SHORT COMMUNICATION

Contribution of red alder to soil nitrogen input in a silvopastoral system

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Abstract Studies on *Alnus rubra* Bong. (red alder) were carried out to assess its potential for use as a component of a silvopastoral system. Comparison was between two treatments: red alder at 400 stems ha^{-1} (silvopasture) and red alder at 2,500 stems ha^{-1} (forestry control). $\delta^{15}N$ values close to zero were recorded in all red alder plant parts except for root nodules, indicating that a large proportion of N in red alder was fixed from the atmosphere. Overall, it was estimated that there was 63.45 kg N ha^{-1} fixed N accumulated in red alder trees, and the rate of N fixation was estimated at 30.95 kg ha^{-1} year^{-1} in the silvopasture treatment. The total amount of N that could potentially be added to the soil in the silvopasture treatment as a result of decomposition of senescent leaves, roots, and dead nodules was estimated at 40.56 kg ha^{-1} year^{-1}. Of the total N added to the soil, 27.1 kg ha^{-1} year^{-1} was due to N fixation from the atmosphere. These results show that red alder has a potential to improve and maintain soil fertility in a silvopastoral system.

Keywords ^{15}N natural abundance · N fixation · Red alder · Silvopasture

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Introduction

Several reports have demonstrated the value of N-fixing trees as sources of N and their potential in soil fertility improvement and maintenance (Giller 2003; Teklehaimanot and Anim-Kwapong 1996; Young 1997). Red alder is an important N-fixing tree species in temperate and boreal ecosystems (Binkley et al. 1994; Rojas et al. 2001). It has been planted in mixture with non-N-fixing trees to provide the much-needed N in forest plantations in the USA (Binkley et al. 1994) and has been experimentally planted with maize in the Pacific Northwest for the same purpose (Seiter et al. 1995). In addition to N fixation, N-fixing trees provide nutrients to the soil through the decay of fine roots, nodules, and leaf litter (Chesney and Nygren 2002; Ruess et al. 1996). The incorporation of this tree species in agroforestry systems is considered cheaper and more environmentally friendly than the use of commercial fertilizers (Teklehaimanot and Martin 1999).

Rates of N fixation in red alder have been previously assessed using the acetylene reduction assay method (Teklehaimanot and Martin 1999; Tripp et al. 1979). However, the acetylene reduction assay method presents limitations and, therefore, may not give reliable results (Minchin et al. 1986).

Binkley et al. (1985) suggested that the ^{15}N natural abundance method was not useful in quantifying the N fixed by the red alder planted in a forestry system, whereas this method was successfully used to measure the N fixation in other alder species (Domench et al. 1989; Hurd et al. 2001; Sanborn et al. 2002). So far, no study has been carried out to quantify the contribution of fine roots, nodules, and leaf litter of red alder to soil N balance.

The present study was, therefore, carried out (1) to assess the rate of N fixation in red alder using the ^{15}N

natural abundance method and (2) to estimate the contribution of red alder to the soil's N content in a silvopastoral system.

Materials and methods

Study site

The study was carried out in a 10-year-old red alder silvopastoral system experimental site at the University of Wales, Henfaes Farm, which is located in Abergwyngregyn, Gwynedd, 12 km east of Bangor city, UK. The study was carried out between 2002 and 2004. The climate of the site is hyperoceanic with an annual rainfall of about 1,000 mm. The soil is mainly a fine loamy brown earth over gravel classified as Rheidol series (FAO–UNESCO, Dystric Cambisol) with a pH of 5.90±0.03 and a high extractable P (9.9±0.3 mg kg^{-1}; Teklehaimanot et al. 2002; Palomo et al. 2006).

Two experimental treatments were used in the present study: red alder at 400 stems ha^{-1} (silvopasture, i.e., widely spaced trees with the space between the trees grazed by sheep) and red alder at 2,500 stems ha^{-1} (forestry control, i.e., without grazing). Both treatments were replicated three times.

An isolated stand of red alder trees planted at the same time as the two experimental treatments was used for the ^{15}N natural abundance study. The stand was established at one corner of the experimental site as a reserve for replacing dead red alder trees (beating up) in the two experimental plots. Other plants growing within the stand were also used as reference plants in the ^{15}N natural abundance study. These included *Salix sp* (willow), *Acer pseudoplatanus* (sycamore), and *Prunus spinosa* (blackthorn). The stand was not grazed by sheep.

Measurement of ^{15}N natural abundance

The measurements of the ^{15}N natural abundance were made to determine the rate of N fixation in red alder. The samples were collected from trees growing in the isolated red alder stand. No samples were taken from the above two experimental treatment plots because of contamination by sheep feces and urine in the silvopasture treatment.

Three replicates of fine roots, nodules, and wood of red alder and reference plants were randomly collected from the isolated stand of red alder in autumn (September), winter (February), spring (April), and summer (July) in 2002 and 2003. Leaves were not collected during the winter season because plant species were deciduous. In addition, three soil samples were taken from the same area.

The plant samples were oven dried at 80°C for 2 days. A ball mortar mill was used to grind the samples to a fine powder. The ^{15}N/^{14}N isotope ratio and total N content of the powdered samples were determined as described by Gathumbi et al. (2002) using an automated N analyzer coupled to a mass spectrometer at the Department of Agricultural Sciences, Imperial College, London, UK.

The standard procedure described by Shearer and Kohl (1993) was used to calculate the fraction of N derived from the atmosphere (FNdfa) in each plant sample using the following formula:

$$FNdfa = \frac{\delta 15 N_o - \delta 15_t}{\delta 15 N_o - \delta 15 N_a},$$

where FNdfa is the fraction of N derived from the atmosphere, $\delta^{15}N_a$ is delta ^{15}N in red alder grown in N-free media (see below), $\delta^{15}N_o$ is delta ^{15}N in non-fixing reference plant sample, $\delta^{15}N_t$ is delta ^{15}N in red alder sample, and $\delta^{15}N_a$ is −0.3 (from Binkley et al. 1985).

$$\delta^{15}N = \frac{1,000(atom\%^{15}Nsample - 0.3663)}{0.3663}$$

The above equation was taken from Shearer and Kohl (1993).

Measurement of total biomass of red alder

The biomass of the stem, branches, and leaves of the red alder was measured destructively by felling sample trees in the isolated red alder stand, instead of the two experimental treatment plots to avoid the early loss of trees in the long-term (50 years) experiment. Three trees were randomly chosen from the isolated red alder stand and felled in 2004 to measure the aboveground biomass of red alder. The wood (stem and branches bulked together) and leaf samples were separated and oven-dried at 80°C for 24 h. The samples were then weighed and recorded.

The belowground biomass of the fine roots and nodules was estimated in the two experimental treatment plots using a modified quarter spiral trench technique, as described by Tomlinson et al. (1998). In this study, core samples were taken instead of trench sampling, as it was difficult to dig the soil being a shallow brown earth with gravel. The modified method, therefore, enabled a large proportion of soil cores to be excavated with only minimal damage to the trees. Soil cores of 30 by 20 cm and 15-cm depth were excavated at three sampling points (30-, 75-, and 100-cm distance from the base of each tree) from nine trees of each experimental plot in 2003. Trees in the border were not selected to avoid edge effects. The core samples were stored in a cold store (4°C) for approximately 1 week before being separated into roots, nodules, and soil at the University of Wales Bangor, UK. All the samples were

oven dried at 80°C for 2 days in a laboratory and then weighed.

Calculation and statistical analyses

The live fine root, leaves, and wood biomass data were used to estimate the total amount of N fixed per tree and the amount of fixed N accumulated per hectare in the silvopasture and forestry treatments. Then, by taking the total wood biomass and dividing it by the number of years (10) the mean annual wood increment was calculated. The biomass of both the live and the dead roots and the biomass of the leaves were assumed to be the annual production. Then, by using the mean annual wood increment and biomass of the fine roots and leaves, the rate of N fixation per annum was calculated.

It was assumed that the amount of fine roots and nodules of the red alder recorded at the site senesce and decompose within a year. It was also assumed that senescent leaves deposited on the soil surface were decomposed within a year. Thus, only senescent nodules, fine roots, and leaves were assumed to decompose. Therefore, the biomass of leaves, fine roots (live and dead), and dead nodules and their N contents were used to estimate the potential contribution by red alder to the N content of the soil. The wood biomass and live nodules were excluded from the calculation. Because red alder nodules are indeterminate, that is, some nodules could be older than 1 year and the wood is ligneous, the turnover of live nodules and wood may be longer than a year.

The data were analyzed using the general linear model analysis of variance (ANOVA). In the case of significant differences, Tukey's comparison test was used to separate all the means.

Results

Table 1 shows the mean $\delta^{15}N$ values in different plant parts during the four seasons. There was a significant difference ($P<0.001$) in $\delta^{15}N$ values between plant species. The $\delta^{15}N$ values of red alder were negative in the summer and autumn, and positive but close to zero in the winter and spring, whereas the reference plants showed highly enriched values of $\delta^{15}N$. There was no significant difference in $\delta^{15}N$ between the different parts of red alder (excluding nodules). The ANOVA also showed no significant difference in $\delta^{15}N$ between the different parts of each reference plant species.

There was no significant difference in N content between species (Table 2) or season. In all species, the N content was significantly higher in the leaves ($P<0.001$) than in other plant parts.

The values of $\delta^{15}N$ and N content were similar in the red alder nodules and soil samples (Tables 1 and 2). Both the red alder nodules and the relative soil were highly enriched with ^{15}N, and these were similar to the $\delta^{15}N$ values of the reference plants (Table 1). There was no significant effect of season on $\delta^{15}N$ and N content of either the root nodules or soils.

The fraction of N derived from the atmosphere (FNdfa) in red alder was calculated as a percentage by using the mean values of $\delta^{15}N$ in the three non-N fixing taken as reference plants. FNdfa was not calculated for nodules, as

Table 1 Values of $\delta^{15}N$ (‰±SE) in different plant parts and soil ($n=3$) in the four seasons

		Summer	Autumn	Winter	Spring	Mean
Willow	Leaf	4.19±0.08	4.30±0.63	–	5.27±0.36	4.59±0.27
	Wood	3.59±0.07	4.46±0.48	3.23±0.25	4.44±1.16	3.93±0.31
	Root	2.91±0.04	3.79±0.57	3.27±0.12	3.89±0.94	3.46±0.26
	Mean	3.56±0.18	4.18±0.30	3.25±0.12	4.54±0.48	3.94±0.18
Blackthorn	Leaf	3.11±0.05	4.09±0.54	–	–	3.59±0.32
	Wood	3.55±0.10	5.77±0.12	5.63±0.16	5.52±0.41	5.12±0.29
	Root	4.53±0.02	4.69±0.23	3.36±0.18	3.53±0.67	4.02±0.23
	Mean	3.72±0.21	4.85±0.30	4.50±0.52	4.52±0.56	4.38±0.19
Sycamore	Leaf	3.22±0.04	3.85±0.24	–	3.81±0.51	3.63±0.19
	Wood	4.59±0.06	3.01±0.36	1.99±0.60	5.25±0.16	3.71±0.41
	Root	0.52±0.05	1.49±0.21	3.39±0.16	4.66±0.21	2.51±0.49
	Mean	2.78±0.59	2.78±0.37	2.69±0.42	4.58±0.26	3.25±0.25
Alder	Leaf	0.23±0.06	−0.73±0.23	–	0.71±0.43	0.07±0.25
	Wood	−0.34±0.06	0.01±0.18	1.40±0.36	1.32±0.65	0.60±0.28
	Root	−0.02±0.02	−0.12±0.48	−1.06±0.30	2.09±0.80	0.21±0.40
	Mean	−0.04±0.08	−0.28±0.19	0.17±0.59	1.37±0.38	0.31±0.19
Alder	Nodule	5.58±0.54	6.29±0.28	–	6.18±0.97	6.01±0.62
Soil		5.44±0.25	5.49±0.21	–	6.93±0.14	5.95±0.22

Table 2 Mean N content (%±SE) of different parts of different plants (n=12) and soil (n=3)

		Summer	Autumn	Winter	Spring	Mean
Willow	Leaf	2.47±0.01	2.69±0.25	–	4.91±0.05	3.36±0.40
	Wood	0.79±0.01	1.02±0.53	0.64±0.09	1.17±0.60	0.91±0.18
	Root	1.16±0.01	1.09±0.18	0.96±0.15	0.77±0.19	1.00±0.08
	Mean	1.47±0.26	1.60±0.32	0.80±0.11	2.28±0.68	1.61±0.22
Blackthorn	Leaf	3.37±0.01	2.68±0.08	–	–	3.02±0.16
	Wood	0.58±0.01	0.54±0.05	0.54±0.02	0.54±0.09	0.55±0.02
	Root	1.17±0.01	1.48±0.42	1.52±0.01	2.10±0.39	1.57±0.16
	Mean	1.71±0.42	1.57±0.33	1.03±0.22	1.32±0.39	1.45±0.18
Sycamore	Leaf	3.12±0.01	2.82±0.16	–	2.56±0.12	2.83±0.10
	Wood	0.56±0.01	0.35±0.07	0.61±0.07	0.54±0.09	0.51±0.04
	Root	1.18±0.01	0.72±0.04	0.53±0.09	0.67±0.06	0.77±0.08
	Mean	1.62±0.39	1.30±0.39	0.57±0.05	1.26±0.33	1.24±0.17
Alder	Leaf	2.88±0.01	2.16±0.05	–	2.12±0.20	2.39±0.14
	Wood	0.70±0.01	0.33±0.02	0.84±0.05	0.44±0.04	0.58±0.06
	Root	0.84±0.01	0.68±0.06	0.40±0.09	0.79±0.11	0.68±0.06
	Mean	1.48±0.35	1.05±0.28	0.62±0.11	1.12±0.26	1.11±0.14
Alder	Nodule	2.05±0.03	1.81±0.04	–	1.70±0.05	1.85±0.03
Soil		0.25±0.001	0.33±0.01	–	0.30±0.01	0.29±0.01

there were no reference plants with nodules. The overall mean value of FNdfa indicated that 85% of N in the red alder was derived from the atmosphere. The highest mean value of fixed N (91%) was found in the leaves and the lowest in the wood (78%); the mean values of FNdfa were higher in the summer and autumn than in the winter and spring.

The total amount of fixed N accumulated in the red alder tree was calculated by using the total biomass of leaves, wood, and fine roots (excluding nodules; Table 3), and their N contents and FNdfa. The results showed that 65.55 and 334.14 kg N ha^{-1} were accumulated in the red alder in the silvopasture and forestry treatment plots, respectively. The calculated rate of N fixation was 30.95 and 117.84 kg ha^{-1} year^{-1} in the silvopasture and forestry treatment plots, respectively.

The contribution of red alder to the soil N in the silvopastoral and forestry systems was calculated by using the data of fine roots (live and dead) biomass, dead nodule biomass, leaf biomass (Table 3), and their N contents. The total amount of N that could potentially be added to the soil as a result of the decomposition of senescent leaves, root, and dead nodules amounted to 40.56 kg ha^{-1} year^{-1} and 111.17 kg ha^{-1} year^{-1} in silvopasture and forestry, respectively. Out of the total N added to the soil, 27.1 kg ha^{-1} year^{-1} and 93.81 kg ha^{-1} year^{-1} (in silvopastoral and forestry systems, respectively) were due to the N fixation by the red alder from the atmosphere.

Discussion

The depleted δ^{15}N values in the red alder indicate a signature of ^{15}N that was similar to that of the N in the

atmosphere, showing that the atmosphere was the main N source in the red alder. This also indicates that the red alder was efficiently fixing atmospheric N as shown by the high FNdfa values (average 85%). Binkley et al. (1985) reported δ^{15}N values in the red alder that were consistent with the results obtained in the present study. Studies carried out on other actinorhizal plants also yielded similar negative δ^{15}N with the corresponding high FNdfa values (Domench et al. 1989; Tjepkema et al. 2000). For example, Domench et al. (1989) reported that *Alnus incana* fixed 75% and *Alnus glutinosa* 97% of the N found in their leaves.

The δ^{15}N values measured in the reference plants at the site, however, showed consistently enriched values of ^{15}N in the samples of leaves, wood, and roots. This shows that the reference plants heavily depended on soil N, which is naturally enriched in ^{15}N, compared to atmospheric N (Shearer and Kohl 1993).

Table 3 Biomass of red alder

Treatment	Plant part	Unit	Value ± SE	kg ha^{-1}
Silvopasture	Leaf	kg tree^{-1}	1.06±0.20	424
Forestry			1.06±0.20	8,500
Silvopasture	Wood	kg tree^{-1}	21.25±5.31	2,650
Forestry			21.25±5.31	53,125
Silvopasture	Live root	kg m^{-3}	0.27±0.01	2,700
Forestry			0.54±0.03	5,400
Silvopasture	Dead root	kg m^{-3}	0.036±0.01	360
Forestry			0.079±0.01	790
Silvopasture	Live nodule	kg m^{-3}	0.088±0.03	880
Forestry			0.080±0.02	800
Silvopasture	Dead nodule	kg m^{-3}	0.052±0.03	520
Forestry			0.031±0.01	310

The results of the present study showed that $\delta^{15}N$ varied between seasons. $\delta^{15}N$ values for the summer and autumn seasons were negative for red alder indicating active N fixation during these periods. FNdfa values were 90 and 99% for summer and autumn, respectively. The average values of $\delta^{15}N$ for the winter and spring seasons were positive but close to zero in the red alder that indicate reduced N fixation during these periods. FNdfa values were 85 and 64% for winter and spring, respectively. Watt et al. (2003) reported $\delta^{15}N$ in broom (Cytisus scoparius L.) to be high with high temperatures during mid-summer and low in spring and winter with low temperatures. Nitrogen fixation estimates by the acetylene reduction assay method also showed that the mean nitrogenase activity in red alder nodules was high in summer and autumn when temperature and moisture regimes were favorable, and N fixing activity was significantly reduced in the winter periods, probably due to low temperature (Teklehaimanot and Martin 1999; Tripp et al. 1979). The daily measurement of acetylene reduction showed higher activities at midday, when temperatures were high, and lower values with declining temperatures at night (Tripp et al. 1979). Therefore, favorable environmental conditions such as available soil moisture, optimum temperature, and light regimes may be contributing to the high N fixation in summer and autumn in the red alder. Such conditions tend to favor plant metabolism, which in turn favors N fixation (Hawkins and McDonald 1993; Sayed et al. 1997). Sayed et al. (1997) found that optimal temperature for Frankia in Alnus spp was 25°C, and it performed very poorly at a higher temperature of 37°C.

The root nodules of the red alder showed enriched values of ^{15}N. The results of the present study are consistent with those reported by Tjepkema et al. (2000) who reported that the nodules of Alnus glutinosa were consistently enriched in ^{15}N relative to other plant parts. This may probably be due to polyamines that have been reported to be highly enriched in ^{15}N (Tjepkema et al. 2000).

The enriched $\delta^{15}N$ values (5.95‰) of soil were also consistent with those reported between 5.0 and 5.8‰ in forest soils by Kreibich and Kern (2000). Values of $\delta^{15}N$ as high as 10‰ were reported in soils in Kenya by Gathumbi et al. (2002). The enrichment of soils may be due to ammonia volatilization, denitrification during plant decomposition, plant uptake of NH_4^+ and NO_3^-, and NO_3 leaching. These processes tend to enrich the residual soil N with ^{15}N (Hogberg 1997; Piccolo et al. 1996).

The N content of the leaves was high, ranging from 2.39% in the red alder to 3.36% in the willow. Hurd et al. (2001) reported similar quantities of N in the leaves of Alnus incana. The wood samples yielded the lowest N content (less than 1%). This was expected, as wood is more ligneous than leaves and roots. The N content of the root

nodules of the red alder was 1.85% lower than the value of 3.28% reported for Alnus incana by Hurd et al. (2001). This may be due to the difference in species and age of trees.

The total fixed N accumulated in red alder trees was 65.55 and 334.14 kg ha^{-1} in silvopasture and forestry, respectively. This included N fixed in leaves, wood, and roots. By considering only leaves, as done in most of the studies on N fixation (Coté and Camire 1984; Sougoufara et al. 1990), the amount of N derived from the atmosphere in leaves was 9.22 and 57.63 kg N ha^{-1} in silvopasture and forestry, respectively. The values agree with that (53 kg N ha^{-1} in both mixed and pure stands of alder grown in Canada) reported by Coté and Camire (1984) and those (40–60 kg N ha^{-1} for Casuarina equisetifolia) reported by Sougoufara et al. (1990).

Nitrogen fixation by red alder was 30.95 and 117.84 kg ha^{-1} year^{-1} in silvopasture and forestry, respectively, thus, confirming what was reported (values ranged from 60 to 150 kg ha^{-1} year^{-1}) by Binkley et al. (1994) for red alder when N fixation was measured by acetylene reduction.

The potential contribution of red alder to the soil was 27.10- and 93.81-kg fixed N ha^{-1} year^{-1} in silvopasture and forestry systems, respectively. This contribution is comparable to values reported in the literature that ranged from 13- to 164-kg fixed N ha^{-1} year^{-1} (Berg and Dorksen 1975; Luken and Fonda 1983).

Although it has been reported that soil acidification occurs if N_2 fixation by red alder exceeds the capacity of the ecosystem to accumulate N (Cole et al. 1990), this may be advantageous because of the increased weathering of minerals resulting from acidification. Consequently, planting red alder can provide N and increases the level of nutrients in the soil. In conclusion, the results of the present study showed that red alder has a potential to improve and maintain soil fertility in a silvopastoral system, and thus, it can be considered a suitable tree species to be incorporated in a silvopastoral system.

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