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DECOMPOSITION OF TALL FESCUE (*FESTUCA ELATIOR* var. *ARUNDINACEA*) AND CELLULOSE LITTER ON SURFACE MINES AND A TALLGRASS PRAIRIE IN CENTRAL MISSOURI, U.S.A.

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SUMMARY

(1) Decomposition of ^{14}C-labelled and unlabelled fescue, and of pure cellulose litter on non-vegetated and vegetated coal surface mine spoils and on a tailgrass prairie soil in central Missouri, U.S.A. was examined.

(2) Losses of ash-free mass, ^{14}C, nitrogen, and phosphorus from decomposing fescue litter were better described by double exponential decay equations than by single exponential decay equations.

(3) Compared to other studies of litter decomposition in temperate grasslands, losses of ash-free mass from fescue litter were rapid. In addition, ^{14}C-labelled fescue litter (initial C : N = 14·2) decomposed more rapidly than unlabelled fescue litter (initial C : N = 25·9), reflecting the influence of initial nitrogen content on decomposition.

(4) Decomposition of fescue and cellulose litter on non-vegetated mine sites was slow, probably because of low exogenous nitrogen inputs and harsh environmental conditions that characterize barren spoil.

(5) Regression models of remaining ash-free mass as a function of C : N, C : P, and N : P ratios increased progressively in complexity from non-vegetated mine to vegetated mine to tallgrass prairie sites, reflecting differences in the structure and function of the decomposer communities among the three sites.

(6) Significantly less ash-free mass, ^{14}C, and nitrogen was lost from fescue situated over very acidic (pH $\leq$ 4·5) spoil than from fescue situated over moderately acidic (pH $\geq$ 5·0) spoil. However, the transfer of ^{14}C from decomposing litter to the spoil directly below was unaffected by either spoil pH or by the presence or absence of vegetation, and its magnitude was comparable to similar studies conducted on unmined soils.

(7) Our results suggest that current reclamation practices, such as liming, fertilization, and mulching, could have conflicting effects on organic matter accumulation and nitrogen and phosphorus dynamics in surface mine spoils.

INTRODUCTION

Surface mining so drastically alters both the physical and chemical properties of soil that natural recovery of unamended spoil is a very slow process (Croxton 1928; Byrnes & Miller 1973; Down 1975a, b; Riley 1975; Richardson 1976; Bradshaw & Chadwick 1980; Roberts *et al.* 1981; Marrs *et al.* 1981). Most studies of surface mine ecology continue to focus on vegetation and soils apart from plant litter decomposition. But many features of restored mineland ecosystems, like those of undisturbed ones, depend on processes accomplished by decomposition subsystems. Specifically, the balance between plant litter deposition and decomposition controls the accumulation of detrital organic matter within

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the ecosystem (Olson 1963). Decomposition also plays an important role in the internal cycling of nutrients within an ecosystem (Swift, Heal & Anderson 1979). Thus, it is the process of plant litter decomposition that ultimately links plant production to most long-term changes in the physical and chemical properties of mine spoil (Roberts *et al.* 1981; Marrs *et al.* 1981).

This report examines plant litter and cellulose decomposition on surface coal mines and, as a reference, on a tallgrass prairie in central Missouri, U.S.A. Unlike most previous studies of grass litter decomposition on mined sites (Lawrey 1977; Lanning & Williams 1979, 1980; Miller & May 1981), we have quantified loss of mass as well as changes in the nitrogen and phosphorus content of decomposing litter. ^{14}C-labelled plant litter was used to examine the transfer of organic carbon from litter to soil. Our results are considered in relation to the potential effects of current reclamation practices on organic matter degradation and nitrogen and phosphorus cycling in mineland ecosystems.

THE STUDY AREAS

^{14}C-labelled fescue litter experiments

Decomposition of ^{14}C-labelled fescue litter was studied on four small (5–15 ha), derelict surface mines clustered in northwest Callaway County, Missouri (38°59′N, 92°06′W). The mines, abandoned between 1938 and 1959, have never been seeded or graded. The characteristic topography of the sites consists of parallel ridges alternating with valleys connected with generally steep, long slopes. Natural vegetation is sparse and occurs in discrete patches surrounded by barren spoil (Game, Carrel & Hotrabhavandra 1982). DeMott (1978) estimated that between 23 and 65% of each site is covered by vegetation. The dominant herbaceous and tree species are yellow sweet clover, *Melilotus officinalis*,* and river birch, *Betula nigra*, respectively. A more complete floristic description of the sites is given by Weems (1979). There is almost no topsoil and no evidence of horizontal soil stratification. The uppermost 5 cm of spoil is low in organic matter (less than 2% of dry mass) and is acidic (average pH 4·2 in barren spoil and 5·3 under vegetation).

Unlabelled fescue and cellulose experiments

Reclaimed surface mine

Decomposition of unlabelled fescue and cellulose was studied on a surface mine in northeast Boone County, Missouri (39°00′N, 92°09′W). The 15 ha site was mined in 1970, and in 1971 ridge tops were partially graded into valleys to form benches, thereby reducing the extent of steep slopes. No topsoil was replaced over the graded spoil. A mixture of alfalfa, *Medicago sativa*, tall fescue, *Festuca elatior* var. *arundinacea*, orchard grass, *Dactylis glomerata*, lespedeza, *Lespedeza stipulacea*, and yellow sweet clover, *Melilotus officinalis*, at the rate of 50 kg ha^{-1} (5 : 5 : 2 : 2 : 2) was aerially seeded in 1972 on the raw spoil. A floristic survey in 1977 (Weems 1979) showed that eleven herbaceous species cover about 45% of the mine surface. Tall fescue and alfalfa dominate the vegetation, accounting together for 91% of the standing crop. The acidity of spoil at this Boone County site is less than at the four Callaway County sites, 5 km to the east; pH of the upper 5 cm of spoil is 4·8 in barren areas and 5·7 in vegetated areas.

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* Nomenclature follows Steyermark (1977).

Tallgrass prairie

Decomposition of unlabelled litter was also studied at Tucker Prairie Research Station, a 58 ha tract of unploughed tallgrass prairie in Callaway County, Missouri (38°56′N, 91°58′W). The terrain is flat to gently sloping. Principal grass species are big bluestem, *Andropogon gerardi*, little bluestem, *A. scoparius*, Indiangrass, *Sorghastrum nutans*, and prairie dropseed, *Sporobolus heterolepis* (Kucera, Dahlman & Koelling 1967). The soil consists of fine loess overlying glacial till. The A horizon is a dark silt loam having approximately 8% organic matter. A claypan B_2 horizon, extending from 40 to 75 cm below the surface, retards internal drainage so that in late winter and early spring the soil is often water-logged.

Climatological data

Data from a national weather station at Columbia Regional Airport, 25 km southeast of the study sites were used to characterize macroclimatic conditions. The 30 year mean annual air temperature is 12·8 °C, with a maximum monthly mean of 25·5 °C in July and a minimum monthly mean of −0·9 °C in January. Mean annual precipitation is 95 cm, about half of which falls from April through August. Evapotranspirational deficits during the growing season were moderate in 1978 and 1979, but they were severe in 1976 and 1980 because of subnormal rainfall and supranormal temperature. In 1977 temperature, precipitation, and soil moisture were normal and growing conditions were considered good.

EXPERIMENTAL DESIGN

^{14}C-labelled fescue litter

Tall fescue, *Festuca elatior* var. *arundinacea*, was grown from seed in a 30 m^2 greenhouse bed. Labelling was accomplished by exposing young, actively growing vegetation to $^{14}CO_2$ under a polyethylene tent (Dahlman 1967; Dahlman & Kucera 1968, 1969). To obtain a uniform distribution of labelled carbon in individual plants, seven labelling treatments were carried out over a 7-week period as described by Wieder & Carrel (1979). Two days after the final labelling treatment, above-ground biomass was harvested and oven-dried at 70 °C for 24 h. Two hundred and eighty-eight litter bags, 10 × 10 cm, were constructed from 1·6 mm mesh aluminium screening. Each litter bag was filled with 5 g of dried grass leaves. The potential problem of variation in the initial ^{14}C content of fescue was minimized by mixing 20–30 g batches of dried grass and preparing three to five litter bags from each batch. Several grams of fescue from each batch were retained in a 5 °C cold room to serve as reference standards.

On 15 May 1976, litter bags were set out in the four abandoned surface mines in Callaway County, Missouri. Because of the disjunct distribution of the vegetation, three patches of herbaceous vegetation were selected in each of the four mines. At each patch, twelve litter bags were placed directly on the barren spoil about 1 m outside the patch perimeter and twelve litter bags were placed on the spoil under cover of vegetation about 1 m inside the patch perimeter. Litter bags were anchored with 10 cm long nails.

Twenty-four litter bags were collected quarterly from 1 July 1976 to 1 January 1978, except on 1 January 1977 when only eighteen were retrieved because of the inaccessibility of one mine due to snow. At each sampling date, two bags were collected from each of the twelve patches, one bag from the non-vegetated region and one bag from the vegetated region.

A soil core, 2 cm in diameter and 5 cm deep, was taken from directly beneath each retrieved litter bag. Soils were oven-dried, ground with a mortar and pestle, and analysed for pH and ^{14}C content. To convert ^{14}C activity of the top 5 cm of spoil (μCi/g spoil) to the total amount of ^{14}C within the 500 cm^3 of spoil beneath each litter bag, bulk densities of different spoils were needed. In the spring of 1978, bulk density of the top 5 cm of spoil was determined in eighteen soil cores collected from non-vegetated regions and eighteen soil cores collected from vegetated regions of the study areas.

Unlabelled fescue and cellulose litter

Tall fescue, *Festuca elatior* var. *arundinacea*, was harvested in autumn 1977 from the partially reclaimed surface mine in Boone County. After oven-drying the fescue, 600 litter bags were each filled with 5 g of leaf material. Also, 600 additional litter bags were each filled with 5 g of pure cellulose (Whatman No. 42, ashless filter paper) that had been shredded into 0·5 cm wide strips to simulate blades of grass.

On 5 December 1977, fescue and cellulose litter bags were set out in the field. For each litter type, one third of the bags was placed on the spoil surface at 1 m intervals along a transect on a barren bench top and one third was similarly spaced on another bench under the cover of *F. elatior* var. *arundinacea* at the partially reclaimed surface mine in Boone County. The remaining one third was placed on the soil surface at 1 m intervals in a 12 × 34 m grid under cover of native grasses at the Tucker Prairie Research Station. At ten dates over the following 27 months, twelve fescue and twelve cellulose litter bags were retrieved from each of the three sites.

ANALYTICAL METHODS

Ash-free mass determination

Retrieved litter bags were oven-dried at 70 °C for 24 h. Litter, especially from non-vegetated mine sites, often was heavily contaminated with clay, which was removed by careful rinsing with tap water over a standard number 35 soil sieve. For ^{14}C-labelled fescue samples this method became unsuitable as decomposition proceeded because the litter became increasingly friable and could pass through the soil sieve. Beginning with the 1 October 1977 collection, ^{14}C-labelled litter was separated from clay by ethanol flotation and subsequent filtration of the litter-ethanol fraction. After either procedure, cleaned litter was redried and weighed.

Fescue samples were ground to pass a 2 mm mesh screen and cellulose samples were cut with scissors into $<0{\cdot}5$ cm^2 pieces. A 0·3–0·8 g subsample from each retrieved fescue or cellulose litter sample was combusted in a covered porcelain crucible at 600 °C for 24 h, and the mass of the residual ash was determined. Ash content was also determined for seventy-two reference subsamples of ^{14}C-labelled fescue and sixty-nine reference subsamples of unlabelled fescue. Carbon content was calculated by assuming that organic matter consists of 56% carbon (Kirkham 1970). All mass data are presented on an ash-free basis.

^{14}C determination

All ^{14}C measurements were made with a Picker gas flow proportional detector using the procedures of O'Brien & Wardlaw (1961), Dahlman & Kucera (1968), and Kirkham (1970). From each retrieved fescue sample and from each of seventy-eight reference standards, three 100 mg subsamples were each counted for 3 min. Percent ^{14}C remaining was determined by comparing the ^{14}C content of retrieved litter to that of its appropriate reference standard. Three 1 g subsamples from each soil core collected from beneath a litter bag were each counted for 1 min.

Nitrogen and phosphorus determination

^{14}C-labelled fescue was analysed for total nitrogen using the Kjeldahl digestion procedure of Gallaher, Weldon & Futral (1975) modified by adding 5 ml instead of 4 ml of concentrated sulphuric acid to ensure adequate refluxing. One 100 mg subsample from each retrieved litter sample and from each of sixty-nine reference standards was digested. Ammonia in digests was quantified with an Orion ammonia electrode and the semi-automated procedure of Gallaher, Weldon & Boswell (1976). Ten ml of digest were mixed with 50 ml of 1·5 M NaOH, rather than 50 ml of 0·5 M NaOH as suggested by Gallaher, Weldon & Boswell (1976), because the stronger base produced rapid and repeatable responses in both standard and digested solutions. Phosphorus was not determined in ^{14}C-labelled fescue.

Unlabelled fescue was digested (standard Kjeldahl) and analysed for total nitrogen and total phosphorus using the colorimetric ammonia-salicylate and phosphomolybdenum methods, respectively, on a Technicon AutoAnalyser (Technicon Industrial Systems 1977). One 0·2 g subsample from each retrieved litter sample and twenty-two 0·2 g subsamples of reference standards were analysed. The accuracy of these determinations was verified by simultaneously analysing standard plant tissue obtained from the U.S. National Bureau of Standards.

Leachability estimation

To evaluate the potential loss of litter components through leaching, ten 1·0 g samples of ^{14}C-labelled fescue reference material were each mixed with 200 ml distilled water for 10 h, rinsed with 200 ml distilled water, and filtered. Fescue retained on the filter was oven-dried at 70 °C for 24 h, weighed, and subsequently analysed for ash-free mass, ^{14}C, and nitrogen as described above. Leaching losses were calculated by subtracting these results from those obtained for unleached fescue reference standards.

Soil pH

Soil pH values were determined by mixing equal volumes of ground soil and distilled water and allowing the mixtures to stand for 4 h. pH was determined to the nearest 0·5 units using EM Laboratories 3-colour indicator strips.

Statistical procedures

The two-way analysis of variance, usually with the effects of date and site and a date-by-site interaction, was extensively used. If a significant site effect was obtained, pairwise comparisons were made between site means at each sampling date using the least significant difference (L.S.D.) procedure (Snedecor & Cochran 1973). Comparisons among dates for each site are not indicated in any of the data tables but L.S.D. values (based on sample sizes of twelve) are given so that such comparisons can be made. In addition, if a significant site effect was accompanied by a non-significant interaction, average overall differences between sites were calculated and are given in the text.

Observed losses of ash-free mass, ^{14}C, nitrogen, and phosphorus from decomposing fescue litter were described by both single exponential,

$$\frac{X_t}{X_0} = e^{-k_1 t}$$

and double exponential,

$$\frac{X_t}{X_0} = A\,e^{-k_2 t} + (1 - A)\,e^{-k_3 t},$$

decay functions, where X_t/X_0 is the proportion of initial material remaining at time t, the ks are decay constants, A is the relatively labile proportion of initial material, and $(1 - A)$ is the relatively recalcitrant portion of initial material. Only single exponential decay functions were fitted to the loss of ash-free mass from decomposing cellulose litter. Untransformed data and nonlinear least squares procedures (PROC SYSNLIN, SAS-ETS 1980) were used. Single exponential fits were obtained using ordinary nonlinear least squares estimation. For each variable, double exponential fits were obtained simultaneously for the two or three sites involved with the restriction that for a particular litter type the initial proportion of A to $(1 - A)$ was the same regardless of site. Double exponential fits were obtained using nonlinear joint generalized least squares estimation. Estimates for the decay constants (ks) were not allowed to be negative.

Because for both single and double exponential decay functions the y-intercept is fixed such that at time zero all of the initial material is present, r^2 values do not always fall between 0 and 1 and thus provide undesirable measures of goodness of fit (cf. Wieder & Lang 1982). For all of the exponential fits in this paper, it was assumed that for each litter type in each site, twelve litter bags were retrieved at time zero, each containing 100% of its initial material. The inclusion of these time zero data had no effect on the parameter estimates, but allowed for the assessment of goodness of fit by calculating a proportion of variance explained, R^2, as

$$R^2 = \frac{\text{Corrected total sum of squares} - \text{Error sum of squares}}{\text{Corrected total sum of squares}}.$$

In all instances, these R^2 values fell between 0 and 1.

RESULTS

^{14}C-*labelled fescue litter*

Loss of mass

Loss of ash-free mass was 8·8% less overall in litter retrieved from non-vegetated mine sites than from vegetated mine sites. Pairwise comparisons showed that for the first 13·5 months differences in ash-free mass between sites were significant. Thereafter, site differences were relatively small and not significant (Table 1).

For both sites, based on a comparison of R^2 values, double exponential decay functions described the loss of ash-free mass better than single exponential decay functions (Table 2). The double exponential equations indicated that 54·2% of the ash-free mass of the fescue was relatively labile. Since only 17% of the ash-free mass of fescue reference standards was lost by cold water extraction, leachable compounds accounted for only 31% of the labile

TABLE 1. Decomposition of ^{14}C-labelled fescue litter. Values are means ± S.E.; $n = 12$ except at 7·5 months where $n = 9$. Beneath each column, P values associated with an analysis of variance (ANOVA), and L.S.D. values are given. Within each column, an asterisk indicates that the two site means are statistically different ($P = 0·05$) at a particular sampling date

		Percent of initial amount remaining			Characteristics of retrieved litter		
Months elapsed	Site	Ash-free mass	^{14}C	Nitrogen	Percent ash	$\frac{\mu Ci^{14}C}{gC}$	C:N
0 = 15 May 1976	—	100	100	100	17·6 ± 0·3	1·95 ± 0·14	14·2 ± 0·4
1·5	Non-vegetated mine	72·8 ± 2·1*	59·8 ± 1·8*	46·4 ± 2·0	18·6 ± 1·6	1·78 ± 0·10	23·6 ± 0·7
	Vegetated mine	63·0 ± 3·2	52·7 ± 2·8	41·4 ± 1·8	13·2 ± 2·4	1·89 ± 0·08	21·9 ± 1·0
4·5	Non-vegetated mine	49·3 ± 3·7*	45·9 ± 2·7*	37·3 ± 2·6	38·3 ± 3·5*	1·96 ± 0·13	18·7 ± 0·9
	Vegetated mine	38·8 ± 2·0	33·5 ± 2·2	33·8 ± 2·0	25·0 ± 3·9	1·87 ± 0·11	16·9 ± 0·5
7·5	Non-vegetated mine	46·3 ± 2·9*	43·6 ± 2·6*	42·1 ± 3·2*	39·9 ± 3·3*	2·15 ± 0·15	16·0 ± 0·5
	Vegetated mine	29·8 ± 1·9	25·6 ± 2·9	30·4 ± 2·6	26·5 ± 4·5	1·85 ± 0·06	14·7 ± 0·3
10·5	Non-vegetated mine	38·7 ± 2·3*	43·6 ± 2·9*	37·5 ± 2·2	47·7 ± 2·1*	2·20 ± 0·12	14·6 ± 0·6
	Vegetated mine	31·2 ± 1·1	29·9 ± 2·7	30·8 ± 1·6	32·4 ± 4·7	1·91 ± 0·13	14·9 ± 0·5
13·5	Non-vegetated mine	32·3 ± 3·8*	33·7 ± 3·6*	31·0 ± 5·3*	54·9 ± 3·9*	2·27 ± 0·16*	16·4 ± 1·3*
	Vegetated mine	21·2 ± 1·3	18·7 ± 2·4	23·4 ± 2·3	43·1 ± 2·2	1·75 ± 0·15	13·3 ± 0·3
16·5	Non-vegetated mine	25·5 ± 2·1	25·2 ± 2·4*	25·7 ± 2·5	61·3 ± 2·8*	1·97 ± 0·09*	13·7 ± 1·3
	Vegetated mine	21·5 ± 1·0	14·2 ± 1·0	24·2 ± 1·0	51·4 ± 3·8	1·44 ± 0·07	13·0 ± 0·3
19·5	Non-vegetated mine	23·6 ± 1·5	20·2 ± 1·7*	24·7 ± 1·7	59·7 ± 2·4*	1·79 ± 0·14*	13·5 ± 0·5
	Vegetated mine	19·8 ± 0·7	12·6 ± 0·8	21·6 ± 0·8	44·5 ± 2·5	1·40 ± 0·08	13·6 ± 0·2
ANOVA P values	Site	0·0001	0·0001	0·0001	0·0001	0·0001	0·0001
	Date	0·0001	0·0001	0·0001	0·0001	0·0001	0·0033
	Site × Date	0·1170	0·5117	0·7129	0·7220	0·0624	0·2589
L.S.D. (0·05)		6·3	6·8	6·8	8·8	0·32	2·03

TABLE 2. Single and double exponential decay parameters describing the decomposition of fescue and cellulose litter. $T_{\frac{1}{2}}$ values for the double exponential fits indicate the time (months) in which half of the initial material is lost from litter. Because $T_{\frac{1}{2}}$ values for the single exponential fits can be easily calculated $(T_{\frac{1}{2}} = 0{\cdot}693/k_1 \times 12)$ they are not provided

	Single exponential functions		Double exponential functions				
	k_1 (y^{-1})	R^2	A (%)	k_2 (y^{-1})	k_3 (y^{-1})	R^2	$T_{\frac{1}{2}}$ (months)
^{14}C-labelled fescue litter							
Ash-free mass loss							
Non-vegetated mine	1·16	0·79	54·2	4·41	0·35	0·89	4·8
Vegetated mine	1·68	0·78	54·2	8·22	0·56	0·96	2·7
^{14}C loss							
Non-vegetated mine	1·20	0·65	44·3	14·21	0·49	0·88	3·2
Vegetated mine	2·11	0·75	44·3	21·01	0·96	0·93	1·8
Nitrogen loss							
Non-vegetated mine	1·38	0·36	58·5	17·96	0·26	0·85	1·2
Vegetated mine	1·85	0·43	58·5	27·00	0·41	0·95	0·8
Unlabelled fescue litter							
Ash-free mass loss							
Non-vegetated mine	0.56	0·75	59·8	1·65	0	0·88	13·2
Vegetated mine	1·31	0·86	59·8	3·31	0·33	0·95	5·0
Tallgrass prairie	1·08	0·88	59·8	2·54	0·31	0·93	6·3
Nitrogen loss							
Non-vegetated mine	0.77	0·60	46·4	4·26	0·08	0·90	12·3
Vegetated mine	0·92	0·74	46·4	4·28	0·21	0·93	7·6
Tallgrass prairie	1·37	0·40	46·4	20·99	0·40	0·86	2·5
Phosphorus loss							
Non-vegetated mine	1·04	0·51	51·7	5·44	0·14	0·81	5·3
Vegetated mine	1·43	0·88	51·7	2·36	0·85	0·89	5·5
Tallgrass prairie	4·26	0·64	51·7	63·43	1·34	0·86	0·5
Unlabelled cellulose litter							
Ash-free mass loss							
Non-vegetated mine	0·06	0·40	—	—	—	—	—
Vegetated mine	0·75	0·79	—	—	—	—	—
Tallgrass prairie	0·25	0·36	—	—	—	—	—

fraction. The remaining 69% of the labile ash-free mass function must have been present as non-leachable, but easily decomposed organic materials.

^{14}C *in litter and soil*

At each sampling date, significantly more ^{14}C remained in litter from non-vegetated mine sites than vegetated mine sites (Table 1). The average difference in ^{14}C between the sites was 11·6%.

For both sites, double exponential decay functions described ^{14}C loss from litter better than single exponential decay functions (Table 2). The double exponential equations indicated that 44·3% of the initial ^{14}C in fescue litter resided in relatively labile materials. Because 30% of the ^{14}C in the reference standards was removed by cold water extraction, leachable ^{14}C accounted for approximately 68% of the labile fraction.

The double exponential decay parameters indicated that the labile and recalcitrant ash-free mass fractions of fescue litter decomposed more slowly than the labile and recalcitrant ^{14}C fractions. Analysis of variance showed significant date and site effects for

TABLE 3. Transfer of ^{14}C from labelled fescue to the 500 cm^3 of spoil directly below. Values are means ± S.E.; $n = 12$ except at 7·5 months where $n = 9$. Beneath each column, P values associated with an analysis of variance (ANOVA), and L.S.D. values are given. Within each column, an asterisk indicates that the two site means are statistically different ($P = 0{\cdot}05$) at a particular sampling date

		^{14}C in spoil	
Months elapsed	Site	Total amount (µCi)	Percent of cumulative loss from litter
1·5	Non-vegetated mine	ND	ND
	Vegetated mine	ND	ND
4·5	Non-vegetated mine	0·33 ± 0·03	13·5 ± 2·1*
	Vegetated mine	0·31 ± 0·03	9·2 ± 0·9
7·5	Non-vegetated mine	0·12 ± 0·01	4·1 ± 0·6
	Vegetated mine	0·12 ± 0·02	3·0 ± 0·6
10·5	Non-vegetated mine	0·22 ± 0·02	8·3 ± 0·6
	Vegetated mine	0·24 ± 0·02	7·3 ± 0·8
13·5	Non-vegetated mine	0·20 ± 0·03	6·3 ± 1·0*
	Vegetated mine	0·14 ± 0·02	3·5 ± 0·5
16·5	Non-vegetated mine	0·17 ± 0·03	4·8 ± 0·8
	Vegetated mine	0·20 ± 0·03	4·5 ± 0·8
19·5	Non-vegetated mine	0·19 ± 0·02	4·8 ± 0·05
	Vegetated mine	0·19 ± 0·02	4·3 ± 0·05
ANOVA P values	Site	0·8625	0·0022
	Date	0·0001	0·0001
	Site × Date	0·4429	0·2007
L.S.D (0·05)		0·07	2·56

ND = not determined.

the specific activity (µCi/gC) of remaining litter (Table 1), suggesting that losses of ^{14}C from decomposing litter did not exactly parallel losses of ash-free mass or unlabelled carbon. Nonetheless, the magnitudes of the differences in specific activity of remaining litter among dates and between sites were sufficiently small to make tenable the assumption that transfer of ^{14}C from litter to soil provided a reasonably good quantitative measure of the incorporation of litter-derived carbon into soil (cf. Wieder & Carrel 1979).

Analysis of variance indicated that there was no difference between non-vegetated and vegetated mine sites in the total amount of ^{14}C in the 500 cm^3 of spoil directly beneath retrieved litter bags (Table 3). Although the date effect was significant, it did not reflect either a general increase or decrease in the ^{14}C content of spoil. If, however, the ^{14}C in soil was expressed as a percentage of that lost from litter directly overhead, both site and date effects were significant (Table 3). An average of 1·7% more ^{14}C was retained in soil underneath litter on non-vegetated mine sites than on vegetated ones.

Loss of nitrogen

Fescue litter on vegetated mine sites consistently lost more nitrogen than fescue litter on non-vegetated mine sites. The average 5·0% difference between sites was significant. Pairwise comparisons between sites, however, were significant on only two sampling dates (Table 1). For both sites, double exponential decay functions fitted the data better than single exponential decay functions (Table 2). The double exponential equations indicated that 58·5% of the initial nitrogen was rapidly lost from fescue litter. Cold water extraction of fescue reference standards resulted in a loss of 30% of the total initial nitrogen, thus leachable nitrogen accounted for about 51% of the labile fraction.

Influence of soil acidity on decomposition

Spoil samples taken from beneath retrieved litter bags had an average pH of 4·2 in non-vegetated mine sites and 5·3 in vegetated mine sites. The effect of soil pH on losses of ash-free mass, ^{14}C, and nitrogen from litter and on transfer of ^{14}C to soil beneath litter bags was examined by pooling all the data into two categories: litter samples situated over soil having pH $\leq$ 4·5 and litter samples situated over soil having pH $\geq$ 5·0. Analyses of variance were performed to identify the effects of sampling date, soil pH, and the date-by-pH interaction. The interaction was non-significant in each analysis. For losses of ash-free mass, ^{14}C, and nitrogen, the pH effect was significant ($P < 0{\cdot}0001$). In general, litter on highly acidic soil lost less of all three materials than litter on moderately acidic soil. Average differences between the two pH classes were 8·1% for ash-free mass, 8·6% for ^{14}C, and 7·7% for nitrogen. For ^{14}C content of soil, expressed either as the total amount present or as the percentage of ^{14}C lost from litter, the pH effect was not significant ($P \geq 0{\cdot}31$).

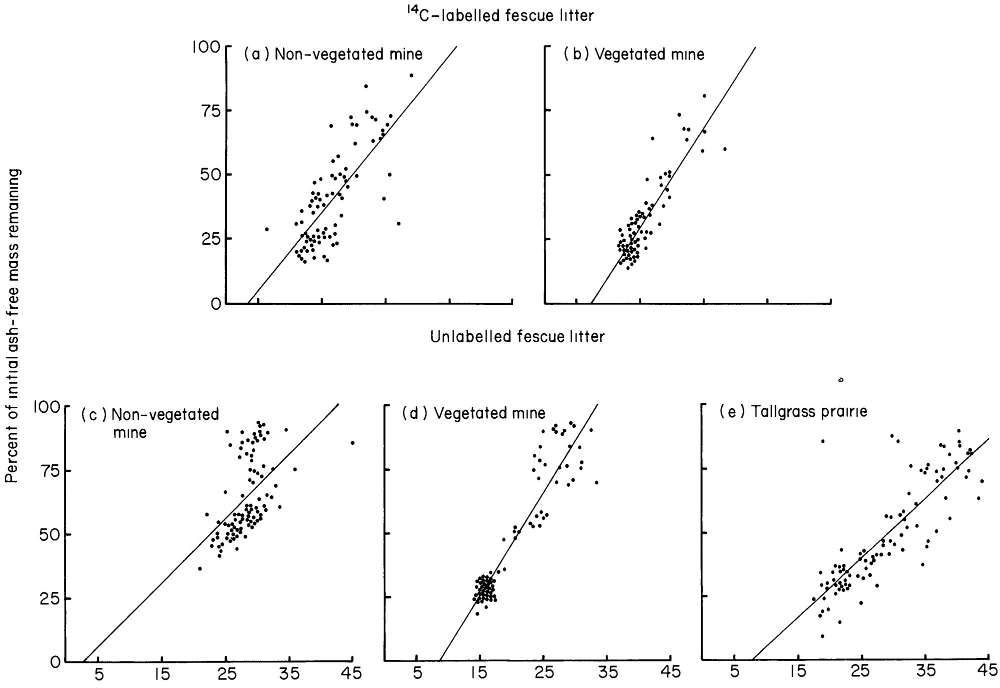

FIG. 1. Linear regressions of ash-free mass remaining as a function of the C:N ratio of retrieved litter for ^{14}C-labelled and unlabelled fescue litter decomposing on non-vegetated mine (a, c), vegetated mine (b, d), and tallgrass prairie (e) sites. The regression equations and their associated statistics are given below. Error degrees of freedom are 79 for ^{14}C-labelled fescue and 94 for unlabelled fescue. For each of the regressions, the F values are highly significant ($P \leq 0{\cdot}0001$).

^{14}C-labelled fescue litter:			
(a) Non-vegetated mine	$y = 3{\cdot}06x - 10{\cdot}01$,	$r^2 = 0{\cdot}56$,	$F = 98{\cdot}7$;
(b) Vegetated mine	$y = 3{\cdot}88x - 27{\cdot}88$,	$r^2 = 0{\cdot}76$,	$F = 250{\cdot}2$.
Unlabelled fescue litter:			
(c) Non-vegetated mine	$y = 2{\cdot}53x - 7{\cdot}23$,	$r^2 = 0{\cdot}29$,	$F = 38{\cdot}5$;
(d) Vegetated mine	$y = 4{\cdot}01x - 34{\cdot}81$,	$r^2 = 0{\cdot}88$,	$F = 716{\cdot}5$;
(e) Tallgrass prairie	$y = 2{\cdot}29x - 17{\cdot}47$,	$r^2 = 0{\cdot}69$,	$F = 209{\cdot}7$.

Changes in C:N ratio

The C:N ratio was an average of 1·2 units greater in litter collected from non-vegetated mine sites than in litter collected from vegetated mine sites. Pairwise comparisons between sites, however, indicated a significant difference on only one sampling date (Table 1). In the first 1·5 months, the C:N ratio rose from 14·2 to 23·6 on non-vegetated mines and to 21·9 on vegetated mines. After these initial increases, C:N ratios gradually declined to approximately 13·5 in both sites by the end of the study.

Linear regression analysis showed that for both vegetated and non-vegetated mine sites, declines in ash-free mass remaining were related to declines in the C:N ratio of remaining litter (Fig. 1). Analysis of covariance indicated that the slopes of these regressions for the two sites were different ($P = 0{\cdot}05$). A comparison of r^2 values suggests that this relationship is stronger for vegetated mine sites than for non-vegetated mine sites.

Unlabelled fescue litter

Loss of mass

In general, the ranking among the three sites in terms of ash-free mass remaining was: non-vegetated mine > tallgrass prairie ≥ vegetated mine sites (Table 4). Double exponential decay functions described the loss of ash-free mass from fescue litter better than single exponential decay functions (Table 2). $T_{\frac{1}{2}}$ values indicate that ash-free mass loss from unlabelled fescue litter was slower than from ^{14}C-labelled fescue litter.

Loss of nitrogen

In general, the ranking among the three sites in terms of nitrogen remaining was: non-vegetated mine ≈ vegetated mine > tallgrass prairie (Table 4). Nitrogen loss at all three sites was described better by double than by single exponential decay functions (Table 2). As with ash-free mass, $T_{\frac{1}{2}}$ values indicate that nitrogen was lost more slowly from unlabelled fescue litter than from ^{14}C-labelled fescue litter.

Loss of phosphorus

As shown in Table 4, consistently less phosphorus remained in litter retrieved from the tallgrass prairie than in litter retrieved from the two mine sites. For the first 5 months, more phosphorus was lost from litter on the non-vegetated mine site than on the vegetated mine site. Thereafter, the situation was reversed: more phosphorus was lost from litter retrieved from the vegetated mine site than from the non-vegetated mine site. Double exponential decay functions described the phosphorus data better than single exponential decay functions, although for the vegetated mine the difference between the single and double exponential fits was small (Table 2). Despite approximately equal $T_{\frac{1}{2}}$ values for non-vegetated and vegetated mine sites, the dynamics of phosphorus loss were quite different. For litter on non-vegetated mine sites, the labile phosphorus fraction was lost relatively rapidly and the recalcitrant phosphorus fraction relatively slowly compared to litter on the vegetated mine sites.

Changes in elemental ratios

The C:N ratio of litter on the non-vegetated mine site remained almost constant at about 28 throughout the study (Table 4). For the vegetated mine and tallgrass prairie sites, however, the C:N ratio of litter showed initial increases followed by gradual declines to relatively stable values of 15–16 and 21–24 for vegetated mine and tallgrass prairie sites,

TABLE 4. Decomposition of unlabelled fescue litter. Values are means ± S.E.; $n = 12$. Beneath each column, P values associated with an analysis of variance (ANOVA), and L.S.D. values are given. Within each column, for each sampling date, values with the same superscripts do not differ significantly ($P = 0{\cdot}05$)

		Percent of initial amount remaining			Characteristics of retrieved litter			
Months elapsed	Site	Ash-free mass	Nitrogen	Phosphorus	Percent ash	C:N	C:P	N:P
0 = 5 Dec 1977	—	100	100	100	8·8 ± 0·1	25·9 ± 0·1	194 ± 1	7·5 ± 0·04
1	Non-vegetated mine	89·3 ± 0·7^{a}	76·7 ± 1·6	67·0 ± 1·5	9·4 ± 0·3^{a}	30·0 ± 0·7^{a}	256 ± 7^{a}	8·5 ± 0·2^{a}
	Vegetated mine	88·9 ± 1·0^{a}	81·2 ± 2·0	88·2 ± 3·3	8·3 ± 0·2^{a,b}	28·2 ± 0·7^{a}	195 ± 7^{a}	6·9 ± 0·2^{a}
	Tallgrass prairie	84·0 ± 0·7	61·7 ± 5·5	39·1 ± 7·1	6·2 ± 0·3^{b}	36·8 ± 2·0	608 ± 116	15·8 ± 2·6
3	Non-vegetated mine	83·7 ± 0·9	72·5 ± 2·4^{a}	61·8 ± 2·4	9·5 ± 0·3^{a}	30·0 ± 1·4^{a}	265 ± 15^{a}	8·8 ± 0·2^{a,b}
	Vegetated mine	73·8 ± 1·1^{a}	68·8 ± 2·8^{a}	69·3 ± 4·0	7·2 ± 0·3^{a,b}	27·8 ± 0·9^{a}	211 ± 13^{a}	7·6 ± 0·5^{a}
	Tallgrass prairie	74·2 ± 0·5^{a}	51·0 ± 1·3	35·8 ± 3·9	5·5 ± 0·1^{b}	37·5 ± 0·9	454 ± 51	12·0 ± 1·2^{b}
5	Non-vegetated mine	72·0 ± 1·6	63·7 ± 0·9^{a}	55·1 ± 1·7	18·8 ± 0·5	29·0 ± 0·8	252 ± 10^{a}	8·7 ± 0·2^{a}
	Vegetated mine	53·0 ± 1·0	60·2 ± 0·9^{a}	66·9 ± 2·2	7·9 ± 0·1^{a}	22·6 ± 0·6	153 ± 5^{a}	6·8 ± 0·2^{a}
	Tallgrass prairie	60·8 ± 1·6	44·8 ± 0·4	24·7 ± 2·6	7·7 ± 0·4^{a}	35·1 ± 1·5	548 ± 80	15·2 ± 1·6
7	Non-vegetated mine	59·5 ± 2·5	53·5 ± 0·7^{a}	51·7 ± 1·6	29·3 ± 2·0	28·4 ± 0·9^{a}	222 ± 10^{a}	7·8 ± 0·3
	Vegetated mine	31·0 ± 0·9	48·9 ± 1·0^{a}	30·6 ± 2·0	12·0 ± 0·3^{a}	16·2 ± 0·4	212 ± 27^{a}	13·0 ± 1·6
	Tallgrass prairie	46·4 ± 1·1	40·4 ± 1·2	18·0 ± 1·2	9·1 ± 0·3^{a}	29·7 ± 1·1^{a}	515 ± 37	17·2 ± 0·8
9	Non-vegetated mine	54·0 ± 1·3	51·5 ± 0·9^{a}	42·9 ± 3·1	28·5 ± 1·4	26·9 ± 0·7	227 ± 51^{a}	10·2 ± 1·7^{a}
	Vegetated mine	28·5 ± 0·6	46·8 ± 1·6^{a}	28·1 ± 1·6	13·4 ± 0·3^{a}	15·6 ± 0·2	199 ± 9^{a}	12·7 ± 0·6^{a}
	Tallgrass prairie	33·8 ± 2·1	36·7 ± 2·0	15·4 ± 1·8	13·2 ± 0·7^{a}	24·0 ± 1·7	478 ± 64	19·9 ± 1·8
11	Non-vegetated mine	54·2 ± 1·5	49·8 ± 0·7^{a}	39·5 ± 2·9	24·1 ± 0·9	27·9 ± 0·8	271 ± 14^{a}	9·8 ± 0·6^{a}
	Vegetated mine	27·3 ± 0·8	44·9 ± 1·2^{a}	28·3 ± 1·4	11·9 ± 0·2^{a}	15·6 ± 0·1	188 ± 10^{a}	12·1 ± 0·6^{a}
	Tallgrass prairie	33·4 ± 2·3	35·0 ± 1·3	14·2 ± 1·2	13·9 ± 1·8^{a}	24·3 ± 1·4	479 ± 49	19·8 ± 1·9
15	Non-vegetated mine	53·6 ± 1·5	49·4 ± 0·9	37·4 ± 2·4	26·7 ± 0·8	27·8 ± 0·7	280 ± 13^{a}	10·2 ± 0·6
	Vegetated mine	25·1 ± 1·0	39·7 ± 1·6	18·3 ± 1·4	14·5 ± 0·5^{a}	16·1 ± 0·2	271 ± 15^{a}	16·9 ± 0·9
	Tallgrass prairie	31·9 ± 2·2	34·1 ± 2·2	9·9 ± 1·1	16·4 ± 1·3^{a}	23·9 ± 0·6	671 ± 65	27·8 ± 2·3
17	Non-vegetated mine	51·0 ± 2·7	47·3 ± 0·9^{a}	39·2 ± 1·9	42·2 ± 1·6	27·5 ± 1·1	250 ± 11^{a}	9·1 ± 0·3
	Vegetated mine	25·7 ± 0·6^{a}	42·6 ± 0·8^{a}	23·4 ± 1·2	18·2 ± 1·7^{a}	15·4 ± 0·2	215 ± 11^{a}	13·9 ± 0·7
	Tallgrass prairie	27·4 ± 2·1^{a}	33·3 ± 2·3	14·4 ± 1·2	18·0 ± 1·3^{a}	20·9 ± 0·6	369 ± 28	17·5 ± 1·0
21	Non-vegetated mine	44·8 ± 2·4	ND	ND	32·3 ± 1·3	ND	ND	ND
	Vegetated mine	25·2 ± 0·8^{a}	ND	ND	17·1 ± 1·3^{a}	ND	ND	ND
	Tallgrass prairie	24·0 ± 2·8^{a}	ND	ND	19·8 ± 2·0^{a}	ND	ND	ND
27	Non-vegetated mine	39·5 ± 3·0	ND	ND	42·4 ± 2·7	ND	ND	ND
	Vegetated mine	23·4 ± 0·7^{a}	ND	ND	18·4 ± 1·4	ND	ND	ND
	Tallgrass prairie	21·1 ± 2·0^{a}	ND	ND	23·7 ± 1·2	ND	ND	ND
ANOVA P values	Site	0·0001	0·0001	0·0001	0·0001	0·0001	0·0001	0·0001
	Date	0·0001	0·0001	0·0001	0·0001	0·0001	0·0001	0·0001
	Site × Date	0·0001	0·0059	0·0001	0·0001	0·0001	0·0493	0·0001
L.S.D (0·05)		4·5	5·2	7·3	3·2	2·7	115	3·3

ND = not determined.

respectively. Throughout the study, the mean C:N ratio was lower in litter from the vegetated mine site than from the other two sites.

The C:P ratio on the tallgrass prairie site increased sharply in the first month from 194 to 608 and remained consistently greater than the C:P ratios of litter retrieved from either of the two mine sites (Table 4). On the other hand, the C:P ratios of litter retrieved from the two mine sites did not deviate significantly from the initial value of 194. Accordingly, differences between the two mine sites were not significant at each sampling date.

The N:P ratio of litter generally increased from 7·5 to 14 on the vegetated mine site and to 17·5 on the tallgrass prairie site, whereas it did not change significantly on the non-vegetated mine site (Table 4). The N:P ratio always was greater in litter retrieved from the tallgrass prairie site than in litter retrieved from the two mine sites.

As with the ^{14}C-labelled litter, linear regression analyses showed that the ash-free mass of retrieved litter was proportional to its C:N ratio for each of the three sites (Fig. 1). The correlation (r^2) between ash-free mass and the C:N ratio of remaining litter was highest for the vegetated mine site and lowest for the non-vegetated mine site. Analyses of covariance indicated that the slope of the regression for the vegetated mine site differed from the slopes for each of the other two sites ($P = 0{\cdot}0002$). Although the slopes of the regression equations for the non-vegetated mine and tallgrass prairie sites did not differ significantly ($P = 0{\cdot}57$), the intercepts were significantly different ($P < 0{\cdot}0001$).

Stepwise multiple linear regressions of ash-free mass remaining *v.* the C:N, C:P, and N:P ratios of remaining litter were performed for each site. The C:N ratio was the first variable entered in each of the regression analyses, with associated r^2 values as given in Fig. 1. For the non-vegetated mine site, the full model included only the C:N ratio. The full model for the vegetated mine site included the C:N and the C:P ratios, with a corresponding r^2 value of 0·89. The full model for the tallgrass prairie used all three ratios and had an r^2 value of 0·74. For the vegetated mine and tallgrass prairie sites, reduction in error sums of squares by addition of C:P or both C:P and N:P ratios, respectively, was significant but relatively small. Thus, ash-free mass of retrieved litter appeared to be much more strongly related to its C:N ratio than either its C:P or N:P ratio.

Unlabelled cellulose litter

Loss of mass

In the first 5 months, from December to May, decomposition of cellulose on all three sites was slow and differences among sites were not significant (Table 5). Thereafter, differences among sites at every sampling date were significant. In general, the ranking among the three sites in terms of ash-free cellulose mass remaining was: non-vegetated mine > tallgrass prairie > vegetated mine.

Because there was no *a priori* reason for dividing initial cellulose into labile and recalcitrant fractions, only single exponential decay functions were fitted to the loss of ash-free mass data. Single exponential decay constants (Table 2) clearly indicate that ash-free mass was lost much more slowly from cellulose litter than from either ^{14}C-labelled or unlabelled fescue litter.

DISCUSSION

Decomposition on mined and unmined sites

Three general patterns of ash-free mass loss were evident in the present study. First, rates of mass loss from fescue on both surface mine and tallgrass prairie soils were generally

TABLE 5. Decomposition of cellulose litter. Values are means ± S.E.; $n = 12$. Beneath the data, P values associated with an analysis of variance (ANOVA), and L.S.D. values are given. At each sampling date, values with the same superscripts do not differ significantly ($P = 0{\cdot}05$)

	Percent of initial ash-free mass remaining		
Months elapsed	Non-vegetated mine	Vegetated mine	Tallgrass prairie
0 = 5 Dec 1977	100	100	100
1	96·7 ± 0·2^{a}	96·2 ± 0·1^{a}	95·8 ± 0·2^{a}
3	97·5 ± 0·2^{a}	96·0 ± 0·2^{a}	95·0 ± 0·8^{a}
5	102·1 ± 0·4^{a}	99·4 ± 0·2^{a}	97·4 ± 1·0^{a}
7	101·5 ± 0·9	67·9 ± 3·5	84·1 ± 5·6
9	97·9 ± 0·7	54·2 ± 6·1	86·0 ± 2·7
11	100·1 ± 1·3	41·8 ± 4·8	76·1 ± 6·4
15	94·8 ± 1·7	30·9 ± 4·5	78·1 ± 6·1
17	91·5 ± 1·4	27·2 ± 4·4	57·0 ± 6·7
21	90·0 ± 3·0	30·1 ± 5·6	68·8 ± 6·7
27	79·9 ± 2·7	14·3 ± 2·4	61·5 ± 8·4
ANOVA P values	Site	0·0001	
	Date	0·0001	
	Site × Date	0·0001	
L.S.D (0·05)		10·8	

faster than rates reported in the literature for litter bag studies of grass decomposition on temperate grasslands (Koelling 1964; Koelling & Kucera 1965; Traczyk 1968; Curry 1969; Kelly *et al.* 1969; Kirkham 1970; Malone & Reichle 1973; Schnauss 1976; Ţesarova 1976). Second, ^{14}C-labelled fescue litter decomposed more rapidly than unlabelled fescue litter. And third, ^{14}C-labelled fescue litter, unlabelled fescue litter, and cellulose litter each exhibited reduced decomposition on non-vegetated mine sites relative to vegetated mine and/or tallgrass prairie sites (Tables 1, 4 and 5). Each of these observations can be explained, at least in part, by differences among the three litter types in initial litter quality, particularly with respect to C : N ratios, and by differences among the three sites in the contribution of exogenous sources of nitrogen to decomposing litter.

Plant materials with large C:N ratios tend to decompose more slowly than plant materials with small C:N ratios (Jensen 1929; Lockett 1937; Brady 1974). The initial C:N ratios of ^{14}C-labelled fescue litter and unlabelled fescue litter of 14·2 and 25·9, respectively, are low compared to litter derived from mature grasses and may account for the generally rapid decay rates we obtained, as well as for the relatively faster decay of ^{14}C-labelled litter compared to unlabelled litter.

The initial nitrogen content of ^{14}C-labelled litter was apparently sufficient to allow considerable decomposition to occur, even on non-vegetated mine sites. In contrast, the initial nitrogen content of unlabelled fescue was only 0·6 times that in ^{14}C-labelled fescue, and was insufficient to support continued decomposition on the non-vegetated mine site, as evidenced by a k value of 0 for the recalcitrant ash-free mass fraction (Table 2). Except for very slight nitrogen inputs from precipitation, essentially all nitrogen required for microbial catabolism on non-vegetated mine sites must come from the litter itself, whereas on vegetated mine and tallgrass prairie sites additional nitrogen could be supplied from leaching of standing vegetation, deposition of insect frass, mineralization of other plant litter, and possibly from symbiotic and non-symbiotic nitrogen fixation (Williams 1975; Dennington & Chadwick 1978; Woodmansee 1979; Marrs *et al.* 1981; Roberts *et al.* 1981; Bloomfield, Handley & Bradshaw 1982). Our cellulose litter decomposed to a considerable extent on both vegetated mine and tallgrass prairie sites, suggesting that exogenous sources of nitrogen were indeed available. By comparison, the exceedingly slow rate of cellulose decay on the non-vegetated mine sites supports our contention that exogenous nitrogen inputs to litter on barren spoil were minor and insufficient to support considerable microbial decomposer activity.

As with ash-free mass, losses of nitrogen and phosphorus from our green-harvested fescue litter were faster than those reported in the literature for temperate grasslands (Koelling 1964; Koelling & Kucera 1965; Tesarova 1976). The fates of nitrogen and phosphorus in decomposing litter are qualitatively influenced by initial C:N and C:P ratios, respectively. Litter with large initial ratios, such as cellulose filter paper, can actually accumulate absolute amounts of nitrogen and phosphorus through microbial immobilization, whereas in litter with small initial ratios, such as the ^{14}C-labelled and unlabelled fescue litter, a net mineralization should occur (Parker, Larson & Bartholomew 1957; Bocock 1964; Reuss & Innis 1978; Swift, Heal & Anderson 1979).

We have used simple and multiple linear regression analyses to examine the relationships between ash-free mass loss and nitrogen and phosphorus dynamics in decomposing litter. The slopes of the linear regressions relating ash-free mass to the C:N ratio of retrieved fescue (Fig. 1) are steeper for vegetated mine sites than for non-vegetated mine sites. Hence, a particular reduction in ash-free mass required greater mineralization of nitrogen on vegetated than on non-vegetated mine sites. In addition, for unlabelled fescue litter, the position of the regression line is lower for the tallgrass prairie site than for either mine site. Thus, at any particular value for ash-free mass, litter in the prairie contained the least amount of nitrogen. Moreover, the stepwise multiple linear regressions of ash-free mass *v.* elemental ratios show an increasing complexity from non-vegetated mine (C:N ratio only), to vegetated mine (C:N and C:P), to tallgrass prairie (C:N, C:P, and N:P) sites. We contend that the increasing complexity of these models reflects a progression in the richness of the microbial decomposer community and a more intricate set of interrelationships between nutrient availability and decomposer activity. Considerable differences in the microflora among our non-vegetated mine, vegetated mine, and tallgrass prairie sites exist. In the mine spoil, fungi are typically more important than bacteria but total microbial abundance and activity are low, especially in non-vegetated areas (Carrel *et al.* 1976; Harrison 1978). In contrast, the tallgrass prairie has a large bacterial component with fungi mainly associated with the root mat (Herman & Kucera 1979). Microbial abundance and activity generally are much higher in grassland soils than in mine spoils (Lawrey 1977; Swift, Heal & Anderson 1979; Miller & May 1981). In addition, because our non-vegetated mine sites support few arthropod detritivores (J. Carrel unpubl. data), plant litter decomposition could be reduced (Howard & Howard 1974; Swift, Heal & Anderson 1979).

In addition to nutrient availability and biotic factors, differences among the three sites regarding abiotic environmental parameters may also have an effect on plant litter decomposition. Fluctuation in temperature and moisture regimes is certainly more pronounced on exposed spoil than on the shaded surfaces of vegetated mine and tallgrass prairie sites (cf. Lawrey 1977; Dennington & Chadwick 1978). Summer temperatures as high as 54 °C have been recorded at the non-vegetated spoil surface at some of our study sites (Burmester 1977). High soil temperature and low soil moisture of surface mine spoil appear to limit plant growth (Richardson 1958; Richardson & Greenwood 1967; Bradshaw *et al.* 1975; Bell & Ungar 1981) and may also reduce decomposer activity. In addition, non-vegetated mine spoil tends to be more acidic than vegetated mine spoil (Tasker & Chadwick 1978). Our finding that ^{14}C-labelled fescue litter decomposed more slowly on very acidic spoil (pH $\leq 4{\cdot}5$) than on moderately acidic spoil (pH $\geq 5{\cdot}0$) is in agreement with the studies of Dyal, Smith & Allison (1939) and Jenkinson (1977) conducted in unmined soils. Acidity and other physicochemical factors may affect decomposition indirectly by modifying the activities and abundances of soil fauna and soil microflora (Williams & Cooper 1976).

In conclusion, decomposition in non-vegetated mine, vegetated mine, and tallgrass prairie sites appears to be controlled mainly by nitrogen, and to a lesser extent phosphorus, availability. The influence of nutrient availability on decomposition is modified by differences among non-vegetated mine, vegetated mine, and tallgrass prairie sites in a variety of environmental factors including soil temperature and moisture regimes, soil pH, soil faunal abundance, microbial abundance, and the structure and function of the microbial community.

Transfer of ^{14}C from litter to spoil

Our objective in using ^{14}C-labelled fescue was to quantify the loss of ^{14}C from decomposing litter and its transfer to the soil column directly below. We found that after 19·5 months, 4–5% of the ^{14}C lost from fescue litter resided in the upper 5 cm of spoil in both non-vegetated and vegetated mine sites. This result is qualitatively similar to those obtained by Kirkham (1970) and Shields & Paul (1973) for unmined soils. Kirkham (1970) found that 3·6 and 2·5% of the radioactivity lost from *Andropogon gerardi* litter was detected after 14 and 48 months in the underlying 30 cm column of prairie soil. Shields & Paul (1973) reported almost 7% of ^{14}C originally in wheat straw was retained after 24 months in the top 3 cm of soil in a field, but none of the label was detected from 3 to 10 cm below the surface.

Carbon from plant litter can become stabilized in soils either through interaction with clays or by incorporation into living biomass or humic substances (Grim 1953; McLaren & Peterson 1965; Mortland & Wolcott 1965; Mortland 1970; Swift, Heal & Anderson 1979). Relative to the tallgrass prairie, our mine soils have high clay and low organic matter contents (Kucera, Dahlman & Koelling 1967; Burmester 1977; Game, Carrel & Hotrabhavandra 1982). Because we obtained no major differences in ^{14}C content between either non-vegetated and vegetated spoil or very acidic and moderately acidic spoil, we suspect that physical rather than biological factors accounted for most of the ^{14}C retention in mine spoil.

Accumulation of organic matter in surface mine spoils is a slow process, resembling primary succession on natural materials (Bradshaw & Chadwick 1980; Marrs *et al.* 1981; Roberts *et al.* 1981). Our results suggest that short-term contributions to soil organic matter from litter decomposing on the soil surface may be comparable on mined and unmined sites if they are covered with herbaceous vegetation.

Implications for surface mine reclamation

Current reclamation practices aim to establish permanent pasturelands or croplands on mine soils (Bradshaw & Chadwick 1980; National Research Council 1981). Lime, fertilizers, and sometimes mulches are applied at various intervals to nurture soils and crops (Schaller & Sutton 1978; Bloomfield, Handley & Bradshaw 1982). In fact, these practices may produce conflicting results. Our data suggest that liming and fertilization could considerably accelerate decomposition of litter, breakdown of soil organic matter, and release of nitrogen in mined lands much as they do in cultivated lands (Swift, Heal & Anderson 1979). Conversely, mulching with wood chips, sawdust, paper, and other plant residues having large C:N and/or C:P ratios can moderate litter decomposition and contribute to the accumulation of soil organic matter but result in immobilization of nitrogen, phosphorus, and other minerals necessary for plant growth (National Research Council 1981). The possibly offsetting effects of different management practices on decomposition processes, soil fertility, and crop production in surface mines need closer examination.

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