>
<tr>
<td>Aggregate stability (mean weight dia. mm)</td>
<td>0.46</td>
<td>0.29</td>
</tr>
</tbody>
</table>

aggregate stability in a pot experiment where roots are restricted to a defined volume of soil. The crops grown were the non-legumes barley, wheat, prairie grass, Italian ryegrass, and the legumes white clover and lupin, most of which are also currently being compared in a 5-y field trial in the Canterbury region of New Zealand (Francis et al., 1994). Other important measurements included root mass and length, microbial biomass C, organic C, total and extractable soil carbohydrate content, bacterial numbers and fungal hyphal length.

MATERIALS AND METHODS

The soil used in this experiment was a Wakanui silt loam (Ustic Dystrochrept; USDA) (Fieldes, 1968), which is commonly used for arable cropping in the Canterbury region of New Zealand. It has a clay content of about 170 g kg$^{-1}$ and its mineralogy is dominated by illite with some inter-layered chlorite and inter-layered hydrous mica. The sample used in the main experiment came from the 0–15 cm layer of a field that had been under arable cultivation for 10 y (rotation of wheat, barley and rape). This site was put back under pasture and when a subsidiary experiment was initiated, the 0–15 cm layer of an adjacent field that had been under arable cultivation for about 20 y was used. Some initial properties of the soils are presented in Table 1. Because of the longer period under arable cultivation, measured properties for the soil used in the subsidiary experiment were lower than those for the soil used in the main experiment.

For the main experiment, soil was sieved (<2 mm) in a field-moist state (20% v/v moisture content) and 1500 cm$^3$ of soil was placed in plastic pots, 13.5 cm dia (four replicates per treatment). A basal fertilizer application was applied. For the non-legumes this consisted of 200 g N m$^{-3}$ as NH$_4$NO$_3$, 150 g K m$^{-3}$ and 120 g P m$^{-3}$ as KH$_2$PO$_4$, 50 g Mg m$^{-3}$ as MgSO$_4$, 1.5 g B m$^{-3}$ as H$_3$BO$_3$ and 80 mg Mo m$^{-3}$ as (NH$_4$)$_6$Mo$_7$O$_{24}$·4H$_2$O. For the two leguminous crops, a basal fertilizer application without N was applied. The seven experimental treatments were: (1) control (no plants present); (2) sown with barley (Hordeum vulgare L. cv. Illia); (3) with wheat (Triticum aestivum L. cv. Sapphire); (4) with prairie grass (Bromus unioloides H.B.K. cv. Matua); (5) with Italian ryegrass Lolium multiflorum L. cv. Moata); (6) with white clover (Trifolium repens L. cv. Huia) and (7) with lupin (Lupinus augustifolius cv. Feste). In each case, plants were hand-thinned to six per pot following emergence. Plants were arranged in a random-block design with four replicates. The pots were maintained at 70% field capacity for 12 wk in a glasshouse thermostatically controlled with a fan vent temperature of 25°C and a heat temperature of 15°C.

At the end of this period, plant tops were harvested, dried at 70°C and weighed. Soil was carefully removed from pots and the resulting “core” was cut down the centre into two halves. Roots were extracted from half of each core under running water using a 300 µm mesh sieve. Roots were dried between blotting paper, weighed and a subsample taken for root length measurement (Tennant, 1975). The remainder of the sample was oven-dried at 70°C and weighed. It was noted that root systems of the legumes were well-nodulated and that root systems of individual plants were nodulated to a similar extent. The other half of each soil core was carefully broken apart and sieved and the 1–2 mm dia aggregates were collected. This fraction was collected since preliminary experiments showed that plant growth in <2 mm dia sieved soil had the greatest effect on the stability of the 1–2 mm dia aggregates. A sub-sample of aggregates was air-dried at 22°C in a drying cabinet with air circulation for 48 h.

Aggregate stability was estimated using a wet sieving technique (Haynes, 1993) using both field-moist and air-dried samples. Field-moist samples had a moisture content of 220–250 mg g$^{-1}$, while that for air-dried samples was 10–30 mg g$^{-1}$. Previous work had shown that initial moisture content can greatly influence measured values of stability. The equivalent of 30 g of oven-dried 1–2 mm soil aggregates was transferred to the uppermost of a set of three sieves having 1.0, 0.5 and 0.25 mm dia apertures. The water level was adjusted so that the aggregates on the upper sieve were just submerged at the highest point of oscillation. The oscillation rate was 25 cycles min$^{-1}$, the amplitude of the sieving action was 35 mm and the period of sieving was 15 min. The results were expressed as a mean weight diameter which is the sum of the fraction of soil remaining on each sieve after sieving for the standard time multiplied by the mean diameter of the adjacent sieve apertures (in this case 1.5, 0.75, 0.375 and 0.125 mm), i.e. mean weight diameter = (fraction of sample on sieve × mean intersieve aperture). The upper and lower limits of mean weight diameter in this case were 1.5 and 0.125 mm, respectively.

Organic C was determined colorimetrically by the Walkley and Black technique (Blakemore et al.,
1972). Total acid-extractable carbohydrate content was measured by successive hydrolysis with 12 M and 0.5 M sulphuric acid and the hydrolysate was analysed by the anthrone method using glucose standards (Cheshire, 1979). A sequential procedure was used to extract carbohydrates from soil (Haynes et al., 1991). Two grams of soil were extracted with cold water (20°C), hot water (80°C), 1 M HCl and 0.5 M NaOH. For each reagent the extraction time was 16 h and the soil-to-extraction ratio was 1:10. The carbohydrate content of the extracts was analysed by the anthrone method. In both the soil-acid hydrolysate and the acid hydrolysate of the hot water extract, five sugars (glucose, galactose, mannose, arabinose, xylose) were identified using a Bio-Rad Laboratories Aminex BPX-87P carbohydrate HPLC analysis column (Angers et al., 1988). Hydrolysates were neutralized with Ba(OH)2 and centrifuged prior to HPLC analysis. Microbial biomass C was estimated by the method of Vance et al. (1987), based on the difference between C extracted with 0.5 M K2SO4 from chloroform-fumigated and unfumigated soil samples using a K2 factor of 0.38.

For the subsidiary experiment, the effects of growth of wheat and lupin on aggregate stability were compared in detail. These two crop plants were found in the main experiment to have a similar root mass, yet lupin growth resulted in a considerably higher aggregate stability. Procedures involved in setting up and running the experiment were identical to those of the main experiment. Pots were arranged in a randomized block design with four replicates. After 12 wk soil was removed from pots, carefully sieved and the 1–2 mm dia aggregates were collected. Aggregate stability was determined on sub-samples of air-dried aggregates as described above. The remaining aggregates were stored moist at 4°C prior to use. Organic C, microbial biomass C and hot water-extractable carbohydrate content of soil from the 1–2 mm fraction were analysed as described above. Root mass and length were analysed as described above after sub-samples of moist aggregates were dispersed by shaking overnight with 1% sodium hexametaphosphate and roots were extracted under running water using a 300 μm mesh sieve.

Suspensions of the 1–2 mm dia aggregates from under wheat and lupin were prepared (1:10 dilution with distilled, sterilized water) by ultrasonification for 2 min and from these 1:50 dilutions were subsequently made. Soil smears were prepared on glass slides, dried at 24°C and stained for 60 min with differential fluorescent stain (2 mM europium chelate and 25 μM fluorescent brightener formulated in 96% v/v ethanol) following procedures adapted from Anderson and Slinger (1975) and Trent (1992, pers. comm.). Excess stain was removed by a decolourising rinse with 50% v/v ethanol. This combination of stains differentiates between nucleic acid containing living cells, which fluoresce red and dead cells which fluoresce blue. Slides were observed by epifluorescence microscopy and the number of red- and blue-stained bacteria and total fungal hyphal lengths were recorded.

![Aggregate stability of soils, measured on field-moist or air-dried aggregates, after growing six crop species in a greenhouse experiment. Means associated with the same letter are not significantly different (P ≤ 0.05).](image)

**RESULTS**

Growth of crop species had no significant effect on measured aggregate stability when field-moist aggregates were used (Fig. 1). However, when air-dried samples were used, significant effects of crop species were observed. The order was control < barley = wheat ≤ prairie grass < Italian ryegrass = white clover < lupin. Italian ryegrass had the highest root mass and root length density, while prairie grass had the second highest values for these parameters (Fig. 2). For root mass density the order was white clover < lupin = wheat = barley < prairie grass < Italian ryegrass. Root length density followed the order white clover = lupin < barley = wheat < prairie grass < Italian ryegrass. Growth of plants had a significant effect on microbial biomass C in soils (Fig. 3), which followed the order control ≤ barley = wheat < prairie grass = white clover < lupin < Italian ryegrass.
For non-legumes, the marked trend in root mass and length density of barley = wheat < prairie grass < Italian ryegrass (Fig. 2) was reflected in a less marked but similar trend for microbial biomass C (Fig. 3), and a still less marked but similar trend for aggregate stability on air-dried aggregates (Fig. 1). Such a trend has been observed by Haynes and Francis (1993) since a larger root mass results in a larger microbial biomass in the rhizosphere, which in turn produces more binding agents and, therefore, increases aggregate stability. None the less, it is interesting to note that in comparison with non-legumes, the legumes white clover and lupin had an unexpectedly high microbial biomass relative to their root mass and length densities (Figs 2 and 3). For example, white clover had the lowest root mass and length density, yet it had a microbial biomass similar to that of prairie grass. This trend was further reflected in the surprisingly high aggregate stability found under the legumes (Fig. 1). For example, lupin had the highest aggregate stability, yet it had a root mass similar to that of wheat and barley and considerably less than that of the two grasses.

There were no significant differences in organic C content (data not shown) or total acid hydrolysable carbohydrate content (Table 2) of soils under the different crop plants. Similarly, there were few significant differences in HCl- or NaOH-extractable carbohydrate between treatments (Table 2), although the HCl-extractable fraction was higher under Italian ryegrass than under the other treatments. None the less, there were significant differences for the more labile cold and hot water-extractable carbohydrate fractions. For cold water-extractable carbohydrates, the order was control = barley = wheat = clover < lupin = prairie grass < Italian ryegrass. The order was the same for the hot water-extractable fraction except that all the soil with plants had higher values than the control. The mean galactose plus mannose-to-arabinose plus xylose [(G + M) - (A + X)] ratio for the total carbohydrate fraction was 1.28, but it was 2.13 for the hot water-extractable fraction (Table 2).

Growth of crop species had no significant effect on these ratios.

Results for the subsidiary experiment are presented in Table 3. As with the main experiment, aggregate stability of soils was greater under lupin than wheat. While root mass was slightly higher for lupin than wheat, root length was lower for aggregates under lupin. Hot water-extractable carbohydrate content was similar under the two crops, but biomass C was higher under lupin. Fungal hyphal length in aggregates from lupin was about four times that of wheat. Although the number of dead and dying (blue-stained) bacterial cells were similar in aggregates under the two crops, there were a greater number of living bacterial cells (red-stained) under lupin.

**DISCUSSION**

When soils were air-dried prior to wet sieving both presence of plants and crop type had significant effects on measured stability. By contrast, when aggregate stability was measured using field-moist samples, the presence of plants did not influence stability values. Similarly, in studies from the same locality, contrasting cropping histories had little effect on aggregate stability when measured
Table 2. Effect of growth of crop species on the soil content of total carbohydrate and various extractable carbohydrate fractions and the galactose (G) plus mannose (M) to arabinose (A) plus xylene (X) ratio in the total and hot water-extractable carbohydrate fractions [G + M]-to-(A + X)]

<table>
<thead>
<tr>
<th>Crop species</th>
<th>Total acid-hydrolysable carbohydrate (g C kg⁻¹)</th>
<th>Extractable carbohydrate (mg C kg⁻¹)</th>
<th>HCl</th>
<th>NaOH</th>
<th>Total</th>
<th>Hot water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cold water</td>
<td>Hot water</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Italian ryegrass</td>
<td>3.5 ns</td>
<td>390°b</td>
<td>320°b</td>
<td>258°b</td>
<td>1193 ns</td>
<td>1.20 ns</td>
</tr>
<tr>
<td>Prairie grass</td>
<td>3.5</td>
<td>150°b</td>
<td>230°b</td>
<td>215°b</td>
<td>1160</td>
<td>1.25</td>
</tr>
<tr>
<td>Barley</td>
<td>3.2</td>
<td>51°a</td>
<td>218°a</td>
<td>219°a</td>
<td>1159</td>
<td>1.32</td>
</tr>
<tr>
<td>Wheat</td>
<td>3.1</td>
<td>57°a</td>
<td>214°a</td>
<td>214°a</td>
<td>1140</td>
<td>1.28</td>
</tr>
<tr>
<td>Clover</td>
<td>3.4</td>
<td>68°a</td>
<td>207°a</td>
<td>208°a</td>
<td>1240</td>
<td>1.30</td>
</tr>
<tr>
<td>Lupin</td>
<td>3.3</td>
<td>129°b</td>
<td>235°b</td>
<td>235°b</td>
<td>1261</td>
<td>1.14</td>
</tr>
<tr>
<td>Control</td>
<td>3.1</td>
<td>55°a</td>
<td>182°a</td>
<td>210°a</td>
<td>1235</td>
<td>1.27</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different (P ≤ 0.05). ns, no significant difference.

using field-moist samples (Haynes and Swift, 1990; Haynes, 1993), yet a clear separation was achieved using air-dried aggregates.

The aggregates used in our study were from soils under continuous arable production with relatively low soil organic matter contents. Partly because of their low organic matter contents, such aggregates are weakly bound together and drying causes incipient fracture faults to develop (Haynes and Swift, 1990). On contact with water the aggregates quickly re-wet and slaking occurs. The mechanical action of wet sieving causes further breakdown of aggregates. The growth of crop plants apparently resulted in aggregates being more strongly held together and as a consequence they remained intact under the disrupting influences of slaking and sieving. When field-moist aggregates from these soils are used there is little slaking effect and the mechanical action of wet sieving is the major disrupting factor (Haynes, 1993). In a field-moist state, aggregates were bound strongly enough together to withstand this disrupting force and measured stability values were 85–90% of maximum values regardless of whether plants were grown in the soil or not. Such results underline the need to air-dry soil samples from the study area prior to analysis of aggregate stability if a meaningful separation is to be achieved (Haynes, 1993).

For the non-legumes in our study, increases in root mass and length density, microbial biomass C, cold and hot water-extractable carbohydrate content and aggregate stability followed the order: barley = wheat < prairie grass < Italian ryegrass. Root growth increases aggregation through a number of different mechanisms. Roots, root hairs and fungal hyphae (particularly those of vesicular arbuscular mycorrhizae) form an extensive network which physically enmesh fine particles of soil into aggregates even after their death (Tisdall and Oades, 1982). In addition, both roots and fungal hyphae exude mucilaginous polysaccharide material which can act as binding and gluing agents, thus, helping in aggregation (Oades, 1978; Lynch and Bragg, 1985). Roots have another important indirect effect on aggregation since large quantities of organic material are supplied to soils from roots. The main source of this rhizodeposition of organic material is through normal growth and senescence of root segments and root hairs, but roots also exude a range of organic substrates (Lynch and Whipp, 1991). The amount of organic C released by roots of a plant is closely related to the total root mass (Shamoot et al., 1968). As a result of this rhizodeposition of C, a large active microbial biomass develops in the rhizosphere. In turn, the rhizosphere bacteria and fungi exude polysaccharide and phenolic binding agents and fungal hyphae have an enmeshing effect (Haynes and Beare, 1995). Thus, crops with the greatest root mass often show the greatest improvement in aggregation (Stone and Buttery, 1989). When crops are compared under field conditions with respect to their ability to improve aggregate stability several workers have observed that the same sequence is generally

Table 3. Aggregate stability, root mass and length and other relevant properties in aggregates from pots in which lupin and wheat were grown

<table>
<thead>
<tr>
<th>Crop</th>
<th>Aggregate stability (MWD, mm)</th>
<th>Root mass (kg m⁻²)</th>
<th>Root length (cm cm⁻³)</th>
<th>Microbial biomass C (µg g⁻¹)</th>
<th>Hot water-extractable carbohydrate (µg C g⁻¹)</th>
<th>Fungal Hyphal length (m g⁻¹)</th>
<th>Bacterial number x 10⁶ (red-stained)</th>
<th>Bacterial number x 10⁶ (blue-stained)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lupin</td>
<td>0.49</td>
<td>8.0</td>
<td>5.1</td>
<td>320</td>
<td>115</td>
<td>1224</td>
<td>8.1</td>
<td>0.92</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.30</td>
<td>6.8</td>
<td>13</td>
<td>300</td>
<td>120</td>
<td>310</td>
<td>5.8</td>
<td>0.90</td>
</tr>
</tbody>
</table>

*Significance of difference at the 10% level. **Significance of difference at the 5% level. ***Significance of difference at the 1% level.
observed as that for root mass or length density (Kay, 1990; Perfect et al., 1990; Haynes and Francis, 1993).

Since the soil microbial community plays a central role in aggregation it is not surprising that several workers have observed a close relationship between short-term increases in aggregate stability and increases in microbial biomass C (Drury et al., 1991; Robertson et al., 1991; Haynes and Francis, 1993). In our study, the major factor affecting the size of the microbial biomass is likely to have been the magnitude of rhizodeposition of C substrate for microbial growth. Thus, for the non-legumes microbial biomass showed a similar but less marked trend to root mass and length density.

Some workers have observed that the hot water-extractable carbohydrate fraction in soils is more closely correlated with aggregate stability than total carbohydrate or organic C content (Haynes et al., 1991; Angers et al., 1993). Indeed, in this study, while both cold and hot water-extractable carbohydrate content showed a similar trend to aggregate stability under the non-legumes, plant growth had no measurable effect on either organic C or total carbohydrate content of soils. Haynes and Swift (1990) suggested that the hot water-extractable fraction represents extracellular polysaccharides mainly of microbial origin, and that they are involved in the short-term stabilization of soil aggregates. Polysaccharides of microbial origin normally have a [(G + M)-to-(A + X)] ratio of > 2, while plant polysaccharides typically have a low ratio (< 0.5) (Oades, 1984). Our results showed that the [(G + M)-to-(A + X)] ratio of hot water extracts of soils was about 2.1 confirming they were mainly of microbial origin. The ratio for the total carbohydrate fraction was 1.3 confirming that total soil carbohydrates are a mixture of those of plant and microbial origin.

The unexpectedly high aggregate stability induced by the two legumes relative to their low root mass and length densities could not be explained by the slightly higher than expected microbial biomass C content. However, in addition to legumes having a proportionately higher microbial biomass than non-legumes for a similar root mass or length density, the subsidiary experiment showed that fungal hyphal length for lupin was about four times that of wheat and viable bacterial numbers also tended to be higher under lupin. Such a finding is somewhat surprising since lupin is poorly susceptible to VA mycorrhizal infection, while the other crops studied, including wheat, are strongly mycorrhizal (Harley and Smith, 1983). Proliferation of saprophytic fungi in the soil where lupin was grown presumably explained the large hyphal length. Indeed, our observation of hyphal morphology indicated that the majority of the hyphae were of non-mycorrhizal species. As already noted, the primary source of C for microbial proliferation in the soils under study is likely to have been rhizodeposition. It is well known that plants vary greatly in the amounts and types of organic materials released by their roots, and consequently the rhizosphere population varies between plant species (Lynch and Bragg, 1985). In the N-deficient soils used in this study, the higher N content of rhizodeposited organic material (e.g. dying roots and sloughed-off nodules) from the legumes is likely to have been a major difference leading to a larger and differing microbial population under the legumes than non-legumes. It may well be that the unexpectedly high microbial biomass under white clover was also partly related to a higher fungal biomass and larger hyphal length, although unfortunately this was not measured. It seems likely that the difference in microbial populations, particularly the greater hyphal length, is the major contributor to the unexpectedly high aggregate stability measured under the legumes. The importance of fungal hyphae in aggregation (particularly through their enmeshing action) is well documented (Tisdall and Oades, 1982; Tisdall, 1991). There seems considerable scope for further research regarding soil aggregation in the rhizosphere of a range of legumes in comparison with that in non-legumes.

Its is interesting that under field conditions where growth of annual grass, wheat and lupin was compared (Francis et al., 1994), aggregate stability values followed the order ryegrass > wheat > lupin. By contrast, in our study the order was lupin > ryegrass > wheat. In a pot experiment, the roots are restricted to a defined volume of soil, while when a field is randomly sampled soil, both affected and unaffected by roots, is sampled. The root mass and length density of lupin under field conditions is low because it has a relatively small, thick, root system which does not ramify far between or within plant rows. In order to observe under field conditions, the very positive effect of lupin on aggregation measured in this study, lupin would have to be planted extremely close together. This may be practicable and may well occur when it is used as a green manure crop.

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REFERENCES


