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Carbon Sequestration in Rangelands Interseeded with Yellow-Flowering Alfalfa (*Medicago sativa* ssp. *falcata*)

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ABSTRACT / Management practices can significantly influence carbon sequestration by rangeland ecosystems. Grazing, burning, and fertilization have been shown to increase soil carbon storage in rangeland soils of the Great Plains. Research was initiated in 2001 in northwestern South Dakota to evaluate the role of interseeding a legume, *Medicago sativa* ssp. *falcata,* in northern mixed-grass rangelands on carbon sequestration. Sampling was undertaken on a chronosequence of sites interseeded in 1998, 1987, and 1965 as well as immediately adjacent untreated native rangeland sites. Soil organic carbon exhibited an increase of 4% in the 1998, 8% in the 1987, and 17% in the 1965 interseeding dates compared to their respective native untreated rangeland sites. Nitrogen fixation by the legume led to significant increases in total soil nitrogen and increased forage production in the interseeded treatments. Increases in organic carbon mass in this rangeland ecosystem can be attributed to the increase in soil organic carbon storage and the increased aboveground biomass resulting from the increased nitrogen in the ecosystem. The practice of interseeding adaptable cultivars of alfalfa into native rangelands may help in the mitigation of elevated atmospheric carbon dioxide and enhance the long-term sustainability of the ecosystem.

Grazing lands in the United States account for nearly 336 million hectares, which includes 161 million hectares of rangelands (NRCS 1994). A majority of these rangelands are in the Great Plains region of the United States and are generally used for livestock grazing. The livestock industry regularly seeks ways to increase productivity of these rangelands and to increase forage quality of the forage resource. Increased production allows for a portion of the forage resource to be grazed during the winter months; thereby reducing the need for supplemental feed. In land resource evaluations, the Natural Resources Conservation Service, US Department of Agriculture (NRCS, USDA) has stated that 67% of the native rangelands in the United States could benefit from improved management or restoration (NRCS 1998). Introduction of legumes into native rangelands in portions of the Great Plains has been a subject of study for numerous years (Berdahl and others 1989, Heinrichs 1975, Krueger and Vigil 1979, Tesar and Jakobs 1972, Waddington 1992). Heinrichs (1975) and Krueger and Vigil (1979) estimated that 70% of the native rangelands in North America were in fair to poor condition and that 10 million hectares of rangeland in Canada could benefit from the introduction of a legume. Nyren (1979) showed an increase in cattle live weight of 75 kg/ha on rangelands interseeded with alfalfa compared to untreated native rangelands. Inclusion of a legume in the forage mixture would significantly increase forage quality, not only from the higher crude protein content of the legume species but also through the increased quality of the native species present in the rangeland ecosystem. Sheehy (1989) stated that for native rangeland to be sustainable under grazing, nitrogen fixation rates of 41 kg N/ha/yr are necessary and recommended an alfalfa stand density of 20% to achieve this fixation rate. With repeated evidence highlighting the benefits of interseeding a legume into native rangelands, researchers continued to assess possible interseeding practices. However, the cultural practices studied were frequently unsuccessful, and even when legume establishment was achieved, reseeding was generally required every few years, making the practice uneconomical. The continued desire to enhance forage production, forage quality, and car-

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bon sequestration through management strategies on rangelands led us to establish research on the Smith Ranch near Lodgepole, in northwestern South Dakota, USA, where *Medicago sativa* ssp. *falcata,* hereafter referred to as alfalfa, had been successfully established on native rangelands for over 80 years. In the early 1900s, seed of this subspecies was brought to the United States from the cold steppe of Siberia and Mongolia and distributed to ranchers in this area of South Dakota. Some of this "falcata" was sown by Charles Smith on what is now the Smith Ranch and is still evident today (Smith 1997). The Smith Ranch has undertaken interseeding large areas of their rangelands with the yellow-flowering alfalfa for nearly 50 years. Therefore, the objectives of our research were to evaluate the effect of interseeding the alfalfa in northern mixed-grass rangelands on carbon sequestration, nitrogen fixation, and forage production.

Methods

The Smith Ranch, operated by the Norman "Bud" and Tim Smith families, is located in Perkins County, South Dakota. The ranch has an elevation ranging from 750 to 874 m, an annual average precipitation of 380 mm, a mean average temperature of 13.1°C, and summer frost-free period of 114 days. To evaluate the effect of the interseeded falcata alfalfa on the carbon balance of this rangeland ecosystem, we selected sites interseeded in 1998, 1987, and 1965. Soils at these sites were: 1998 interseeding was an Amor loam (fine, loamy, mixed, super active, frigid, Typic Haplustoll), 1987 interseeding was a Reeder loam (fine, loamy, mixed, super active, frigid, Typic Argiustoll), and the 1965 interseeding was a Vebar fine sandy loam (coarse, loamy, mixed, super active, frigid, Typic Haplustoll).

The alfalfa interseeding had been accomplished in the spring of each of the three years selected. Interseeding was done with a chisel plow equipped with 25 cm sweeps, spaced at 152 cm, to undercut the native sod and prepare an opening 5 cm deep and 15 cm wide. A seedbox placed directly behind the sweeps enabled the seed to be planted directly into the center of the furrow where the sod had been removed (Smith 1997). The interseedings were made on the contour of very shallow slopes. The 1998, 1987, and 1965 sites are generally east, north, and west facing aspects, respectively, with an untreated control located immediately adjacent to each interseeding date. Grazing is accomplished by yearlings, mature cows, and cow–calf pairs and a given pasture is only grazed once during a year. The 1965 pasture is grazed in early May by cow–calf pairs, the 1987 pasture is grazed during the winter (December–January), and the 1998 pasture is grazed in August or September.

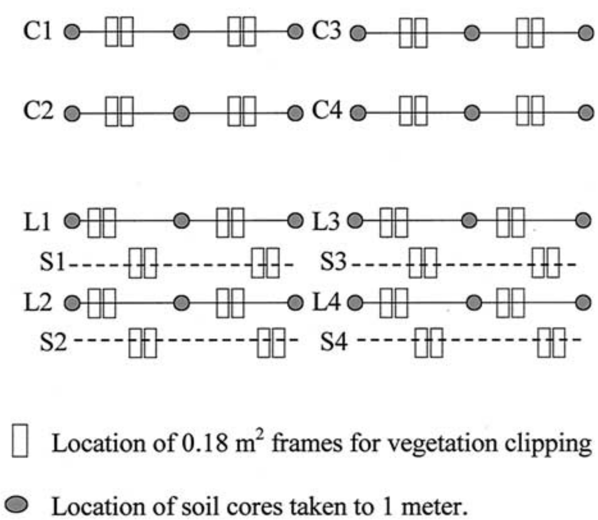

Figure 1. Field plot diagram showing experimental design (paired-plot) and sampling design on the native rangeland and interseeded rangeland, Lodgepole, South Dakota, USA. C, control transects; L, interseeded legume rows; S, interspace between interseeded rows.

In April 2001, four replications of each treatment (interseeded and control) were located on each interseeding date using a restricted completely randomized design. Randomization is restricted because these sites had been established years ago (Figure 1). Four 40-m transects were located in interseeded and control plots for each treatment date. In the interseeded treatment, the transect was located directly over the interseeded falcata alfalfa row. Soil samples were collected about 10 cm off of the seeded row at 0, 20, and 40 m locations on each transect and separated into depth increments of 0–5, 5–15, 15–30, 30–60, and 60–100 cm. Duplicate cores were obtained and combined at each site to ensure adequate soil was available for soil analyses. The samples were air-dried and ground to pass a 2-mm screen, and plant crowns and roots were removed through hand picking and air elutriation. Roots were washed to remove soil particles and dried at 60°C and weighed. Plant biomass was estimated by clipping four 0.18 m^2 quadrats located along each transect and four quadrats clipped in the interspace between the seeded rows. These quadrats were located in 1-m^2 exclosures to prevent livestock grazing. Vegetation was separated into the following growth forms: annual forbs, perennial forbs, alfalfa, C_3 grasses, C_4 grasses, other grasses (*Carex* sp., *Bromus inermus, Agropyron cristatum*), weedy grasses (*B. tectorum, B. japonica*), standing dead, and litter. Veg-

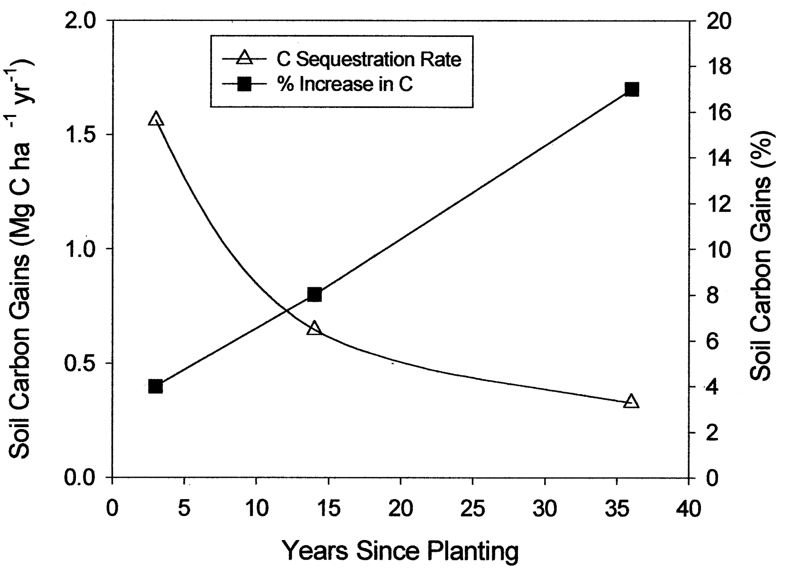

Figure 2. Carbon sequestration rates and percent carbon stock gains on falcata alfalfa interseeded rangeland after 4, 14, and 36 years, Lodgepole, South Dakota, USA.

etation samples were dried at 60°C and weighed to estimate plant biomass.

Plant material (root and aboveground) was ground to pass a 40-mesh screen using a Cyclo-Tech grinder and subsamples were then further ground on a roller grinder (100-mesh) and analyzed for total carbon and nitrogen. Soil samples for total carbon and nitrogen analyses were also ground on a roller grinder and both plant and soil samples analyzed using dry combustion methods by a Carlo-Erba C/N Analyzer (Nelson and Sommers 1982). Inorganic soil carbon was determined by a modified pressure-calcimeter method (Sherrod and others 2002) and subtracted from the total soil carbon to give total soil organic carbon. Root material was ashed to obtain an ash-free weight for the root material for calculating root carbon and nitrogen mass. Organic carbon and nitrogen concentrations of soil and plant material and respective biomass and soil bulk density were used to calculate carbon and nitrogen mass and assess system carbon and nitrogen balance.

Representative root biomass estimation is difficult using soil coring methods. The low soil moisture content during sampling prevented us from taking the desired 10-cm-diameter soil cores (we were only able to obtain 4.6 cm cores). Therefore, we used a root–shoot ratio of 27:1 as reported by Schuman and others (1999) from a similar northern mixed-grass prairie ecosystem to calculate root carbon and nitrogen contributions as well as a more conservative root–shoot ratio of 10:1 to estimate root carbon and nitrogen contributions. Sims and others (1978) reported root–shoot ratios from 2 to nearly 24 on rangelands in the Great Plains and southwest desert. They also reported that grazing generally increased the root–shoot ratio, indicating greater partitioning of photosynthates into the root systems.

Statistical analysis were accomplished using a completely randomized design with each treatment site being analyzed separately. Mean separation was carried out using Least Significant Difference procedures. All statistical analyses were evaluated at $P \leq 0.10$.

Results and Discussion

Alfalfa plant density was found to be similar within the interseeded row and within the row interspace for the 1987 and 1965 interseeding dates. Alfalfa plant density both within the row and interspace was 4.4 plants/m^2 for the 1987 interseeding date and 5.4 plants/m^2 within the row and 5.2 plants/m^2 within the interspace for the 1965 interseeding date. No alfalfa plants were observed within the interspace area in the 1998 interseeding date, indicating that three growing seasons after initial seeding was not adequate time for either vegetative or seed propagation of new plants between the seeded rows.

Soil organic carbon exhibited increases of 4% for the 1998, 8% for the 1987, and 17% for the 1965 interseeding date compared to their respective control plots for the 1-m soil profile depth (Figure 2). This increase in soil organic carbon was linear over the 36-year time period. Soil organic carbon mass for the 1-m soil depth was not significantly different in the interseeded treatments compared to the control plots for the 1998 and 1987 interseeding dates (Table 1). Soil carbon sequestration was significantly greater in the 1965 interseeding date for the 1-m soil profile com-

Table 1. Carbon mass associated with vegetation components, soil, and ecosystem on native rangelands and falcata alfalfa interseeded rangelands for 1965, 1987, and 1998 treatment dates

	C (MT/ha)					
	1965		1987		1998	
System component	Interseeded	Control	Interseeded	Control	Interseeded	Control
Live vegetation	1.34a[c]	0.81b	1.30a	0.51b	1.07a	0.74b
Total vegetation	2.37a	1.57b	2.79a	0.74b	2.10a	1.51b
Root						
27:1[a]	44.79a	24.04b	38.33a	15.55b	40.87a	22.96b
10:1[b]	16.59a	8.91b	14.2a	5.76b	15.14a	8.50b
Soil						
0–30 cm	41.8a	37.7a	59.7a	49.0b	58.0a	47.9b
0–100 cm	81.6a	69.8b	120.3a	111.2a	112.5a	107.8a
Ecosystem						
0–100 cm[a]	128.7a	95.4b	161.4a	127.5b	155.5a	132.3b
0–100 cm[b]	100.54a	80.23b	137.27a	117.71b	129.75a	117.83a

[a]Root–shoot ratio of 27:1 used to calculate root carbon mass (Schuman and others 1999).
[b]Root–shoot ratio of 10:1 used to calculate root carbon mass ratio generally cited by plant scientists.
[c]Means within a treatment year between interseeded and control treatment with different lower case letters are significantly different, $P \leq 0.10$.

Table 2. Nitrogen mass associated with vegetation components, soil and ecosystem on native rangelands and falcata alfalfa interseeded rangelands for 1965, 1987, and 1998 treatment dates

	N (MT/ha)					
	1965		1987		1998	
System component	Interseeded	Control	Interseeded	Control	Interseeded	Control
Live Vegetation	0.064a[c]	0.026b	0.064a	0.016b	0.045a	0.024b
Total Vegetation	0.109a	0.051b	0.102a	0.021b	0.081a	0.048b
Root						
27:1[a]	1.371a	0.545b	0.834a	0.280b	1.014a	0.530b
10:1[b]	0.508a	0.202b	0.309a	0.104b	0.375a	0.196b
Soil						
0–30 cm	4.10a	3.19b	5.60a	4.66b	5.57a	4.26b
0–100 cm	8.49 a	5.61 b	11.61 a	10.99 a	11.35 a	9.90 b
Ecosystem						
0–100 cm[a]	9.97a	6.21b	12.55a	11.29b	12.44a	10.48b
0–100 cm[b]	9.10a	5.87b	12.03a	11.11a	11.81a	10.15b

[a]Root:shoot ratio used to calculate root nitrogen mass (Schuman and others 1999).
[b]Root:shoot ratio of 10:1 used to calculate root carbon mass ratio generally cited by plant scientists.
[c]Means within a treatment year between interseeded and control treatment with different lowercase letters are significantly different, $P \leq 0.10$.

pared to its control. While we expected the 1998 interseeding to not have had adequate time to exhibit a significant increase in carbon sequestration, we did expect the 1987 interseeding treatment to exhibit a difference after 14 years due to the fact that a uniform stand density of alfalfa had developed. However, the 1998 and 1987 interseeding dates did exhibit a significant increase in soil carbon mass in the 0- to 30-cm soil depth. The lack of significant difference in the organic carbon of the 1-m soil profile for the 1987 interseeding date may be attributable to the large soil variance exhibited in rangeland ecosystems and may also be partially explained by the lack of a difference in soil total nitrogen (Table 2). Differences in soil organic carbon were in the 60- to 100-cm soil depth on the 1965 interseeding. However, major differences occurred in the surface 30 cm in the 1987 and 1998 interseeding dates compared to their respective native rangeland sites, indicating that these two interseeding dates had not had time to sequester significant amounts of carbon in the lower portions of the soil profile. Live and total aboveground biomass carbon, root biomass carbon,

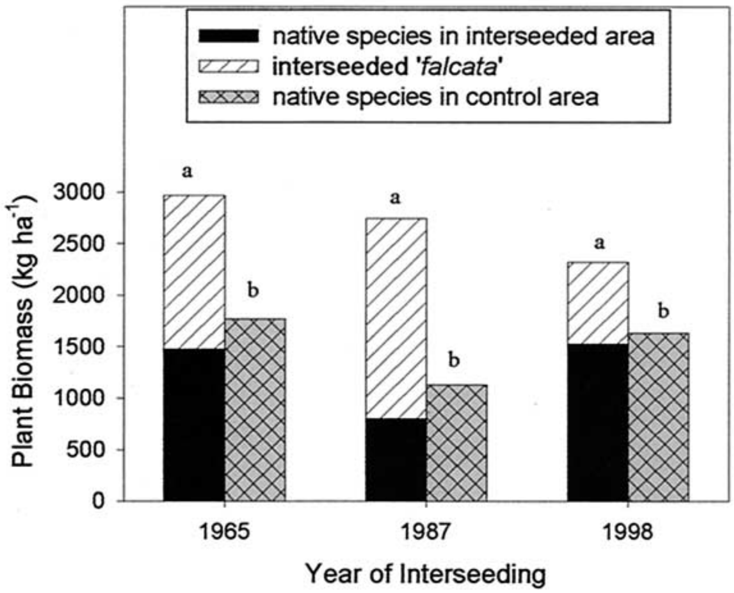

Figure 3. Forage production on native rangeland control and interseeded treatments for the 1965, 1987, and 1998 treatment year, Lodgepole, South Dakota, USA. Means within a treatment year with different lowercase letters are significantly different, $P \leq 0.10$.

and ecosystem carbon were all significantly greater where alfalfa had been interseeded into the rangeland compared to their respective control sites. Soil organic carbon represented 60%–75% of the ecosystem carbon mass highlighting the importance of the soil organic carbon component of these systems, whether supplemented by the legume or native rangeland where no pertubations have been imposed. It is also important to point out the significant contribution represented by the root carbon mass in these rangelands systems.

Carbon sequestration rates were 1.56 MT/ha/yr after 4 years, 0.65 MT/ha/yr after 14 years and 0.33 MT/ha/yr after 36 years (Figure 2). These data demonstrate that carbon sequestration rates will be greater immediately after a management treatment is imposed because of the lower inherent soil carbon levels, added nitrogen levels, and a simple gradient response. The sequestration rate will reach an equilibrium with respect to soil carbon in response to any management change or system input such as fertilizer. However, these findings stress the importance of reporting the lapsed time since a management strategy or system input was initiated when calculating carbon sequestration rates from field data because it would be very easy to overestimate carbon sequestration if the system had not been in place at least 20 years.

Since both the control and interseeded rangeland areas for a given site were grazed by cattle for the same length of time the observed differences in carbon sequestration are a result only of the benefits attributable to the addition of the legume into the ecosystem. Therefore, to assess the full benefit of good grazing management and the addition of the legume in this rangeland ecosystem it would seem appropriate to include the increased carbon sequestration (0.30 MT/ha/yr) that Schuman and others (1999, 2001) reported due to grazing of a northern mixed-grass rangeland. Hence, the total carbon sequestration potential for these northern mixed-grass rangelands could be as much as 0.63 MT/ha/yr for the 1965 interseeding date if these two management strategies (grazing and interseeding of a legume) produce an additive affect.

The vegetation response to the nitrogen fixed by the alfalfa and the production from the alfalfa itself was dramatic (Figure 3) and accounts for 14%–36% of the ecosystem carbon mass. Live and total aboveground biomass (includes litter and standing dead) carbon was significantly greater in the interseeded legume treatments compared to the native range for all three interseeding dates. Root carbon mass was significantly greater, regardless of whether the 27:1 or 10:1 root–shoot ratio was used, in the interseeded treatments compared to the native rangelands for all three interseeding dates. Carbon mass in the ecosystem (aboveground biomass, roots, and soil), to a depth of 1 m, was significantly greater in the interseeded treatments compared to their respective native rangeland controls. These data clearly demonstrate the benefit of interseeding a legume into these mixed-grass rangelands as it relates to carbon sequestration potential.

To aid our understanding of these systems we also assessed ecosystem total nitrogen. Total soil nitrogen was significantly increased by the interseeded alfalfa in the 1965 and 1998 treatment sites (Table 2). The fact

Table 3. C:N ratio of system components on native rangelands and falcata alfalfa interseeded rangelands for 1965, 1987, and 1998 treatment dates.

	C:N ratio					
	1965		1987		1998	
System component	Interseeded	Control	Interseeded	Control	Interseeded	Control
Litter	22:1	27:1	26:1	43:1	27:1	28:1
Live Vegetation	21:1	31:1	20:1	32:1	24:1	31:1
Total Vegetation	22:1	31:1	27:1	35:1	26:1	31:1
Root	33:1	44:1	46:1	56:1	40:1	43:1
Soil (100 cm)	10:1	12:1	10:1	10:1	10:1	11:1
Ecosystem	13:1	15:1	13:1	11:1	13:1	13:1

that soil nitrogen was not statistically different between the 1987 interseeded site and its control may also help explain why we did not observe significant soil carbon mass differences on that site. Aboveground biomass nitrogen, root nitrogen mass, and ecosystem nitrogen mass (27:1 root–shoot ratio) were significantly greater in the interseeded treatments compared to their respective rangeland control treatments. However, when we used the 10:1 root–shoot ratio in our calculations, the ecosystem nitrogen mass was not significantly different between the interseeded and control treatments in the 1987 interseeding date.

The C:N ratios of the litter, live aboveground biomass, and total aboveground biomass strongly reflect the addition of nitrogen to the system through nitrogen fixation by the alfalfa (Table 3). The C:N ratios of the vegetative components of the system were 20%–30% lower for the interseeded treatments. This reduction in the C:N ratio of these vegetative components would indicate a greater rate of decomposition/turnover in the interseeded treatments compared to the vegetative components in the native rangeland sites. Soil and ecosystem C:N ratios were fairly constant and uniform across all three treatment dates and interseeded vs native treatments.

Interseeding alfalfa into native rangelands, where feasible and adaptable, can be an excellent management practice for long-term carbon sequestration. Rangelands in the Great Plains are generally deficient in nitrogen (Power and Alessi 1971). Our results show that nitrogen fixed by interseeding legumes significantly enhances the nitrogen status of the rangeland ecosystem, which should result in increased microbial activity and water use efficiency, all of which will enhance the overall productivity and nutrient cycling capacity of the system. The results of this research have allowed us to assess carbon sequestration in a similar soil and climatic environment using various age chronologies and, moreover, have elucidated the importance of time in determining the rate of sequestration. Establishment of a legume in this northern mixed-grass rangeland ecosystem has enhanced soil nitrogen, which has resulted in increased carbon sequestration, and it indicates that sequestration will continue at a rather constant rate for the next 35 years or longer. These results have demonstrated a rangeland practice that can be utilized to increase forage productivity and forage quality, which has the potential to reduce supplemental winter forage inputs for the rancher. Based upon the characteristics of falcata alfalfa it should be adaptable to interseeding in rangelands where annual precipitation is greater than 275 mm and grazing is practiced on a rotational basis. Native legumes may also be available that can be used to achieve these same goals; however, little is known about their potential nitrogen fixation rates and seedbed ecology when interseeded into native rangelands.

Rangelands have typically not been considered an important component for potential carbon sequestration because scientists have stated that they are at an equilibrium and are “full” of carbon and have little potential to store additional carbon. However, this research and numerous other studies have demonstrated that rangeland management practices such as fertilizing, burning, and grazing can result in significant carbon sequestration (Schuman and others 2002). Carbon dioxide flux data collected over 6 years on a northern mixed-grass rangeland site have also demonstrated the potential (0.29 MT CO_2-C/ha/yr), for rangelands to sequester carbon (Frank 2003). The sequestration rates may seem low but one must keep in mind that the potential is large because of the large land area that rangelands represent in the United States; 336 million hectares.

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