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DECOMPOSITION OF *BOUTELOUA GRACILIS* PLANT MATERIALS IN A GRASSLAND ECOSYSTEM

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ABSTRACT

A study was made of blue grama (Bouteloua gracilis) decomposition under field conditions and in the laboratory using carbon-14 labeled plant material. The field work was carried out at the intensive study area of the U. S. International Biological Program Grassland Biome (Pawnee Site) in northeastern Colorado. Determinations of radiocarbon in soil-plant mixtures were made by combusting samples in a modified Coleman Nitrogen Analyzer and collecting the evolved carbon dioxide in an absorption solution, aliquots of which were assayed using liquid scintillation techniques. Soil was amended with blue grama herbage and roots in February, 1971 and sampled at intervals until March, 1972. For ground blue grama herbage buried in the top 2.6 cm of soil at two amendment levels (128 and 1280 kg/ha) 54-57% of initially added carbon-14 was lost in 412 days. For plant root material at amendment levels of 384 and 1920 kg/ha, only 26-37% of the carbon was lost in this time period. Rates of carbon loss were significantly effected by season of burial; plant material buried in February and May exhibited losses of 56% in 335 days and 42% in 314 days, respectively. Segments of blue grama herbage mixed with the soil and placed on the soil surface for 412 days showed carbon losses of 39 and 50%, respectively. Additions of fresh, blue grama herbage to soil containing partially degraded plant material had no significant effect on radiocarbon loss rates.

The relation of decomposition rate to soil moisture content and temperature was examined in laboratory studies. Soil samples amended with labeled ground blue grama herbage were incubated in the laboratory for a minimum of 560 hr at various temperatures (3-60^{o}) and water contents (2.6-36%). Radiocarbon losses were assessed and the results used to develop a multiple regression equation, which predicted (R^2=.866, n=485) percent carbon loss (D) as a function of percent soil water, soil temperature, and time.

Three laboratory experiments were designed to measure soil drying rates and the effect of simulated rainfall on moisture distribution in soil. Soil samples receiving a 12.5 cm simulated rainfall were dried at various temperatures and exponential regression equations developed for soil drying rates at each temperature. A constant rate phase correction factor (CORR) was developed to correct soil drying rates for increased evaporation rates at water contents above 8%.

A mathematical model was developed to integrate the hydrologic and decomposition data collected in the laboratory. An exponential soil water loss submodel expressed as $M_{t+1}=(M_t+RAINADD_t)e^{-b}$, where percent soil water at hour t+1 (M_{t+1}) is predicted from the percent soil water at time t (M_t), $RAINADD_t$, and the soil drying rate (b). The value of b at time t was calculated from hourly soil temperature data, laboratory-derived temperature-drying rates and the CORR factor. The hourly percent carbon loss of blue grama herbage is estimated by calculating the laboratory-derived D and multiplying this by 3. Significant correlations were found between field

measurements and predictions of soil water (r^2=.852, n=51) and percent blue grama carbon loss (r^2=.957, n=13).

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INTRODUCTION

The Grassland Biome Program of the U. S. International Biological Program has attempted to synthesize trophic level ecosystem models of the shortgrass prairie at the Pawnee Site. A large part of this effort has involved an evaluation of decomposition processes under field conditions. Most of the net primary production of this ecosystem decomposes in the soil.

The investigator evaluating the role of soil microorganisms in a research program such as this is faced with several problems. The International Biological Program (IBP) represents an effort to bring together scientific information from many disciplines, but there have been very few successful attempts to integrate soil microbiology with other natural sciences. Another major problem arises because ecosystem models developed in the IBP program must be validated with field data, whereas by far the largest effort in soil microbiology has been expended in evaluating activities of soil microorganisms under laboratory conditions. Frequently, the extreme variability of the results of such field experiments has led to limited success in accomplishing a given research objective, even where sampling and analytical procedures are carried out with extensive replications.

The current state of knowledge and present experimental techniques pose immediate limitations for field-oriented research approaches in soil microbiology. One approach has been to equate total or selective census counts of microorganisms with overall field decomposition processes. However, this approach has enjoyed limited success,

because degradation is not a function of biomass alone. In the present study the rate of change of plant material buried in soil is measured and microbial biomass is not taken into consideration. This appraoch was used to evaluate the decomposition of blue grama in a shortgrass prairie at the Pawnee Site. Blue grama was chosen because it is the major native forage species at the Pawnee Site. The specific research objectives were:

1. To develop routine procedures for the determination of radiocarbon levels in mixtures of soil and carbon-14 labeled blue grama.

2. To determine the kinetics of blue grama decomposition in soil using C-14 labeled plant material in field experiments.

3. To determine quantitatively the effects of environmental factors (soil temperature and soil water content) on the decomposition rate of blue grama herbage under controlled conditions in the laboratory.

4. To evaluate the effects of temperature, rain events, and soil water content on soil drying rates under controlled conditions in the laboratory.

5. To demonstrate an approach to modeling decomposition of plant material added to soil and changes in soil water content.

6. To evaluate the decomposition and soil water models using data collected from field experiments.

The hydrologic and decomposer models developed in this work cannot be the "best of all possible models", because such a thing does not exist. The model building efforts were used as a means of integrating hydrologic and decomposer information at the Pawnee Site. The main reasons for this integration of data were to force clarification of microbiological and hydrologic concepts, to obtain an idea of how

abiotic factors influence decomposer activity, and to attempt to forecast decomposer activity.

LITERATURE REVIEW

The decomposer population of an ecosystem is the single most important group in the annual turnover of energy trapped by photosynthesis (17). In spite of this fact, the microflora (fungi, bacteria and actinomycetes) and the microfauna (protozoa, nematodes, rotifers and other microscopic soil animals) of grassland ecosystems have received less attention than microorganisms in other ecosystems. Most of the investigations of decomposer microorganisms have been laboratory-oriented; however, the approach taken in this review of the literature has been to consider various factors which influence decomposer activity under field conditions. Topics included are: methodology for the determination of decomposer activity, the effects of substrate differences, soil temperature and water on decomposition kinetics, and selected approaches for modeling changes in decomposer activity and in soil evaporation rates.

A. The Influence of the Nature of the Substrate on Decomposition Kinetics

In grassland habitats, gravimetric methods involving cellulose strips buried in soil and litter bags to hold vegatative matter are frequently used to measure decomposition rate. Data from several studies employing these approaches have been compiled in Table 1 and allow some interesting comparisons. Seasonal or annual differences within an area can result in ten-fold differences in rates of decay of organic materials. A large difference is apparent in the rates of cellulose decomposition between different sites: 85% in 300 days in

Table 1. Rates of decomposition of organic materials in grassland field experiments.

Locale descriptor	Substrate	Burial date	Retrieval date	Field incubation period (days)	Amount decomposed (% of total)	Calculated decomposition rate(%/mo.)	Reference
Colorado (5-7 cm)*	cellulose	10/1/69	12/4/69	64	3.3	1.6	15
"	cellulose	10/1/69	7/28/70	300	84.6	8.5	15
"	cellulose	2/23/70	4/24/70	60	4.6	2.3	15
"	cellulose	5/26/70	7/28/70	63	43.3	20.6	15
"	bluestem hay	5/09/70	7/28/70	70	47.0	20.1	15
"	cellulose	4/12/71	6/14/71	63	22.4	10.7	16
	bluestem hay				32.0	15.2	16
"	cellulose	5/03/71	7/06/71	64	11.5	5.4	16
	bluestem hay			64	27.7	13.0	16
"	cellulose	5/24/71	7/27/71	64	4.3	2.0	16
	bluestem hay			64	25.0	11.7	16
"	bluestem hay	5/24/71	6/14/71	21	17.6	25.1	16
	bluestem hay	5/24/71	7/06/71	43	25.2	17.5	16
South Carolina (0-5 cm)	cellulose	2/29	4/02	34	68.0	60.0	31
	cellulose	4/02	5/04	32	70	65.6	31

Table 1. (Continued)

Locale descriptor	Substrate	Burial date	Retrieval date	Field incubation period (days)	Amount decomposed (% of total)	Calculated decomposition rate (%/mo.)	Reference
South Carolina (0-5 cm)	cellulose	5/04	6/12	39	92.0	70.8	31
	cellulose	6/12	7/07	26	96.0	110.8	31
Nebraska (0-15 cm)	blue grama roots	----	----	365	55.0	4.5	83
"	big bluestem roots	----	----	365	36.0	3.0	83
"	little bluestem roots	----	----	365	50.0	4.1	83
Kansas (5-7 cm)	cellulose	4/01	5/05	35	55.0	47.1	36
"	cellulose	4/02	6/19	79	97.0	36.8	36
"	cellulose	5/17	6/16	60	94.0	47.0	36
"	bluestem hay	5/17	6/16	60	60.0	30.0	36

* Depth below soil surface.

Colorado (15) compared with 96% in 26 days at a South Carolina site (31). Cellulose alone does not decompose at the same rate as cellulose in combination with other plant components, either on an annual basis or within a given seasonal period. In view of this fact, cellulose decomposition should be considered only as a rough index of microbial activity, that is, conditions favorable for the decomposition of plant material are also favorable for cellulose decomposition.

The production of plant materials uniformly labeled with carbon-14 has added new dimensions to decomposition experiments. Since 1953, substrates labeled with carbon-14 have been used in over 130 investigations concerned with soil decomposition; this area of work has recently been the subject of an extensive review (47) and an annotated bibliography (18). The use of labeled plant material has enjoyed much success since it allows one to follow accurately losses of added plant carbon in the presence of large amounts of unlabeled soil carbon even after extensive decomposition.

In spite of the popularity of the radiocarbon methods, very few decomposition investigations have been executed in the field (Figure 1). Jenkinson allowed ground labeled ryegrass tops and roots to decompose for four years under field conditions at the Rothamsted Experimental Station (44,45,46). About 67% of the plant material decomposed in the first year of these field experiments, irrespective of the soils or plant materials used. Oberlander and Roth carried out field experiments in northeastern Austria to determine the rate of decomposition of carbon-14 labeled maize plants (56). Although there were no differences in decomposition rates in different soils; 53 and 67% of the plant material decomposed annually when plant material was buried in

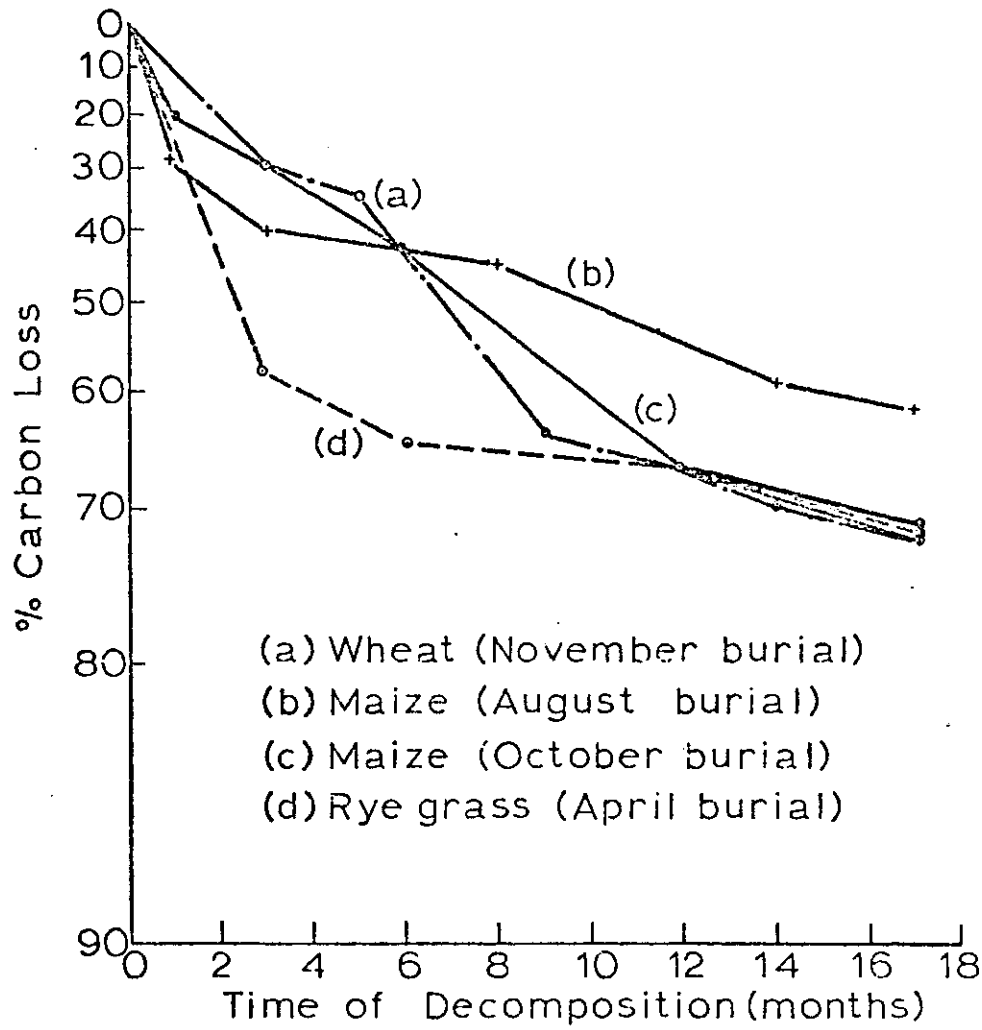

Fig. 1. Decomposition of carbon-14 labeled wheat (27), maize (56) and ryegrass (44) as a function of time in field experiments.

August and October, respectively. Fuhr and Sauerbeck determined how fast radioactive wheat straw and wheat chaff decomposed in fallow field plots and under different cropping sequences (27). The results compared quite favorably with that of previous workers: 69% decomposition annually at the 0-11 cm soil depth (Figure 1).

Decomposition kinetics are effected by the quantity of plant material added to the soil, but there is much conflicting information in the literature as to the nature of this effect (47). If amendment levels are expressed on the basis of a herbage to soil ratio, the results of field experiments indicated that increasing the amendment level from 0.3% to 0.6% has no effect on the rate of decomposition of residues (44), but with an increase of 0.3% to 1.5% the total amount of substrate decomposed in one year increased by 7% (56). When the level of wheat straw mulch was increased from 4,480 to 17,920 kg/ha, the decomposition rate of this material decreased from 67% to 29% during a 6-month decomposition period (52). A close examination of the results of these experiments verifies van Schreven's observations (79) based on laboratory experiments that "the greater the amount of plant material added to a soil, the longer is the time required for a given percentage to decompose". Nonlinear relationships between levels of straw added and rates of loss in short term experiments can result because the soil's supply of nutrients needed by microbial populations may be insufficient for maximal decomposition at all amendment rates (43).

Kinetics of decomposition processes are not only influenced by the amount of substrate added, but also by the particle size of the material. Physical, chemical and microbiological processes affect the particle size and other physical properties of plant materials in

various stages of decay (51). Starkey (73), reviewing the work of Wollny and others, has indicated that the decomposition rates of organic materials increase with decreasing particle size, but only if the organic residue is quite recalcitrant, such as cornstalk residue (52). Decreasing the width of pieces of cornstalk pith from 12.5 to 4.7 mm caused a doubling of the decomposition rate in laboratory and field experiments (52,71). However, the mineralization of nitrogen from legume residues increased 2.4-fold as the particle size of the residue increased (74). Weaver found a continuous decrease in the quantity of coarse root materials (greater than 3.96 mm diameter) but an increase in fine residue fraction (0.25 to 1.08 mm diameter) during the decomposition of the roots of 12 range grasses (83). Thus, the influence of particle size on decomposition does not lend itself to making generalities over a wide range of plant residues due to differences in plant composition (87).

The chemical composition of plant material is also a factor influencing decomposition kinetics. Plant materials of different ages and taxonomic groups contain varying amounts of water-soluble constituents, lignin, and a wide variety of other organic compounds. Younger plants contain higher proportions of water-soluble organic compounds and less lignin than more mature plants and usually decompose faster than older plants (1,82,84). The ratio of carbon to various mineral elements, such as the C:N ratio, has also been used as an index of biodegradation. Thus, when the C:N ratio of the plant material is greater than 30:1, added nitrogen can increase decomposition rates (82,84). Fresh organic residues with high C:N ratios can usually be

rapidly degraded in soil as a result of the rapid destruction of the water-soluble plant constituents, which are abundant in this material.

The kinetics of herbage degradation and the composition of the decomposer population (17) are affected by the positioning of the herbage beneath or on the soil surface. Laboratory studies have shown that increasing the relative humidity of the air above the soil from 68 to 93% will result in a 50% increase in decomposer activity at the soil surface, while the decomposition of corn residue below the soil surface is unaffected (58). However, although decomposer activity on the soil surface is susceptible to moisture stress in less humid ecosystems, litter buried just below the soil surface is also subject to moisture stress (14). The ratio of observed decomposition rate on the soil surface to that within the soil is also influenced by the nature of the substrate and by the level of addition (52). Values have been reported of 1.00 for alfalfa plant tops (52), 0.55 for wheat straw (52), and 0.77 for cornstalk residue (59).

Newly-added substrate may change the decomposition rate of organic matter already present in the soil. Much work on this effect has been carried out from the aspect of how added carbon-14 labeled substrates affect the decomposition of soil organic matter (42, 47, 67). Very few investigators have determined the influence of unlabeled organic substrates on the decomposition rate of radioactive plant materials at various stages of decay, an aspect which would seem to be meaningful for natural environments in which the soil receives frequent substrate additions. When soil was incubated with radioactive glucose and then given a second addition of unlabeled glucose, the rate of decomposition of the labeled residue was not increased (39,80). When radioactive

alfalfa meal was allowed to decompose for 42 days in soil, unlabeled glucose additions resulted in a 2- to 3-fold increase in the rate of alfalfa decomposition (77). Maximum alfalfa mineralization rates occurred at the same time that glucose utilization was highest, indicating increased decomposer activity contributed to the increased rates of decomposition.

B. Effects of Soil Temperature and Soil Water Content on Decomposition Kinetics

Soil temperature may influence decomposer activity by affecting growth and metabolism of the microflora and microfauna. Changes in temperature may influence different groups of soil organisms in various ways resulting in a complex interpretation of the effect of temperature on soil processes.

To find a quantitative relationship between microbial activity measurements and soil temperatures reported in the literature, comparisons must be made from different studies. Three major problems arise in evaluating the literature concerned with the influence of temperature on soil decomposition rates. Studies have been carried out at many different temperatures and temperature ranges. In many cases, the experimental temperatures do not approach the temperature extremes in nature. In addition, the units of measurement of decomposition rates are different in each study, and frequently not enough information is given to allow conversion to common units of rate measurement.

One approach to making comparisons among different studies is on the basis of the temperature quotient, i.e., the ratio of the velocity constants of decomposer activity at two temperatures. Although the most precise method would be to compare temperature coefficients varying by

some small change in temperature in order to avoid interpolation errors, it is customary to record the quotient for an interval of 10°C, expressed as the Q_{10}.

In reviewing the influence of temperature on microorganisms, Buchanan and Fulmer have indicated that Q_{10} values for many chemical and physiological reactions decrease with an increase in temperature (9). In fact, it is suggested that Q_{10} is a linear function of the reciprocal of absolute temperature. When soil samples are incubated in the laboratory at various constant temperatures and the temperature quotients calculated ($\log Q_{10} = (10 \div (Tp_2 - Tp_1)) \times \log(K_2 \div K_1)$), this relationship holds true for temperatures below 35-45°C (Table 2, Figure 2). Decreased Q_{10} values from about 45° to 65°C indicate decreased activity of thermophilic and thermotolerant microorganisms.

Soil water influences decomposer activity by acting as a medium for the transport of substrates, nutrients, enzymes, and end products to and away from the cell, by playing a direct role in cell metabolism, by influencing the movement of decomposer organisms, and by interacting with other physical-chemical factors effecting decomposer activity. The effect of soil water content on decomposer activity has been extensively studied. Unfortunately, soil water content is often expressed as a percentage of a soil characteristic such as water-holding capacity, making comparisons among soils difficult.

The influence of water on respiration in different soils can be compared if water contents are expressed on a tension basis. The rate of respiration generally reaches a maximum value at tensions ranging from 0.05 to 0.15 bars (4,53,65,85). Microbial activity at zero tension (water-saturated soil) shows a 1.1 to 3.1-fold decrease

Table 2. Influence of temperature on the Q_{10} of soil respiration measured in the laboratory.

Temperature range of data (°C)	Q_{10} value*	Parameter measured: CO_2 Evolution	Parameter measured: O_2 Consumption	Amendment	Reference
0 - 10	4.17	x		straw	81
10 - 20	6.00		x	none	10
8 - 18	2.55		x	glucose	21
7 - 18	3.47	x		oat straw + nutrients	81
8 - 18	2.55		x	glucose	21
8 - 27	4.40	x		none	55
10 - 25	1.95	x		straw	81
15 - 35	2.29	x		wheat straw + nutrients	8
20 - 25	3.33		x	none	10
20 - 25	2.42	x		none	10
18 - 27	1.87	x		oat straw + nutrients	81
18 - 28	1.46		x	glucose	21
30 - 37	3.30		x	none	10
30 - 37	2.21	x		none	10
28 - 38	1.15		x	glucose	21
30 - 35	2.66	x		none	55
27 - 37	.99	x		oat straw + nutrients	81

Table 2. (Continued)

Temperature range of data (°C)	Q_{10} value*	Parameter measured: CO_2 Evolution	Parameter measured: O_2 Consumption	Amendment	Reference
25 - 40	.89	x		straw	81
35 - 55	.59	x		wheat straw + nutrients	8
44 - 50	2.16		x	none	10
44 - 50	1.41	x		none	10
38 - 48	3.94		x	glucose	21
40 - 45	1.98	x		none	55
40 - 50	1.03	x		straw	81
35 - 55	.59	x		wheat straw + nutrients	8
50 - 56	2.29		x	none	10
50 - 56	1.96	x		none	10
50 - 55	2.21	x		none	55
55 - 65	1.01	x		none	55

* $\log Q_{10} = (10 \div (Tp_2 - Tp_1)) \times \log(K_2 \div K_1)$.

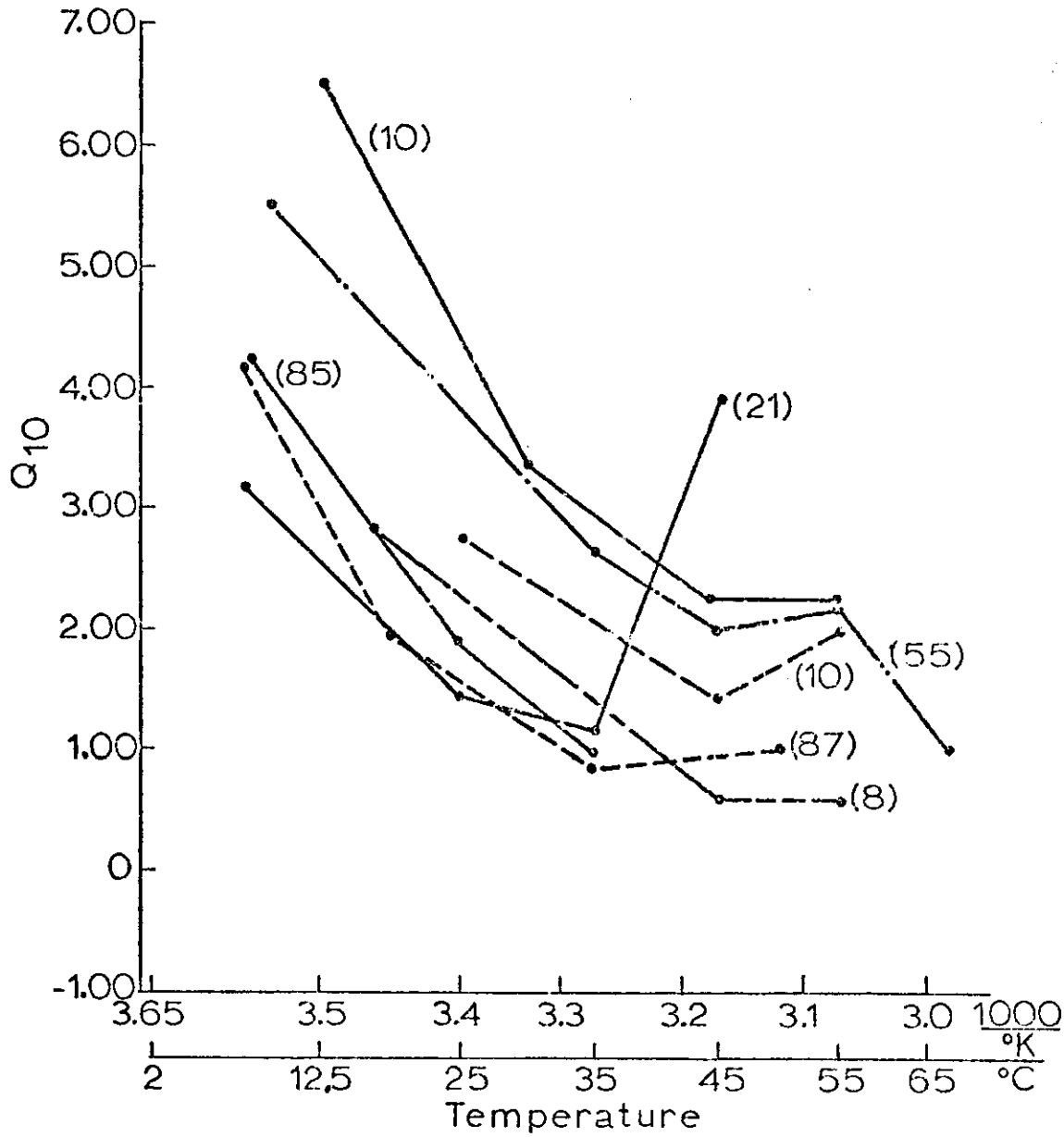

Fig. 2. Influence of temperature on Q_{10} for soil respiration data from laboratory experiments (numbers in parentheses refer to literature cited in text).

relative to the maximum value. At a tension of 3 bars, a 1.1 to 1.5-fold decrease in respiration relative to maximum activity is observed. At tensions greater than 50 bars (air-dry soil) a 12 to 13.5-fold decrease in respiration occurs (4,53,65,85).

Most studies of soil decomposer activity have been carried out under constant conditions of temperature and moisture, quite unlike the fluctuating environmental conditions found in nature. Drobnik studied the influence of temperature transition phenomenon on endogenous soil respiration and on the respiration of soils amended with glucose (21). Unamended soil samples experiencing a temperature increase from 8^{o} to 28^{o}C consumed 10-30% more oxygen than soil samples kept at 28^{o}C. Soil samples amended with glucose and brought from 8^{o} to 28^{o}C showed increased oxygen consumption of 289-470%, compared with samples incubated constantly at 28^{o}C. A 20^{o}C-diurnal temperature fluctuation is not uncommon in nature. Drobnik did not study the influence of smaller temperature transitions on soil respiration.

Freezing and thawing of soil has been shown by many workers to increase the amount of carbon dioxide, ammonia, and nitrate released on subsequent incubation (34). Soulides and Allison have shown that the total carbon dioxide evolution of soil samples subjected to ten intermittent freezing and thawing cycles was increased by 8-19% over soil samples not subjected to the freezing treatment (72).

Few experiments have been designed to determine the influence of fluctuating soil water on microbial activity. Soulides and Allison (72) reviewed the available literature on moisture fluctuations and determined that a prolongation of soil drying increased the rate of decomposition of organic matter once the soil had been rewetted. Soils

moistened 1 and 10 days after drying exhibited 20% and 40% higher respiration rates, respectively, than samples maintained at constant water content. Multiple dryings had a cumulative effect; soil samples moistened and dried three times had 14% higher respiration rates than samples dried only once. Sauerbeck (67) has also shown that the wetting-and-drying process has a large effect on the decomposition of native humus with a smaller influence on the mineralization of carbon-14 labeled straw.

C. Modeling Decomposer Activity

A number of equations have been proposed to describe changes in the levels of organic materials in soil (43,61). Laboratory and field experiments indicate that decomposition and residue accumulation processes in soil can be represented as exponential functions of time. This implies that decomposition rates can be represented logarithmically in such a way that a fixed decomposition factor determines residue loss.

Kirkham and Bartholomew derived several exponential models for describing the rates of immobilization and mineralization of plant nutrients in soil (49,50). Mineralization rates were calculated by multiplying the change in weight of a nutrient per unit time by a factor derived from kinetic theory, thereby converting the mineralization rate into an exponential function of time.

Olson proposed a simplified decomposition model (57) which has been utilized in many more recent models. With this approach, a change in amount of organic material per year is set equal to the annual production of organic matter minus the amount of the material decomposed per year. At the steady state of the ecosystem, there is no change in

organic matter levels on an annual basis; that is, the amount of material decomposed is equal to that produced annually. This implies that the decomposition rate is simply equal to a fixed amount of the annual production. These basic modeling relationships have made it possible to investigate the effect of various management practices on the turnover of organic materials in soils (33).

Jenny and co-workers, using an approach similar to that employed by Olson, had earlier considered decomposition rates to be functions of the soil-forming factors (48) Their modeling efforts were based on productivity measurements, which were corroborated with the results of alfalfa decomposition experiments in temperate and tropical soils.

Some models take into account the fact that different chemical components of organic matter decompose at different rates and that short-term seasonal variations occur in nature. Woodruff related the decomposition rates of humus and manure to the abilities of these materials to supply various crops with mineralized forms of nitrogen, expressing the mineralization rates of these nitrogen sources as decreasing exponential functions of time (88). Minderman indicated that the decomposition of leaves occurs as a non-exponential function of time and can be expressed by a curve summing up the exponential decomposition rates of the individual chemical components of the plant material (54). Russell expressed the seasonal variations in decomposition and production rates with a model that represented these rates as a trigonometric of Fourier series (66).

Witkamp related fluctuations in microbial activity in a forest ecosystem to changes in environmental conditions (86). His regression model contained the independent variables: litter temperature, (moisture

content of the litter)$^{\frac{1}{2}}$, log of number of bacteria, and time since leaf fall and predicted annual measured carbon dioxide evolution rates with moderate success (R^2=.50, n=198). This model aids in the prediction of rates of decay and mineral cycling in the forest floor under various environmental conditions.

Efforts of the I. B. P. Grassland Biome Program to model decomposition processes have been in relation to the development of total system models. In the PWNEE model, the index of the decomposer activity of a microbial group was conceived as being equal to the maximum population of the group multiplied by three operators that relate decomposer activity to soil water, soil temperature, and substrate levels (7). The most recent system model, entitled ELM, expresses decomposition of plant material as a sum of the decomposition of "hard" and "soft" substrates which decompose exponentially, and the total decomposition rate is influenced by soil temperature, soil water, physical leaching, and nitrogen functions (2). Fluctuations in microbial biomass, microbial carbon dioxide evolution rates, and litter biomass are predicted in this model on the basis of literature estimates of microbial activity under laboratory conditions.

D. Approaches to Modeling Changes in Soil Water Content

The process of evapotranspiration brings about an important exchange of water between the earth surface and the atmosphere, since about 70% of the precipitation reaching land is returned to the atmosphere by evapotranspiration (3). The rate of soil water loss from an ecosystem has a profound effect on producers, decomposers, consumers,

and abiotic ecosystem components; conversely, evapotranspiration is itself a function of meteorological, physical and biological processes.

Attempts to analyze complex interrelationships between soil, plants, and climate on a universal basis has resulted in the development of the concept of potential evapotranspiration. Using an approach involving empirical relationships, Thornthwaite expressed potential evapotranspiration solely as an exponential function of the mean monthly air temperature and applied a daylength adjustment to correct the relationship for latitude and season (78). A large group of deterministic potential evapotranspiration models are available and have been reviewed recently (3,13). Many of these models are based on Penman's model, in which monthly potential evapotranspiration is calculated from a complete set of climatological observations (62).

The rate of actual evapotranspiration can be calculated from a knowledge of how the potential evaporation rate is modified by the availability of water to the evaporative surfaces. In a recent review article, Baier indicated that there is no generally applicable solution for converting potential to actual evapotranspiration under various soil and climatic conditions (3).

Since many of the more empirical evapotranspiration models only yield reliable predictions on a monthly or annual basis, the deterministic models have been more popular in ecosystem analyses. Several of these deterministic evapotranspiration models have involved the use of Penman's equation (62) or some modification of this equation, such as SOGGY (35), ALGOI (29), and the first version of ELM (2). The major problem limiting the successful evaluation and use of these models has been the stringent data input requirements. In ALGOI, for example, the Penman

equation is composed of 12 terms, and once this equation is solved, actual evapotranspiration is calculated from a knowledge of two parameters defining plant-available soil water.

Another group of deterministic models has been developed that requires relatively less data input to predict changes in soil water. The Stanford Watershed Model IV accepts input data from a number of different recording gauges throughout a watershed and predicts stream-flow (19). Daily potential evapotraspiration is calculated solely from adjusted pan evaporation data in this model. Gardner successfully predicted evaporation rates from soil moisture flow theory during periods from May to October (30). For a given soil, he found a curvilinear relationship between fractional water loss and the square root of time divided by the initial soil water content. His model was validated using lysimeter data collected in the field.

The influence of temperature fluctuations on soil water movement has been used to evaluate moisture changes on a small scale. One approach has been to measure fluctuations in soil thermal conductivity and relate this to soil water changes. Based on these relationships, a conductivity probe was designed and used to measure soil water changes under field conditions (23). Another approach to modeling soil water fluctuations involves evaluating the rate of soil drying as a function of applied temperature gradients. Campbell determined the influence of various isothermal conditions on the evaporation rates from various bare soils (12). Sutor developed an empirical model expressing soil moisture distribution as a cubic function of distance along an applied temperature gradient multiplied by a constant

that was a function of bulk density, initial soil water content, mean soil temperature, and the magnitude of the temperature gradient (76). Fritton, Kirkham and Shaw (26) found that equations derived from heat and mass transfer theory could adequately describe soil evaporation rates in non-isothermal conditions such as those found near the soil surface in nature. The work involved laboratory observations on one soil; a field test of the model would seem to be desirable for evaluating the model's forecasting potential.

MATERIALS AND METHODS

A. Preparation of Carbon-14 Labeled Blue Grama

Dormant blue grama sods were harvested at the Pawnee Site on April 27, 1970 and grown in a closed system to which carbon-14 labeled carbon dioxide was added. The details of the labeling procedure and the apparatus for growing the plants and continuously supplying labeled carbon dioxide are given by Green and Cole (32). During the period of growth in the modified glove box, the carbon dioxide concentration in the biosynthesis chamber was continuously recorded, and when the concentration dropped to 300 ppm, additional labeled carbon dioxide was automatically supplied to allow blue grama photosynthesis. Prior to the start of each growth period, the stems and leaf sheaths of the sods were clipped to within 5 cm of the soil surface. Three successive harvests of tagged plant top material were made during the growing period beginning on July 8 and terminating on September 12, 1970.

After the last harvest of herbage, the sods were dried in a forced air oven at 60°C for three days; the plant material within 5 cm of the soil surface (stubble) was removed. The dried sods were then broken up, and roots were collected on a 4 mesh screen.

The harvest of carbon-14 labeled blue grama above-ground herbage and the radioactive root material collected at the end of the growth period were used in laboratory and field studies of decomposition. Part of the blue grama herbage and root materials was cut into approximately 2-cm lengths for use in field experiments, while the rest of the material was ground to pass a 20 mesh screen using a microWiley mill.

B. Use of Radioactive Blue Grama in Field Experimentation

Consideration of potential radiological hazards involved in field experimental work

Before any radioactive plant material was buried at the Pawnee Site, an evaluation was made of the potential radiological hazards involved in such a large field experiment. The evaluation contained calculations and approximations portraying "the worst possible situation" relative to radiation hazards. This evaluation was incorporated into an application, which is included in Appendix A.

Design of field experiments

Six major field experiments were planned to study the decomposition of the carbon-14 labeled blue grama. The first two experiments were designed to determine the influence of amendment level on the decomposition rates of herbage and root materials. Experiments three and four allowed an evaluation of the influence of season of burial on herbage decomposition rate and the effect of additions of fresh unlabeled herbage on the decomposition of partially degraded radioactive herbage. The objectives of experiments five and six were to compare the rates of decomposition of herbage in 2-cm segments with that of the ground material and to measure the rate of decomposition of herbage segments placed on the soil surface. The experimental designs of all six experiments are summarized in Table 3.

Preparation of field decomposition containers and study area

The field decomposition containers were constructed from half-gallon plastic freezer containers manufactured by the Mobil Chemical Company (Macedon, New York). The containers were 16 cm high and

Table 3. Description of field experiments with radioactive blue grama.

Experiment number and parameter studied	Amendment date	Type of plant material used	Amendment level (kg/ha)	Method of Amendment	Total number of containers
1. Influence of level of addition on herbage decomposition	2/11/71	ground herbage, composite of harvests 1 and 2	1280	mixed into top 3.7 cm soil	80
			128		80
2. Influence of level of addition on root decomposition	2/11/71	ground roots	1920	"	80
			384		80
3. Influence of season of burial on herbage decomposition	5/20/71	ground herbage from harvest 3	128	"	70
4. Effect of addition of fresh herbage on decomposition of partially degraded radioactive herbage	2/11/71	ground herbage, composite of harvests 1 and 2	128	"	165
	6/04/71	unlabeled ground herbage	1280	mixed into top 2.6 cm. soil	80
	7/07/71	"	1280	"	80
5. Decomposition of herbage and root segments	2/11/71	herbage segments from harvest 3	128	mixed into top 3.7 cm soil	80
		root segments	384	"	80

Table 3. (Continued)

Experiment number and parameter studied	Amendment date	Type of plant material used	Amendment level (kg/ha)	Method of Amendment	Total number of containers
6. Decomposition of herbage at the soil surface	2/11/71	herbage segments from harvest 3	128	placed on soil surface under glass wool	80

12.5 x 12.5 cm wide at the top, tapering down to a width of 11.2 x 11.2 cm at the base. Each box was modified by drilling five holes of 3.5-cm diameter in the bottom using a drill press, one hole in the center and one in each corner. A layer of glass wool (.08-.12 mm thick, 11 x 11 cm) was then glued to the inside of the bottom of the container and a sample identification number melted into the side of the container. The original container tops were modified by cutting a 12 x 12 cm plastic square out of the top with a razor blade and then welding a square of curtain material to the top by melting the plastic to the curtain material by the use of a hot plate. The dacron curtain material had 1 x 1 mm openings and was manufactured by the National Curtain Corporation.

The field experiments were located at the Pawnee Site of the Grassland Biome of the U. S. International Biological Program, 12 miles northeast of Nunn, Colorado. The specific site was at the north side of the enclosure of Microwatershed 8 in the northeast quarter of Section 15, T10N, R66W. The study area was 62 m long (extending in an east-west direction) and 9.3 m wide. A center strip, 3.1 m in width, was not used for experimental work due to the presence of a series of old post holes and ant hills. In the remaining area, 100 rows of 5 decomposition containers per row were installed and containers were spaced 0.5 m apart.

The empty decomposition containers were installed in premarked field positions starting in late September through early December of 1970. The installation procedure was as follows: (1) A hole was dug in the sod with roughly the same dimensions as the decomposition container; (2) The corners of the hole were cut with a knife to the dimensions of the container and excess soil removed; (3) The bottom of

the hole and the decomposition container were filled with approximately 1 cm of crumbled soil to insure soil-container contact; (4) The intact sod was placed into the decomposition container; (5) The container was inserted into the hole, using excess soil to insure good contact between the sides of the containers; and (6) The container's depth in the ground was adjusted so that its top edge was from 1.0 to 1.5 cm above the level of the adjacent ground.

The top 4 cm of soil from each field decomposition container was removed on January 23 and 24, 1971. The soil was then processed to pass through a screen with 6 x 6 mm openings (large pieces of plant material were removed) and mixed in a cement mixer. The soil was placed on sheets of paper outdoors at the Agronomy Farm for a period of one week to equilibrate to a uniform water content and then placed in lined garbage cans. One hundred and twenty-nine soil samples (3.17 kg each) were amended with either 1, 3, 10 or 15 g of radioactive blue grama, corresponding to amendment levels of 128, 384, 1280, and 1920 kg/ha, according to the experiment descriptions given in Table 3. The radioactive plant material was mixed with the soil for 5 min using a twin shell dry blender (manufactured by Patterson-Kelley Co., Inc., East Stroudsburg, Pennsylvania). An additional 71 soil samples were also mixed in the blender for 5 min, but were not amended with blue grama.

The soil samples were brought to the Pawnee Site on February 13, 1971 at which time 355 decomposition containers received 634 g each of soil unamended with labeled plant material. Amended samples (645) were left in partially opened plastic bags placed in the decomposition containers. These bagged samples were added to the containers during the period of February 14-16. The transfer procedure was as follows:

(1) A plastic collar made from an inverted half-gallon freezer container was placed down into the decomposition container; (2) The plastic bag containing the radioactive plant-soil mixture was placed into the collar and the bag emptied; (3) The collar was removed and the soil distributed evenly within the decomposition container; (4) The added soil was pressed down with the bottom of a half-gallon freezer container so that the topsoil inside and outside the decomposition container was approximately at the same ground level; and (5) The top was then placed on the decomposition container.

The experiment designed to study the decomposition of radioactive herbage segments at the soil surface (Experiment 6) was put out on February 17. The transfer procedure was much the same as for the other experiments, with the exception that a glass wool collar was placed over the labeled herbage segments which had been previously positioned on the soil surface. Each collar consisted of a .08-.12 mm thick, transparent glass wool layer sandwiched between two 12 x 12 cm plastic squares. Thus, a 10 x 10 cm area of soil was exposed in each decomposition container, civered by a transparent layer of glass wool.

An additional 165 field containers of soil amended with labeled blue grama were set out on February 19, 1971, to determine the effect of additions of unlabeled blue grama herbage on the decomposition rates of tagged substrate (Experiment 4). For this purpose, each of 80 containers received no additions of untagged plant material. The nonradioactive blue grama was harvested from the U.S.D.A. Central Plains Experiment Station blue grama plots on May 26, 1971. Amended and non-amended soil samples were harvested and mixed with the nonlabeled plant material, using procedures already described, and returned to the

decomposition containers at the site within one day after removal. No attempt was made to keep each soil sample in its original container, but samples amended with unlabeled blue grama were always kept separated from nonamended samples.

Sampling schedule and procedures for field decomposition study

Five replicate containers of soil were collected at each sampling date for Experiments 1, 2, 3, 5, and 6. Samples were taken for Experiments 1, 2, 5 and 6 on the following dates: (1) February 19, 1971; (2) April 1, 1971; (3) May 20, 1971; (4) June 15, 1971; (5) July 16, 1971; (6) August 12, 1971; (7) September 16, 1971; (8) October 13, 1971; (9) November 17, 1971; (10) January 12, 1972; and (11) March 29, 1972. Samples for Experiment 3 were taken on May 21, 1971 and then on dates (4) to (10) above. For Experiment 4, one set of 5 replicate samples was taken on February 19, 1971, 10 samples were taken on June 4, 1971 before amending with unlabeled blue grama, and 15 samples were taken of each subtreatment (amended and nonamended with unlabeled blue grama) on November 17, 1971.

The sampling procedure for harvesting the decomposition containers was as follows: (1) The entire container was pulled out of the soil and placed in a large plastic bag; (2) The samples were transported in the bags to the laboratory where the contents were dried for one week at 60°C in a forced-air oven; (3) The top 400 g of soil (Experiments 1-5) or the top 200 g of soil (Experiment 6) was removed and three 10-g composite samples, each of which consisted of twenty 0.5-g subsamples from the bagged soil sample were obtained; and (4) The composite samples were placed in individual stainless steel vials, in which they were ground

and blended on a Pica blender-mill for 3 min. All of the soil collected in Experiments 5 and 6 were ground and blended, whereas only the 10-g composite samples were processed in the other experiments. All soil samples, including the containers with unsampled soil, were then stored at $-3^{o}C$.

Characteristics of experimental soil

The experimental soil from the 0-4 cm soil depth was classified as a non-calcareous Ascalon sandy loam; the mineralogical characteristics and soil water potential curves have been established for this soil (25, 28). The gravimetric water contents of soil samples at .10 and .33 bars tension, performed by methods described by Black et al. (5), were 14.6 and 12.3%. The soil contained 0.92% total carbon, exhibited a pH of 6.8 in a 2:1 soil:water mixture, and had a bulk density of 1.4 g/cc.

C. Radiocarbon and Total Carbon Analyses of Plant and Soil Samples

Description of dry combustion system used for radiocarbon and carbon analyses

A Coleman Nitrogen Analyzer (Model 29A) was modified to combust soil and plant samples for radiocarbon and carbon analyses. Although the combustion tube packing material, Coleman Cuprox reagent (manufactured by the Perkin-Elmer Corporation, Maywood, Illinois), is the same for nitrogen and carbon analyses on this instrument, three modifications were made in order to perform the carbon analyses: (1) Commercial oxygen was used as the carrier gas; (2) The post heater tube packing material was changed; and (3) A diversionary gas line was installed at the nitrometer inlet connection. The post heater tube contained a stainless steel plug, followed by consecutive layers of

glass wool (3 mm), Coleman Cuprox platinum catalyst (8.5 cm), glass wool (6 mm), silver vanadate (3.1 cm), glass wool (6 mm), Cuprox platinum catalyst (5 cm), and glass wool (3 mm), and closed with another stainless steel plug.

The gas flow through the Nitrogen Analyzer was diverted at the nitrometer inlet connection using a pyrex socket joint used with a ball 12 mm in diameter. The glass tubing of this joint was L-shaped, 16 cm long, and had an inside diameter of 2 mm. The socket joint was attached to the nitrometer inlet connection, using a spring clamp, and was connected to a 95 cm length of vinyl tubing (5 mm inside diameter) containing consecutive layers of glass wool (2 mm), 10-20 mesh Drierite (49 cm), glass wool (1 cm), technical grade coarse manganese dioxide powder (40 cm) and glass wool (2 mm). When total carbon determinations were being performed, a Nesbitt absorption bulb was attached to the end of the Drierite-MnO_2 column, but a gas dispersion attachment was used to bubble the carrier gas through the absorption solution for radiocarbon analyses.

The gas dispersion attachment was constructed from a 1.5-cm length of a polyethylene gas dispersion tube (12 mm outside diameter, 30-40 micron porosity), which was sealed on the bottom end with a piece of plexiglass (5 mm thick, 12 mm outside diameter). The rest of the gas dispersion attachment consisted of a 52-cm length of vinyl tubing (2 mm outside diameter), one end of which extended into the dispersion tube and the other end was jointed to a 2.5-cm length of glass tubing (4 mm outside diameter). A number 0 rubber stopper with two holes in it was attached to the middle of the vinyl tubing and acted as the

stopper of the test tube into which the gas dispersion attachment was inserted.

Liquid scintillation counting of carbon-14

Two systems were used for radiocarbon analyses. The first system was used in a few preliminary experiments and consisted of: (1) hyamine hydroxide (New England Nuclear, Boston, Massachusetts), (2) a scintillation solution made by adding 4.000 g of PPO (2,5-diphenyloxazole) and 50 mg of POPOP (1,4-bis-2-(5-phenyloxazlyl)-benzene) to one liter of toluene (Nuclear-Chicago, Des Plaines, Illinois); (3) a set of quenched carbon-14 standards and standard background sample provided by Nuclear-Chicago, and (4) a Nuclear Chicago Mark I scintillation counter. The second carbon-14 system was used for most of the research analyses and consisted of: (1) an absorption solution made by making a 2:1 (volume:volume) mixture of 2-methoxyethanol and ethanolamine (Isolab, Inc., Akron, Ohio); (2) a scintillation solution consisting of a 2:1 (volume:volume) mixture of toluene and 2-methoxyethanol, plus 7 g of butyl-PBD (2-4'-tert-butylphenyl)-5-(4''-biphenyl)-1,3,4-oxydiazole) per liter of toluene (Isolab, Inc., Akron, Ohio); (3) a set of quenched carbon-14 standards (described below); and (4) a Nuclear-Chicago Mark II scintillation counter. The routine procedure for radiocarbon determinations was to pipette a 3.0-ml aliquot of the carbon dioxide absorption solution into a scintillation vial and then add approximately 16 ml of scintillation solution to the vial.

The absorption solution in the second system was previously used by Jeffay and Alvarez (40). However, the scintillation solution differs

in that it contains the scintillator butyl-PBD, which has higher counting efficiencies for quenched samples than many other commonly used fluors (69).

The external standard method was used to calibrate the channel counting efficiency and to correct for sample quenching in radiocarbon determinations using the second scintillation system. A set of quenched samples were made so that a given amount of quenching in any sample could be related to the sample's counting efficiency. Seven 0.25-ml aliquots of a solution of carbon-14 labeled DDT (1,1,1-trichloro-2,2-bis(p-chlorophenyl) ethane), which had an activity of 1.00 uCi per ml, were pipetted into scintillation vials. Varying quantities of the quenching agent carbon tetrachloride were added to the scintillation vials to produce amounts of quenching that would reduce the counting efficiency to the level of that likely to be found in experimental samples. Thus, 0, 20, 40, 60, 80, 100, and 130 ul of carbon tetrachloride were added to the seven vials, followed by 16 ml of scintillation solution.

The quantitative relationship between counting efficiency and amount of quenching was determined using the external standard method of calibration to quantitatively determine counting efficiency. The sample was counted once without and then with the external gamma source; counts were registered in channels A, B, and C of the instrument. The ratio of the difference of the two counts in channel B was found to be sensitive to quenching. Thus, this C:B ratio was related to counting efficiency for the standard quenched samples. The unquenched and the highly quenched samples consistently demonstrated counting efficiencies of 94% and 80%, respectively. The standard quench curve was determined

every time a set of samples was counted. Since this information was to be used in a computer program to calculate radiocarbon levels, a regression equation was developed relating the inverse of counting efficiency to the C:B channel ratio (Figure 3). A quadratic regression model was found to be superior to a linear regression model in the range of counting efficiencies normally encountered with routine samples (84-88%).

Calculation of sample radiocarbon content and related variables

Samples consisting of labeled blue grama or mixtures of soil and labeled blue grama were combusted in the Nitrogen Analyzer. A 3.0-ml aliquot of the total 5.0 ml of absorption solution was taken for counting on the scintillation spectrometer. The carbon-14 activity of such a sample was calculated as:

$$SA = (SB-B)(1/E)(5/3)(1/W)$$

Thus, the sample activity of the combusted sample (SA), expressed in dpms/g sample, is a function of the counting rate (cpm) of the sample (SB), the counting rate (cpm) of a background sample (B), the inverse of the counting efficiency (1/E), and the weight (grams) of the sample (W). The background sample is a blank sample containing no added radioactivity but having the same chemical composition as the unknown sample. Thus, the counting rate of the background sample (B) is subtracted from the counting rate of the sample being determined (SB) to obtain the true net counting rate. The (1/E) term is calculated using the quadratic regression equation to relate the C:B channels ratio of the individual sample to the inverse of the counting efficiency.

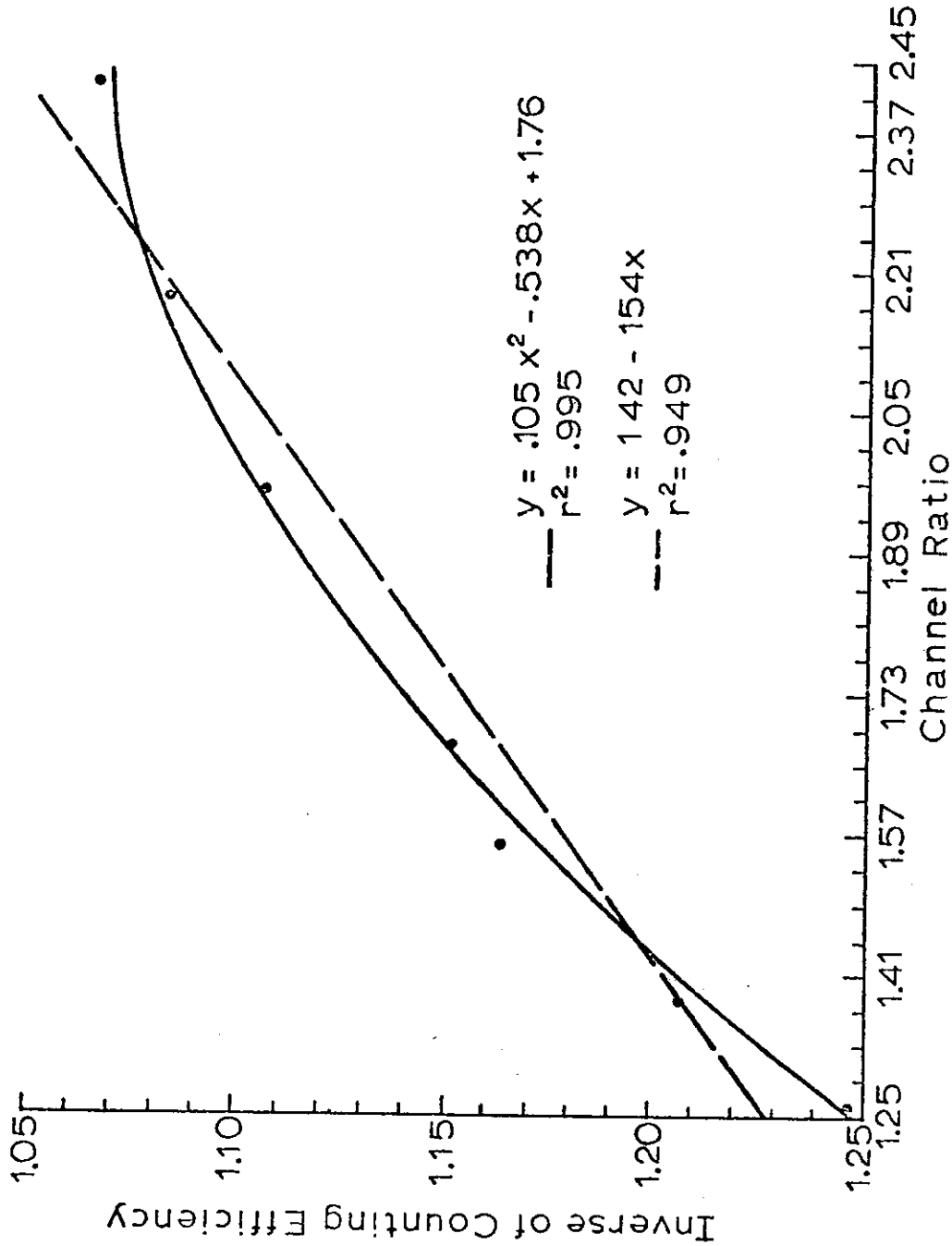

Fig. 3. Standard radiocarbon quench curve for the determination of sample counting efficiency using the external standard method.

Radiocarbon contents of soil samples from field containers were expressed on the basis of oven-dry soil weights. Soil samples were routinely dried for one week at 60°C in a forced-air drying oven prior to combustion. Determination of moisture in samples taken on each sampling date by the standard procedure (24 hours at 110°C) indicated no measureable water remained in the soil. Thus, no correction for soil water content was necessary for field samples subjected to radiocarbon analysis.

The terms percent radiocarbon recovery and percent carbon retention, which appear in the text, are calculated by dividing the measured value of SA by the expected radiocarbon activity in the soil-plant mixture at time zero and multiplying the result by 100. The expected radiocarbon activity is calculated from the amount of blue grama added at time zero and its measured radiocarbon activity. Percent carbon loss is calculated by subtracting percent carbon retention from 100.

Total carbon determinations using the Nitrogen Analyzer

Total carbon determinations were made by a modification of methods described by Black et al. (6). Plant and soil samples were combusted in the Nitrogen Analyzer and the carbon dioxide combustion endproduct absorbed by 20-30 mesh Ascarite and 8-20 mesh Caroxite contained in Nesbitt absorption bulbs. The increase in weight of the absorption bulb, due to the addition of this carbon dioxide, was measured on an analytical balance. The percent total carbon was calculated by dividing the weight of the carbon dioxide carbon by the weight of the sample, and multiplying the result by 100. Calcium carbonate samples (75 mg each) and glucose samples (100 mg each) were combusted to determine the efficiency of carbon recovery.

D. Laboratory Investigation of the Effect of Soil Water Content, Temperature, and Time on the Decomposition of Carbon-14 Labeled Blue Grama

Soil was collected on March 8, 1972 from the 0-4 cm depth within the center strip of the Pawnee experimental site and was treated to pass a screen with 6 x 6 mm openings; large pieces of plant material were removed in the process. The soil was then stored in a large plastic garbage can at -3°C until April 17, 1972.

Laboratory incubation flasks consisted of 500-ml Erlenmeyer flasks closed with number 7 rubber stoppers. A hole with a 13-mm diameter was drilled in the center of each rubber stopper, and a rubber serum cap septum was hammered into the hole. A length of plastic covered wire was attached to the underside of the rubber stopper with a straight pin. This wire was used to hold a scintillation vial, which contained the carbon dioxide absorption solution. The bottom of the vial was suspended approximately 2 cm above the soil surface.

The stored soil was amended with ground radioactive herbage from harvest three and mixed in a twin shell dry blender for five min in the -3°C cold room. The preweighed incubation flasks were then placed in the cold room and 51.5 g of soil containing 0.2 g of plant material was weighed out and added to each flask. Weighed quantities of crushed ice made from distilled water were added to the flasks and mixed into the soil by rotating the flask to produce desired soil moisture levels. Scintillation vials containing 1.0-ml quantities of 10 N KOH were wired into place in each flask and the incubation flasks were brough out of the cold room. The flasks were allowed to equilibrate for 8 hr at room temperature (to allow the ice to melt) and for 3 hr in an incubator set at the temperature of the incubation period. At the

end of the last 3-hr equilibration period, the scintillation vials containing the KOH were removed and empty vials wired into place. The latter event marked the starting time for measuring the decomposition of the labeled plant material at 6 soil water regimes (2.6, 5, 10, 20, 25 and 36% soil water on an oven-dry weight basis) and 6 soil temperature regimes (3°, 10°, 25°, 40°, 50°, and 60°C), with 4 replicate incubation flasks per water-temperature regime.

Respired carbon-14 labeled carbon dioxide and soil water changes were determined during the incubation periods. The standard procedure used was as follows: (1) Three ml of the 2-methoxyethanol-ethanolamine absorption solution was injected through the septum in the stopper of the flask into a scintillation vial; (2) The carbon dioxide was absorbed for 8 hr; (3) The flask was opened and the scintillation vial removed; (4) The flask and contents were weighed; (5) An empty scintillation vial was wired in place and the incubation flask closed; and (6) The flask was equilibrated at the appropriate incubation temperature for 30 min and then equilibrated with atmospheric pressure by puncturing the septum with a syringe needle attached to an 8-cm length of tygon tubing filled with 20-30 mesh Ascarite. A radiocarbon determination was made on the absorption solution by adding 16 ml of scintillation solution to the vial and submitting the vial to liquid scintillation counting, using the second system described previously.

Oxygen (O_2) consumption in the incubation flasks was measured by gas chromatography using an Aerograph model A-90-P gas chromatograph equipped with a thermal conductivity detector. A stainless steel column, 150 cm in length and 63 mm in diameter, was packed in 30-60 mesh Molecular Sieve 5A. This column was maintained at 90°C and helium

was used as the carrier gas. The detector output was recorded on a Sargent model SR strip chart potentiometric recorder.

The oxygen determinations for the incubation flasks were performed at the end of the incubation periods. Gas samples were taken with a Plastipak 1.00-ml tuberculin syringe by pushing it through the rubber septum in the top of the incubation flask (after carbon dioxide absorption) or, for the oxygen standard curve, from the air outside of the laboratory. The oxygen standard curve was constructed by plotting oxygen concentration as a function of peak height. Replicate samples of air (0.2, 0.4, 0.6, 0.8, and 1.0 ml) were used to construct the oxygen standard curve; it was assumed that the air contained 21% oxygen. The resulting oxygen standard curve prepared was linear with respect to detector response over the range of oxygen concentrations used.

E. Influence of Temperature and Soil Water Content on the Drying Rate of Soil

One hundred decomposition containers holding unamended soil were taken from the experimental site on November 10, 1971 to determine the influence of temperature on soil drying rates. Each container received a 12.5-mm simulated rain within a 30-min period. The simulated rain was applied using a 49 x 31 x 23 cm plexiglas tank, which contained a sheet of rubber 5 mm thick glued to the tank's plexiglas bottom, into which 26 gauge hypodermic needles (12.5-mm length) were imbedded. The needles were positioned 3 cm apart and the simulated rain was applied to each container through 20 needles located 55 cm from the soil surface. After the rain was applied, the containers were placed in laboratory incubators set at 5°, 20°, 30°, 40°, 50°, and 60°C. Ten containers were placed at each temperature. A model MMX-110 Mini-mixer was used

to replace all of the air in each incubator 14 times a day. Two soil samples were taken to a depth of 2.5 cm at various sampling times with a number 3 cork borer, and gravimetric soil water determinations were performed on both samples. The first set of soil samples for moisture analyses was taken 30 min after the rain application. Additional soil samples were analyzed at varying times depending on the drying temperature: (1) 5°C: 24, 48, 67, 89, and 115 hr; (2) 20°C: 12, 25, 50, and 78 hr; (3) 30°C: 10, 29, 51, and 77 hr; (4) 40°C: 12, 36, 50, 75, and 103 hr; (5) 50°C: 7, 17, 24, 31, and 42 hr; and (6) 60°C: 5.5, 11, 21, 28, 35, and 46 hr.

The top 3 cm of soil was removed from 30 decomposition containers taken from the field on November 10, 1971, for use in an experiment designed to determine the influence of soil water content on soil drying rates. Two hundred-g quantities of soil (oven-dry weight basis) were placed in the bottoms of 24 plastic sandwich boxes (12.2 x 12.2 x 3 cm). Water was slowly pipetted onto the soils to bring the water contents to 2, 7, 12, 17, 22, 27, 32, and 36% (oven-dry weight basis). Three replicates of each moisture treatment were used. The plastic tops were placed on the boxes, and the soil was equilibrated for 24 hr at room temperature. At the end of this time, the plastic tops were taken off, field decomposition container tops put on, and the box-top combination weighed. All 24 boxes were then placed in an incubator set at 20°C with the incubator air exchanged with laboratory air 14 times a day using the Minimixer pump. The boxes were taken out of the incubator at 4.5, 10, 23, 31, 58, 105.5, and 123.5 hr after drying was initiated and weighed to determine water loss.

F. Effect of Rain Events of Various Sizes on Soil Water Content

A total of 14 containers of soil were taken from the field experiment site on November 10, 1971, to be used to determine the effect of simulated rain event on changes in soil water content. Tap water was pipetted evenly over the entire soil surface of each container, in a amounts corresponding to rain events of 1.25, 2.50, 3.75, 6.25, 8.75, 12.50 and 18.75 mm. Each rain event was applied over a period of 10 min to duplicate containers. Fifteen min after the water addition, one side of the plastic container was cut away and the entire contents of the box harvested with a putty knife in 1.0-cm increments. The soil samples were placed in plastic bags and allowed to equilibrate for 24 hr at room temperature. Then two water determinations were performed on each bagged soil sample. The increase in water content was then calculated for each container, taking the soil water content before rain addition to be equal to the average water content of the 2-cm soil depth which was 1 cm below the rain penetration depth.

G. Monitoring Soil Water Content, Precipitation, and Soil Temperature in the Field Decomposition Containers

Soil water content of the field decomposition containers was monitored by taking weekly soil samples to a depth of 2.5 cm. A total of 6 decomposition containers holding unamended soil, randomly located within the group of 1000 containers, were used for this purpose. Five of the 60 containers were sampled on each sampling date from April 1, 1971 to March 29, 1972, and one water determination was performed on each soil sample collected.

The daily rain gauge data was collected at Microwatershed 8 and assembled by Dr. W. D. Striffler of the Department of Watershed Sciences,

Colorado State University. The rain gauge recorder charts from the time period April 1, 1971 to March 29, 1972 were further analyzed to determine the duration and hour of each daily rain event. Thus, average hourly precipitation data could be calculated from the daily precipitation data.

A remote recording, three point thermograph (Weather Measure Corporation, Sacramento, California) was used to obtain continuous monitoring of soil temperature at the experimental site for weekly intervals from April 1, 1971 to March 29, 1972. Two of the thermograph probes, which were 18.5 cm long and 1.5 cm in diameter, were fastened in holes drilled in an empty decomposition container. The probes extended 3 cm beyond the container side wall. The decomposition container with attached thermograph probes was brought to the site and filled with the soil from another decomposition container. The probe depths were 0.5 to 2.0 cm and 4.0 to 5.5 cm below the soil surface. The data reduction process consisted of taking hourly readings from the thermograph recorder sheets and listing these on computer data sheets.

H. Computer Programs Used for Routine Calculations and Modeling Efforts

Three computer programs were written by Jerry Peltz of the Natural Resources Ecology Laboratory for use with the soil temperature data, the carbon-14 determinations, and soil drying rates. One program used the thermograph data from two depths as input and was designed to produce: (1) a frequency distribution of the temperatures for a particular time period, in terms of percentages or total number of hours of a specific temperature; (2) mean temperature of that time interval; and (3) standard deviation of the soil temperature. The

second program, entitled "DECOMP", used sample identification information, scintillation counter counts from three channels, and the standard carbon-14 quench curve scintillation counter counts, as basic input and yielded: (1) the results of a quadratic regression analysis of the standard quench curve; (2) a list of the calculated radiocarbon contents for each identified sample; and (3) a statistical analysis of field samples at the composite and sampling date level, which included means, standard deviations and coefficients of variation. The third program, entitled "SOIM", used soil water data, rain gauge data and soil temperature data to predict successive hourly soil water values.

Unless otherwise specified, all regression analyses of the hydrologic and decomposer processes were performed using the STAT38R program of the Colorado State University Statistical Laboratory. This stepwise regression program is a modification of the University of California Biomedical Computer Program BMD02R.

I. Development of Model to Describe Decomposition of Blue Grama in the Field

The decomposition modeling efforts were carried out using a program entitled "DECOM 1". This computer program was developed so that a simulation of blue grama decomposition in the field could be performed. The input to this computer program consisted of hourly soil temperature data, hourly rain gauge data, and average soil water content and the standard deviation of soil water content for one hour of a week. Given this data input, DECOM 1 predicted hourly average soil water content, hourly average soil water content plus or minus 3 standard deviations of

the average soil water content, and the hourly decomposition rates and cumulative decomposition at these three soil water regimes.

RESULTS AND DISCUSSION

A. Analysis of Soil and Plant Samples for Total Carbon and Radiocarbon

Total carbon determinations

To analyze soil and plant samples for total carbon, a procedure was developed in which samples were combusted in a stream of oxygen in the Coleman Nitrogen Analyzer, and the carbon dioxide formed during combustion was absorbed by Ascarite and Caroxite. The total carbon measurements were performed using glucose and calcium carbonate samples to determine carbon recovery for the combustion-absorption system. Three 100-mg samples of glucose were combusted and yielded carbon recoveries of 98.8, 99.1 and 98.9% of the carbon calculated to be in the samples. Three 75-mg samples of calcium carbonate were combusted and decomonstrated carbon levels of 99.4, 95.5 and 97.6% of the total theoretical carbon content. On the basis of these results, the combustion technique and CO_2 trapping system were considered to yield carbon recovery values satisfactory for performing routine analyses.

Radiocarbon determination

A procedure was developed to determine the radiocarbon content of soil amended with carbon-14 labeled blue grama. Soil samples were combusted in the Coleman Nitrogen Analyzer and the resulting labeled carbon dioxide was bubbled through an aliquot of which was taken for C-14 analyses in a liquid scintillation counter.

Carbon dioxide absorption capacity of the absorption solution - Five soil samples amended with labeled blue grama were combusted in the

Coleman Nitrogen Analyzer, and the combustion products were directed through a train of three test tubes (16 x 125 mm) each containing 5 ml of the absorption fluid, a 2:1 (volume:volume) 2-methoxyethanol:ethanolamine mixture found to absorb labeled carbon dioxide satisfactorily in other analytical systems (40). Radiocarbon determinations were performed on a 3-ml aliquot of solution from the first test tube in the absorption train for each combusted sample. These five samples had radiocarbon activities corresponding to 1111, 1238, 1215, 1187 and 1284 disintegrations per minute (dpms). The radiocarbon contents of the second and third test tubes in the absorption train were also determined for each soil sample combusted, and all ten of these samples had counting rates equivalent to that of the carbon-14 background sample. For all practical radiation health and analytical purposes, the radioactive combustion endproducts were trapped in the first test tube of absorption solution. Thus, the standard radiocarbon combustion procedure consisted of bubbling combustion endproducts through absorption solution in a single test tube.

Statistical analyses of the effect of varying the lengths of combustion and combustion-sweep times on radiocarbon recovery from soil - The Coleman Nitrogen Analyzer (Model 29A) automatically proceeds through the following series of timed cycles: purge cycle (0.67 min), preheat cycle (2.00 min), combustion cycle (3.67 min), combustion-sweep cycle with furnaces extended (4.00 min), and combustion-sweep cycle with furnaces retracted (0.67 min). A manually operated cycle delay switch can be activated during any of these cycles for an indefinite time period. The flow rate of the carrier gas was maintained at 30-40 cc/min during the sample combustion process.

A 2 x 3 factorial completely randomized experiment was designed to determine the effect of varying combustion-sweep and combustion times on the recovery of blue grama radiocarbon from soil samples combusted in the Analyzer. Five 500-mg soil samples were combusted for each of the six treatments, the resulting carbon dioxide absorbed in the 2-methoxyethanol-ethanolamine solution, and the sample counting rates of the absorption solution determined. Table 4 contains the results of the statistical analyses of these data, including analysis of variance and orthogonal comparisons of the six treatments. Although no significant differences were found in radiocarbon levels of samples combusted for various lengths of time, there was a significant combustion-sweep treatment effect. The results of the orthogonal comparisons of individual treatments indicated that samples receiving the preset combustion-sweep and preset combustion treatment (S_1C_1 in Table 4) exhibited significantly lower radiocarbon recoveries than any other treatment. In view of the more efficient radiocarbon recovery with increased combustion-sweep time, the standard radiocarbon combustion procedure adopted utilized the extended combustion-sweep cycle and the pre-set combustion time (S_2C_1 in Table 4).

Influence of different ratios of radioactive to nonradioactive carbon on carbon-14 recovery values - A small amount of the mixture of oxygen carrier gas and combustion products formed during a sample run on the Coleman Nitrogen Analyzer is bled to the atmosphere during the pre-heat and combustion cycles. Thus, portions of sample radiocarbon would be lost, the amounts varying with the magnitude of radiocarbon in different samples.

Table 4. Statistical analyses of the effect of varying the lengths of combustion and combustion sweep times on radiocarbon recovery from soil.

1. Treatment descriptions and average radiocarbon levels (dpms/3 ml absorption solution/0.500 g sample)

Preset Combustion Sweep Time			Preset Combustion Sweep Time + 2 Minutes		
Preset Combustion Time (S_1C_1)	Preset Combustion Time + 2 Minutes (S_1C_2)	Preset Combustion Time + 4 Minutes (S_1C_3)	Preset Combustion Time (S_2C_1)	Preset Combustion Time + 2 Minutes (S_2C_2)	Preset Combustion Time + 4 Minutes (S_2C_3)
1165	1452	1382	2168	1434	1664

2. Analysis of variance table for 2x3 factorial randomized complete block design

Source of Variation	df	Sum of Squares	Mean Square	F
Treatments	5	2,969,616	593,923	2.65*
Combustion-Sweep Time	1	1,336,052	1,336,052	5.97
Combustion Time	2	255,504	127,752	.57
Interaction	2	1,378,060	689,030	3.08*
Replications	4	594,869	148,717	.64
Error	20	4,478,364	223,918	
TOTAL	29	8,042,849		

Table 4. (Continued)

3. Orthogonal comparisons of individual treatments

Treatments Compared	Treatments						Mean Square	F
	S_1C_1	S_1C_2	S_1C_3	S_2C_1	S_2C_2	S_2C_3		
S_1C_1 vs. rest	-5 0	+1 +1	+1 +1	+1	+1	+1	863,818	3.85**
S_2C_1 vs. S_1C_2, S_1C_3, S_2C_2, S_2C_3	0	+1	+1	-4	+1	+1	1,874,709	8.37***
S_1C_2, S_1C_3 vs. S_2C_2, S_2C_3	0	+1	+1	0	-1	-1	86,593	.39
S_2C_2 vs. S_2C_3	0	0	0	0	+1	-1	132,250	.59
S_1C_2 vs. S_1C_3	0	+1	-1	0	0	0	12,250	.06

* Significant at .10 level.

** Significant at .025 level.

*** Significant at .01 level.

An experiment was designed to determine the effect of varying quantities of labeled carbon in soil samples on the recovery of radiocarbon. Soil amended with radioactive blue grama was mixed with nonlabeled soil to give radiocarbon levels ranging from 10 to 87.5% of that in the amended soil. The relationship between the measured and expected levels of radiocarbon in samples containing different ratios of radiocarbon is shown in Table 5. Regression analysis of the expected (E) and measured (M) radiocarbon levels for each of the 13 combusted soil samples resulted in a regression equation, $M = 59 + .93E$, with a coefficient of determination equal to .950. Thus, there is a good correlation between expected and observed radiocarbon recoveries over the range of radiocarbon levels studied.

Preparation and sampling of mixtures of soil and labeled plant material - Two experiments were designed to develop a satisfactory procedure for mixing labeled blue grama with soil and sampling the soil-plant mixture.

The first experiment involved mixing 2.0- and 0.2-g quantities of labeled plant material with 600-g quantities of air-dried soil in a twin shell dry blender and then taking five 500-mg subsamples for combustion and radiocarbon analysis. The amendment procedure consisted of putting the soil in a twin shell dry blender, placing the labeled herbage in a small furrow on the soil surface, and mixing for 5 min. The overall percent recovery of radiocarbon in this first experiment was only 93%, perhaps, as a result of the way the plant material was added to the soil in the blender. If ground plant material is placed too close to the soil surface in the amendment process, a portion of the material is observed to come in contact with parts of the blender lids

Table 5. Influence on radiocarbon determinations of different ratios of radioactive and nonradioactive carbon in combusted samples.

Percent of total sample weight consisting of soil amended with labeled blue grama	Radiocarbon levels (dpm/3 ml absorption solution/0.5 g)	
	Expected (calculated)	Observed
100.0	-----	1286*
87.5	1125	1212
75.0	965	930
63.0	810	702
50.0	643	620
33.0	424	551
25.0	322	340
10.0	129	191
0.0	0	0

* Average of four replicate determinations; all other values represent the average of two determinations.

with the initiation of mixing and is not mixed into the soil mass. The analysis of variance (Table 6) indicated no significant differences in radiocarbon recoveries due to level of addition of plant material, but radiocarbon recoveries from different soil-plant mixtures did vary significantly. This procedure was considered unsatisfactory because each of the mixes were to be used in the field decomposition experiment, where variation in radiocarbon recovery due to mixing had to be minimized and recovery values had to be consistently close to 100%.

Since the first mixing-sampling procedure did not meet the latter requirements, a more detailed recovery experiment was designed to promote better mixing and improved sampling of these materials, which differed in density and particle size. Two 2250-g mixtures of soil from the experimental site were weighed and each amended with 0.500 g of ground radioactive herbage. Amendment procedures were identical to those used in the previous experiment, except that the plant material was placed near the center of the soil in the dry blender and was completely covered before initiating mixing. Each of the two soil mixtures were divided into three 750-g mixture subsamples and placed in plastic bags. Three 10-g composite samples were procured from each of two of the 750-g mixture subsamples by selecting twenty 0.500-g random subsamples. After the composite samples had been pulverized and mixed in the Pica blender-mill, three 0.500-g subsamples were weighed out from each composite sample, combusted and subjected to radiocarbon analysis. The overall recovery of radiocarbon in this experiment was found to be 107% (coefficient of variation = 13%), attributed in part to the improved mixing observed between soil and plant particles. Statistical analysis of the experimental results indicated that mixtures and

Table 6. Recovery of carbon-14 from labeled plant material added to soil at two levels.

1. Experimental results

Amounts (g) of labeled plant material added to 600g soil	Mixture number	% Recovery of radiocarbon from subsamples				
2.0	1	96.18	82.08	82.75	86.77	97.74
2.0	2	86.22	99.23	104.65	102.13	97.71
0.2	1	87.15	69.12	80.53	79.16	81.70
0.2	2	98.33	95.82	103.12	133.46	97.64

2. Analysis of variance table

Source of variation	df	Sum of squares	Mean square	F
Rate of addition	1	4.45	4.45	.005
Mixtures/addition rate	2	1905.82	952.91	9.602***
Subsamples/mixture	16	1587.90	99.24	
TOTAL	19			

*** Significant at the .01 level.

composites per mixture subsample were not significant sources of variation, but there was a significant difference in mixture subsamples taken from soil within soil-plant mixtures (Table 7). Thus, this sampling scheme was considered to yield acceptable recovery values for radiocarbon from mixture to mixture and was adopted as the standard method of sampling soil samples from the field experiments, i.e., all of the mixture subsamples per mixture were harvested on each sampling date.

Analysis of experimental soil and blue grama samples for total carbon and radiocarbon - The radiocarbon and total carbon content of the blue grama plant materials to be used in the decomposition experiments was determined. Three 1-g subsamples of the blue grama from each biosynthesis chamber harvest were ground and blended in a Pica blender-mill for 3 min. Radiocarbon determinations were performed on 25-mg quantities from each subsample and the values are given in Table 8.

B. Decomposition of Carbon-14 Labeled Blue Grama in Field Experiments

Results of decomposition experiments carried out in the field.

Once the experimental designs were established for the field experiments, an estimate of the number of samples to be taken on each monthly sampling date was needed. Since no field data was available, results of a recovery study of radioactive blue grama added to soil (Table 7) were used to provide estimates of the sampling variation that might occur in a sampling period. The assumption was made that blue grama decomposition rates would decrease exponentially with time.

Dr. Robert Francis of the Grassland Biome Statistical Services section developed a statistical analysis of numbers of samples to be taken for theoretical decomposition patterns (24). The estimates of the

Table 7. Recovery of Carbon-14 from labeled blue grama in soil.

1. Experimental results

Mixture number	Mixture subsample number	Composite number	Percent recovery of radiocarbon		
1	1	1	103.06	97.40	119.14
1	1	2	106.13	127.95	95.79
1	1	3	105.51	113.48	105.90
1	2	1	94.41	95.71	94.56
1	2	2	93.57	133.00	79.25
1	2	3	87.90	115.16	95.94
2	1	1	107.35	99.62	123.28
2	1	2	100.46	110.41	109.04
2	1	3	151.61	94.10	100.23
2	2	1	122.82	100.23	102.99
2	2	2	101.23	107.43	107.50
2	2	3	111.49	115.09	118.84

2. Analysis of variance table

Source of variation	df	Sum of squares	Mean square	F
Mixtures	1	399.06	399.06	1.975
Mixture subsamples/mixture	2	404.06	202.03	4.522*
Composites/mixture subsample	8	357.42	44.68	.296
Subsamples/composite	24	5477.78	288.24	
TOTAL	35			

* Significant at the .05 level.

Table 8. Radiocarbon content, total carbon content and specific activity of the plant materials and soil used in experimental work.

Sample description	Average carbon-14 content (uCi/g oven-dried matter)*	Average percent carbon +	Specific activity (uCi/g carbon)
Blue grama top regrowth, harvest 1	5.92*	42.8	13.84
Blue grama top regrowth, harvest 2	7.36	43.5	16.92
Blue grama top regrowth, harvest 3	7.25	42.8	16.94
Blue grama roots	1.30	34.5	3.78
Blue grama herbage harvested from Pawnee Site experimental plots	----	42.9	----
Soil used in field experiments	----	.918	----

* Average of 4 replicate determinations.

\+ Average of 3 replicate determinations.

number of samples to be taken each month were designed to detect significant monthly changes in decomposition processes within a 50 or 25% annual exponential decomposition pattern, with probability b when testing at the .05 level of significance. If the coefficient of variation is set at 14% (as in the recovery experiment data) and there is 25% annual decomposition, monthly sample sizes estimates are 8 (b=.8) and 9 (b=.9). Increasing the annual decomposition to 50% decreased the monthly sample size estimates to 3 at both probability levels when the coefficient of variation was kept at 14%. When the coefficient of variation is increased to 25%, estimates of sample sizes for 25% annual decomposition were 14 (b=.8) and 18 (b=.9), whereas only 4 samples were needed to detect monthly differences with 50% annual decomposition at both probability levels. Since 50% annual decomposition is usually achieved in field experiments, 5 samples per month was selected as being a sufficient number of samples for the field work.

Results of the six experiments dealing with the decomposition of carbon-14 labeled blue grama in the field, previously described in Table 3, are given in Tables 9 and 10, as well as in Figures 4, 5 and 6. A list of the radiocarbon recovery values for each decomposition container is provided in Appendix B.

Several interesting observations can be made from the results of field Experiments one and two. Since varying amounts of the standing crop of blue grama herbage or roots could be added to soil at any time in the field, amendment levels in these two experiments were chosen relative to the maximum standing crop of blue grama at the Pawnee Site on ungrazed, nonirrigated land. The high amendment level of herbage

Table 9. Loss of labeled blue grama carbon in field studies (Experiments 1, 2, 3, 5 and 6).

Experiment number and parameter studied	Amendment level (kg/ha)	Sampling date	Incubation time in field (days)	Percent loss of labeled carbon per sampling date	
				Mean	± one standard deviation of mean
1. Influence of rate of addition of herbage decomposition	1280	3/29/72	412	54.31	52.27 - 56.35
	128	1/12/72	335	56.23	53.34 - 59.12
	128	3/29/72	412	56.98	53.93 - 60.03
2. Influence of rate of addition on root decomposition	1920	3/29/72	412	37.10	32.57 - 41.63
	384	3/29/72	412	26.42	19.89 - 32.95
3. Influence of season of burial on herbage decomposition	128	3/29/72	314	42.15	37.19 - 47.11
5. Decomposition of herbage and root segments	128	3/29/72	412	39.07	33.63 - 44.51
6. Decomposition of herbage at the soil surface	128	3/29/72	406	50.08	46.88 - 53.28

Table 10. Effect of the addition of fresh herbage on the decomposition rate of partially degraded, labeled blue grama herbage (Experiment 4).

Description of Treatment	Sampling date	Total days from initial amendment date	Percent loss of labeled carbon/sampling date: Mean (Number of Observations/Mean)	Percent loss of labeled carbon/sampling date: ± one standard deviation of mean
Soil samples amended with labeled blue grama herbage on 2/11/71	2/19/71	8	10.01 (6)	4.57 - 15.45
	6/04/71	113	48.01 (27)	43.48 - 52.54
	11/17/71	279	58.47 (26)	55.70 - 61.24
Soil samples amended with labeled blue grama herbage on 2/11/71 and with non-radioactive blue grama herbage	11/17/71	279	63.10 (25)	59.83 - 66.37

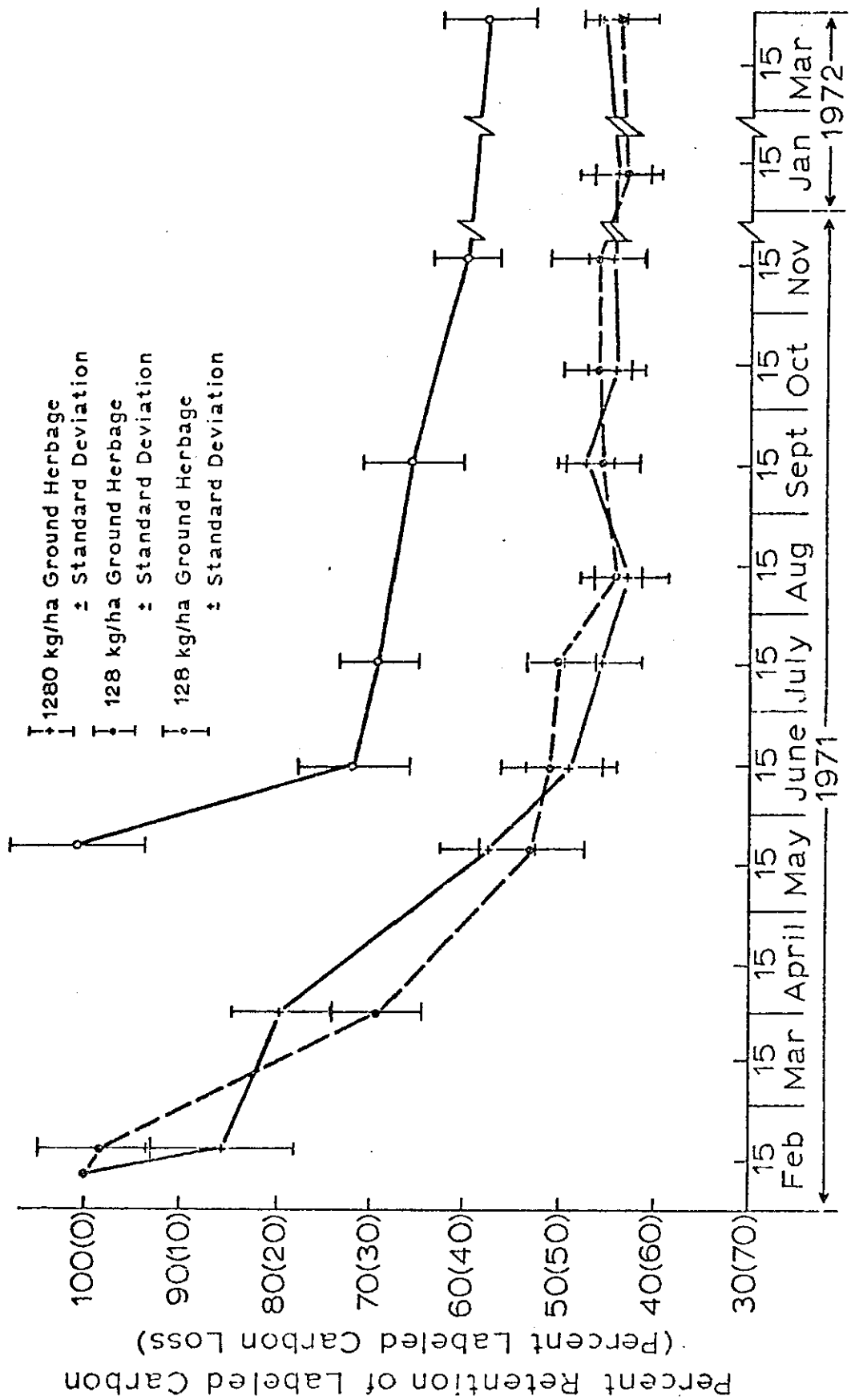

Fig. 4. Effect of burial date and level of amendment on retention of radiocarbon of blue grama herbage buried in field decomposition containers.

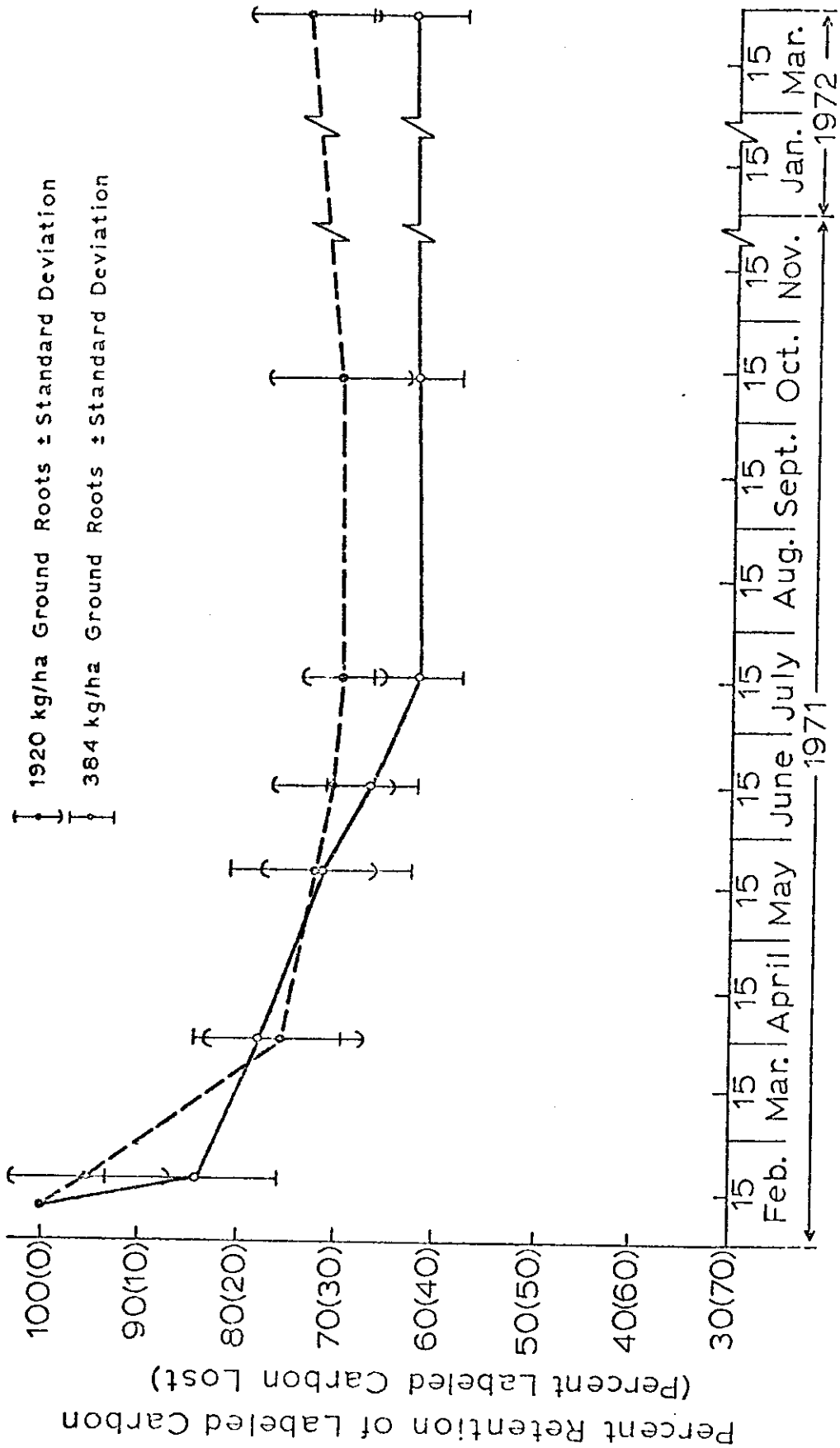

Fig. 5. Retention of radiocarbon of ground blue grama roots buried in field decomposition containers.

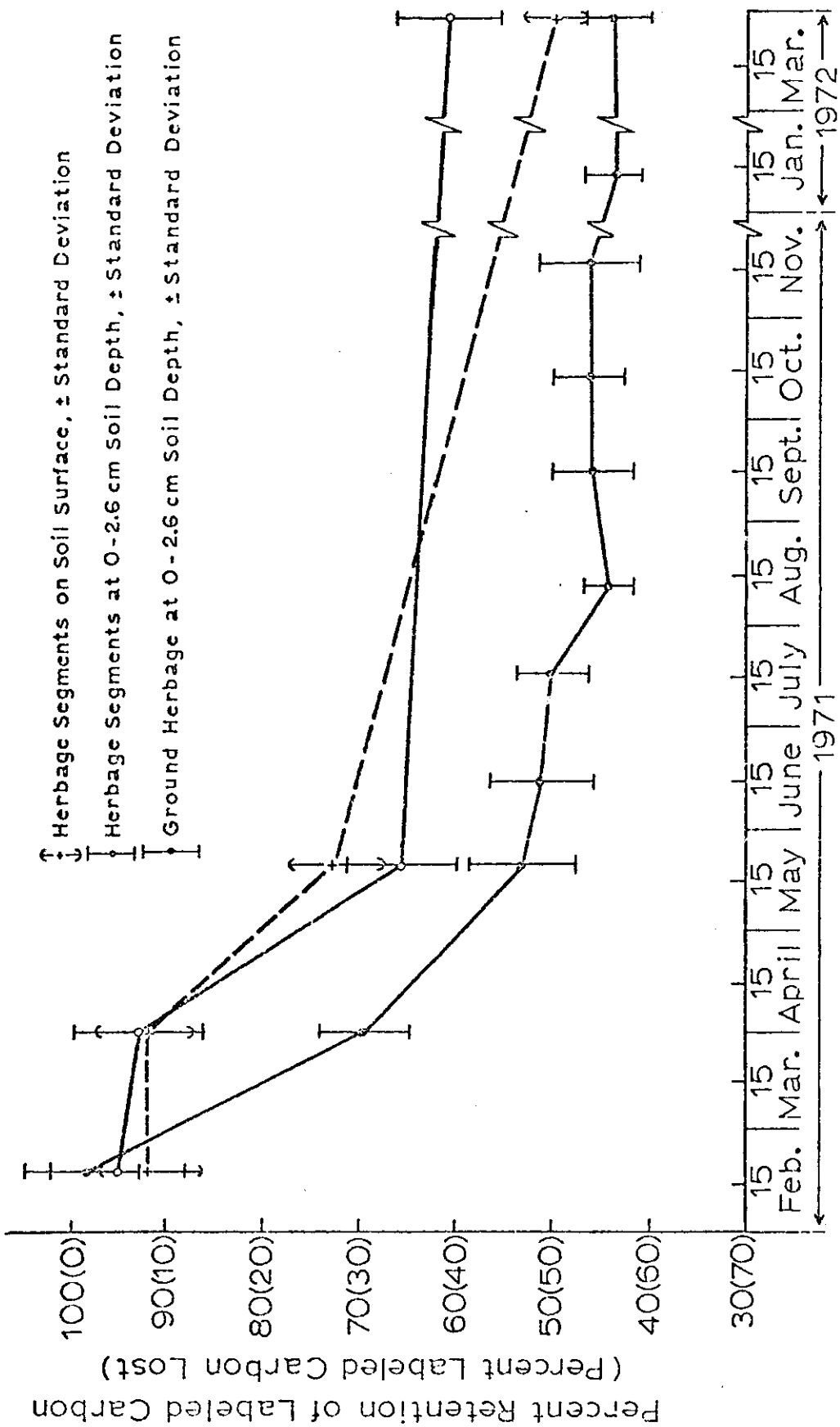

Fig. 6. Retention of radiocarbon of blue grama herbage in field decomposition containers (128 kg/ha amendment level).

(1280 kg/ha) for example, roughly corresponds to an addition of the maximum standing crop, whereas only 10% of this amount is added to the soil receiving the low amendment level of blue grama. The rates of carbon loss from either blue grama roots or herbage were not significantly different at two levels of addition of the plant materials on any sampling date (Figures 4, 5). However, the carbon loss rates of the ground roots at the low (26.4%) and high (37.1%) amendment levels were significantly lower than 412-day carbon losses of ground herbage at the low (57.0%) and high (54.3%) amendment levels.

The fact that the blue grama root material decomposed more slowly than the plant tops is not in full agreement with Jenkinson's results with ryegrass (44). Jenkinson reported that ryegrass roots decomposed at a slower rate than plant tops after 3 months of field decomposition, but there were no significant differences in decomposition rates after this sampling date. However, there are several possible explanations for this apparent difference: (1) Blue grama roots could be more resistant to decay than ryegrass roots; (2) Jenkinson's ryegrass roots were harvested at the same time as the plant tops (41), whereas the blue grama roots and tops were not; thus allowing time for possible decreases in the water-soluble fractions of older blue grama roots; and (3) Jenkinson's ryegrass roots consisted of roots of all sizes, whereas the blue grama roots used in experiment 2 represented only the larger pieces of roots extracted from the dried sods.

Season of burial was a significant factor influencing the rate of carbon loss of ground blue grama tops. The comparison can be made between the plant tops buried in February in Experiment 1 (low amendment rate) and the plant tops buried in May in Experiment 3 (Figure 4).

Although the plant tops used in these two experiments came from different lots this comparison is valid, since an examination of the results of Experiments 1 and 4 indicated that the two lots of blue grama lost carbon at identical rates (see Appendix B). The blue grama plant tops buried in May lost labeled carbon at a faster initial rate than those buried in February (Figure 4). However, the plant tops buried in May exhibited a 42.15% loss of labeled carbon in 314 days, whereas the blue grama buried in February lost 56.23% of its labeled carbon in 335 days (Table 9). These significant differences were due, in part, to the different soil water and temperature regimes of these two seasons. The blue grama buried in May exhibited a pattern of carbon loss similar to that of bluestem hay buried at the Pawnee Site during this same time interval (Table 1).

The decomposition rates of ground blue grama tops (Experiment 1) and herbage segments incorporated into the soil (Experiment 5) can be compared with herbage segments decomposed on the soil surface (Experiment 6). The interrelationships of the carbon loss patterns of these three experiments are shown in Figure 5, in which it can be seen that the initial rate of carbon loss from ground plant tops is more rapid than that of the whole plant segments. The plant segments on the soil surface or mixed into the top 2.6 cm of soil showed losses of 7-8% of labeled carbon by April 1, 1971, whereas the ground herbage showed a loss of 31% by this date. After 13 months of decomposition, significantly more carbon had disappeared from the ground plant material than the whole plant segments. The herbage segments placed at the soil surface lost carbon significantly faster than herbage segments mixed into the top 2.6 cm of soil from May 20 to March 29, although carbon disappearance

rates in these two experiments were similar before this time period (Figure 5). The latter observation could be explained by the fact that there were times following precipitation events when only the upper most layer of soil was moistened; the rate of decomposition of plant material in this zone might then be greater than that further down the profile, where water was limiting microbial activity.

Experiment 4 was designed to determine the influence of newly added substrate on the decomposition rate of partially-degraded, labeled blue grama. Since soil in natural environments probably receive frequent substrate additions, an interaction such as this could play a significant role in the determination of steady state relationships in the ecosystem. The results of Experiment 4 are given in Table 10 and indicate there was no significant effect of plant tops on the rate of carbon loss of partially degraded, labeled blue grama herbage. Although the samples which were amended twice with nonradioactive blue grama have not been corrected for carbon-14 dilution due to the addition of the nonradioactive carbon, this dilution factor was an insignificant contribution, amounting to a maximum of 1% of the radiocarbon originally added to the soil. The possibility exists that the carbon loss rate of the labeled material could have been accelerated if unlabeled plant amendments were made in a season of the year in which conditions were more favorable for microbial activity.

Evaluation of estimates of blue grama carbon losses in field experiments

There are several possible sources of errors in the estimation of labeled carbon loss from the decomposition containers in the field experiments. The carbon loss rates might be overestimated under field

conditions as a result of: (1) soil additions to the decomposition container, resulting in a dilution of the carbon-14; (2) loss of radioactive soil-plant mixture from the container by wind action; and (3) translocation of labeled carbon out of zone of soil sampled in the decomposition container. Four empty decomposition containers with solid bottoms were placed in the field to measure the extent of soil addition. An average of 5.60 g of oven-dried soil was added to each decomposition container during the 412 days of the duration of the field experiments. This represents a maximum dilution of carbon-14 in the top 400 g of soil of 1.4%. Four decomposition containers with 12 x 12 x 3 cm polyethylene boxes holding oven-dried soil at 0-3 cm depth, exhibited a 5.21 g average weight gain in 412 days. Since this weight of soil represented the amount of soil that had been blown into the box minus the amount that had blown out of the decomposition containers. Thus, if 0.39 g of radioactive soil-plant mixture blew out of the top 400 g of the decomposition containers, the carbon loss would be overestimated by about 0.5%.

The third factor contributing to an overestimation of carbon loss from soil at a specific depth would be translocation of radiocarbon in the decomposition container, especially in the period of cold temperature and high rainfall from 8 to 124 days. To evaluate this factor, all of the soil in two decomposition containers which were harvested on each of three sampling dates (8, 124, and 412 days after initiation of the field experiment) in Experiment one was removed in successive 2-cm depth increments, and radiocarbon determinations were performed on composite soil samples for each depth (Table 11). The radiocarbon levels in the 5-15 cm soil depths probably originated mainly from the upper, more radioactive soil layers during the sampling

Table 11. Recovery of radiocarbon at various soil depths in the decomposition containers (Experiment 1).

Depth of soil in decomposition container (cm)	Percent recovery of added radiocarbon at various times		
	8 days	124 days	412 days
0 - 3	62.45*	35.52	33.36
3 - 5	12.19	8.15	8.22
5 - 7	.82	.72	1.02
7 - 9	1.30	1.17	.77
9 - 11	1.05	.71	.53
11 - 13	.73	.58	.56
13 - 15	.34	.42	.40
Total Recovery			
0 - 5 cm	74.64	43.67	41.58
5 - 15 cm	4.24	3.60	3.28
0 - 15 cm	78.88	47.27	44.86

* Time of incubation in the field.

** Represents average of six radiocarbon determinations; all other values represent the average of two radiocarbon determinations.

process. This idea is supported by the fact that radiocarbon levels in the 0-5 cm soil depth are similar to those for the 5-15 cm depth when these are expressed as ratios of the carbon levels at 8 and 124 days and at 8 and 412 days. In addition, there is no statistically significant difference in the rates of radiocarbon loss at the 0-3 cm, 0-5 cm, and 0-15 cm depths. The radiocarbon loss for each depth falls within one standard deviation of the relative radiocarbon levels of the 0-3 cm depth. Thus, it appears that if some radiocarbon were translocated below the 3-cm depth, it moved into a soil horizon where the rate of its disappearance was similar to that in the 0-3 cm depth.

There are a number of reasons why the rate of loss of labeled blue grama carbon might be an underestimation. Radiocarbon could be blown into decomposition containers from adjacent decomposition containers, but analyses on unamended soil in decomposition containers harvested at 412 days showed no statistically significant increase in radiocarbon level over that harvested at 8 days. It is possible that a large fraction of the labeled organic carbon was transformed into inorganic forms which remained in the soil. The content of radiocarbon carbonate was estimated by placing 2 g of soil in a 250-ml Erlenmeyer flask, adding 25 ml of 0.5 N HCl, trapping the carbon dioxide formed in 3 ml of absorption solution, and submitting an aliquot of this solution to liquid scintillation counting. This factor was found to be negligible, however, as the amount of carbonate radiocarbon in soil remained constant (.08%) from 8 to 412 days. Since some of the decomposition containers had plants established in them, another factor contributing to an underestimate of labeled carbon loss would be assimilation of the radiocarbon by plants, thus returning the carbon to soil, i.e., as labeled root exudates.

Since the maximum amount of plant material found in any decomposition container was 5.0 g and plants normally take up a maximum of about 2% of their total carbon from soil (11), plant assimilation was considered to play a negligible role in recycling radiocarbon.

Microbial assimilation of organic or inorganic labeled radiocarbon may be the most influential factor causing an over-all underestimate of blue grama decomposition. Jenkinson (45) has indicated that about 10% of the original ryegrass radiocarbon added to the soil was in the form of microbial biomass after one year. However, this value might have been higher earlier in the season, when the radioactive microbial tissue had undergone less decomposition. Algal crusts incubated in closed laboratory incubation vessels are known to fix 0.20 and 11% of the carbon dioxide in the incubation vessel per day in the dark and the light, respectively. In the present work, no algal crusts were observed in the decomposition containers; thus it seems likely that the algal contribution to recycling labeled carbon would be slight.

Discussion of blue grama carbon loss measurements in field decomposition containers

The pattern of decay of native blue grama could differ from that measured in the field experiments due to the chemical composition of the blue grama. Since the sods in the biosynthesis chamber received nutrient solution applications and were grown at accelerated growth rates, they probably contained different concentrations of many mineral elements than would be found in native blue grama. Although the nitrogen fertilization (131 kg NO_3-N/ha) received by the experimental blue grama probably had little effect on cellulose and lignin content (84), total plant nitrogen of grassland sods receiving nitrogen fertilization has

been shown to increase. The expected relatively higher nitrogen content of the experimental blue grama would probably contribute to faster initial degradation rates than would be expected for native plants. However, nitrogen fertilization at these rates is also known to decrease water-soluble carbohydrates by 54% (84), which might make initial carbon loss rates of the blue grama slower than for native blue grama receiving no nitrogen fertilization.

One of the assumptions made in using the labeled blue grama is that the plant material was uniformly labeled with carbon-14, so that radiocarbon losses accurately reflected the decomposition of the total plant material. To obtain plants in which the specific activity of the cellulose and lignin was comparable to that of the easily labeled water-soluble part, the blue grama herbage was grown for long periods in the presence of uniformly labeled carbon dioxide. Plants grown using techniques similar to those employed in the present study are usually either uniformly labeled within the limits of detection (89) or have a water-soluble fraction with a specific activity about 3% higher than that of the unfractionated plant material (41,68). If the blue grama used in the present study had exhibited a 3% variation in the water-soluble fraction, this would have represented a much smaller source of variation than overall experimental sampling error.

Another limitation in evaluating the rate of native blue grama decomposition at the Pawnee Site is that the labeled blue grama was decomposed in the experimental containers and not within the native grassland system. Precipitation had no difficulty penetrating the screen lids of the decomposition containers, so that soil water levels at the 0-2.5 cm depth should be comparable inside and outside of the containers.

Soil samples taken on May 20 and July 15, inside the containers and 25 cm away were analyzed for water content; no significant differences in soil moisture were detected. However, during long periods of cold, very wet weather, the downward movement of soil water could be impeded by the glass wool layer in the container bottom, resulting in higher soil water content in the upper 2 cm of soil for a period of time, compared with native prairie conditions. The latter possibility would cause an increase in carbon loss rates in the containers over that observed in the prairie.

In spite of any other proposed differences between the grassland environment and the environment of the decomposition containers, the fact remains that the carbon loss rates (Experiment 3) agreed with the rate of decomposition of big bluestem at the Pawnee Site (Table 1). This would suggest that conditions inside the decomposition container were not extremely different from those of the prairie.

C. Modeling Changes in Soil Water Content

To model decompositon process under field conditions, it was necessary to obtain an accurate measurement of soil water content, a factor known to significantly influence decomposer activity. In the absence of frequent soil water determinations in the field, a soil water model was developed to predict changes in water content within the containers. Pre-existing soil water models were not used because of their stringent micrometeorological data input requirements or their inability to predict soil water changes on a short time-scale basis.

Although several meteorological and soil factors influence drying rates, some mathematical models have predicted soil water movement solely on the basis of temperature fluctuations. Several of these soil water models were described in a recent review (13); it appears that Thornthwaite's potential evapotranspiration model (78) has been used most extensively. Thornthwaite found a linear relationship between the log of air temperature and the log of potential evapotranspiration. Since regional potential evapotranspiration estimates can be successfully predicted solely from soil temperature data, evaporation processes may be relatively insensitive to average regional fluctuations in other meteorological conditions.

A simplistic model was developed to generate rough approximations of the hourly changes in soil water in the field decomposition containers. Laboratory experiments were performed to gather hydrologic data to be used in a soil water model. The influence of temperature and soil water content on the drying rate of soil in the decomposition containers was determined in two experiments. A third study was designed to measure increases in soil water content after a simulated rain.

Laboratory investigations of the influence of soil temperature, water content, and precipitation events on changes in soil water content

A simulated rainfall of 12.5 mm was applied to soil in the decomposition containers, which were dried at six temperatures. Water contents of the top 2.5 cm of soil were then determined for each temperature. These data are given in Appendix D. A regression analysis of soil water content versus hours of drying time was performed for each temperature and the results of these statistical analyses are

are given in Table 12. Since soil water is known to be lost at an exponential rate during part of the drying process (37), an exponential regression model was used to express percent soil water content (M) as a function of the intial percent soil water multiplied by the term e^{-bt}, where e is the base of the common logarithms, b is the soil drying rate (percent soil water loss per hour) and t represents the hours of drying time.

The exponential regression model predictions of soil water content varying with time are shown in Figure 7 for each temperature. From this figure, it can be seen that as temperature is increased, the soil at 0-2.5 cm depth experiences a rate of water loss that is increasingly greater than the rate of supply of water to this layer from soil below 2.5 cm. Setting the soil drying rate at 5°C equal to one, the relative drying rates of the soils at 20°, 30°, 40°, 50° and 60°C become 1.51, 1.87, 3.18, 8.83, and 11.48, respectively. Thus, at soil temperatures between 40°C and 50°C the rate of drying of the upper 2.5 cm of soil is greatly accelerated over that at lower temperatures.

An important factor influencing the soil drying rates at various temperatures in this experiment was the rate of exchange of the incubator air with laboratory air. Since evaporation would not occur if the incubators were saturated with water vapor, the incubator air was exchanged 14 times daily. To evaluate the potential water-removing capacity of this exchange rate, the weight of water vapor in the incubator atmosphere was calculated, knowing the vapor pressure of water at a given temperature. The rates of removal were then calculated relative to water removal rates for incubators set at 5°, 20°, 30°, 40°, 50°, and 60°C: 1, 2.6, 4.5, 7.5, 12.2 and 19.1. Since the calculated

Table 12. Exponential regression models expressing percent soil water (M) as a function of hours of drying time (t) for soil dried at various temperatures.

Temperature (°C)	Exponential regression model	Number of observation pairs	Coefficient of determination (r^2)
5	$M = 16.37e^{-.99738t}$	30	.715
20	$M = 16.66e^{-.0118t}$	24	.788
30	$M = 18.56e^{-.01382t}$	25	.730
40	$M = 18.76e^{-.02347t}$	30	.893
50	$M = 17.91e^{-.06514t}$	28	.953
60	$M = 13.90e^{-.08469t}$	34	.871

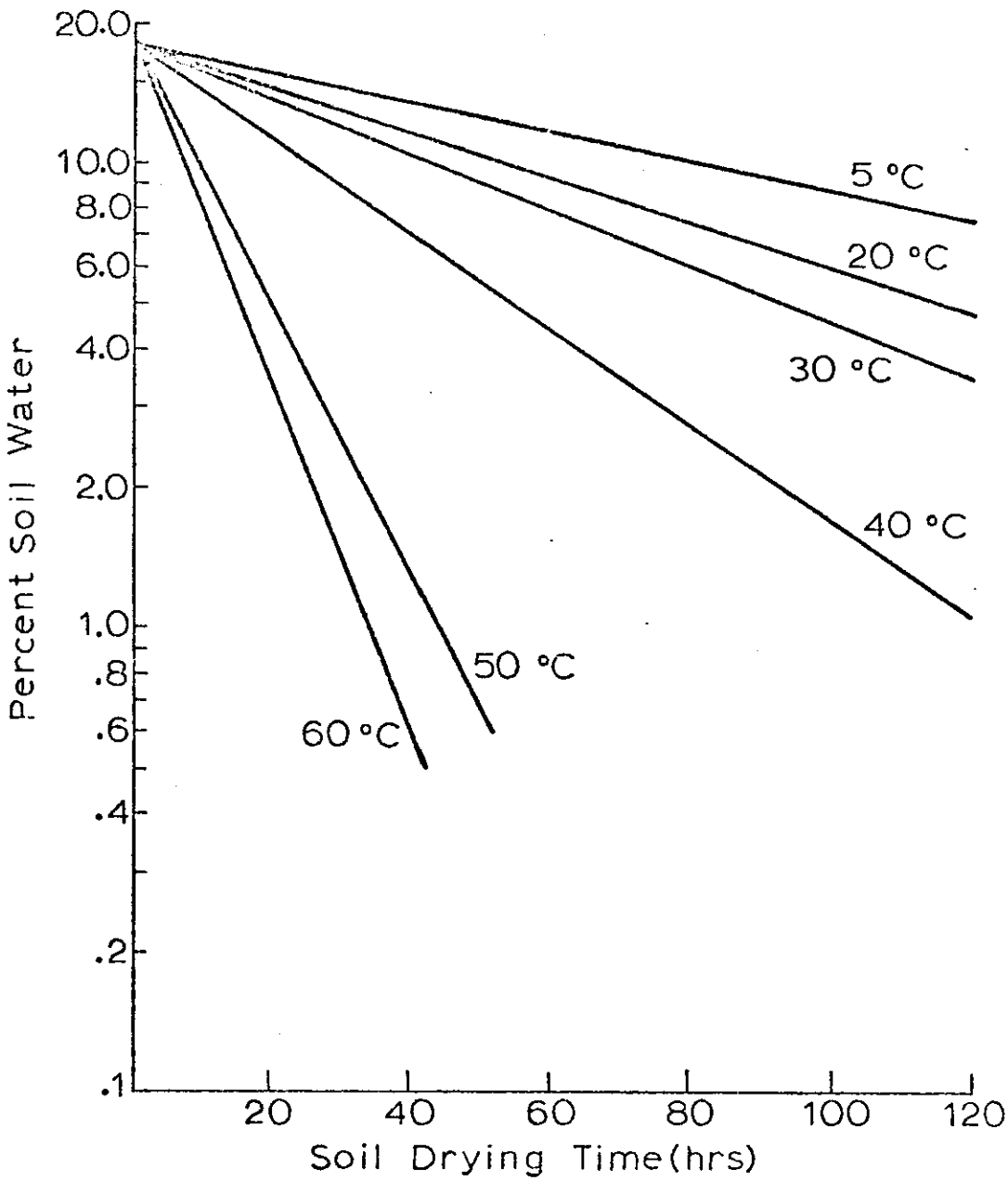

Fig. 7. Relationship of regression predictions of percent soil water to drying time for soils dried at various temperatures.

relative rates of removal of water from the incubators are twice as large as the relative rates of soil evaporation at all temperatures, it would appear that the exchange rate did not inhibit soil drying rates at low temperatures more than it increased evaporation rates at high temperatures.

A second experiment was designed to determine the effect of water content of the top 2.5 cm of soil on drying rates, independent of supply of soil water below 2.5 cm. As can be seen in Figure 8, the drying process occurs in two fairly distinct stages, which were originally described by Fisher (22) and recently used to model dryland evaporative flux of the upper 3 cm of soil (63,64). The "constant rate stage" of soil drying was estimated to occur at water contents above 8% and the "falling-rate stage" below this value. A regression analysis was performed on the data presented in Figure 8, expressing soil drying rate as a function of independent variables related to initial water content (Table 13). Although the 1/M, $(M-18)^3$, and M^2 terms in this regression equation did not significantly contribute to an increase in the regression mean square, these three terms were included so that the predicted evaporation rate versus initial soil water content curve approximated Fisher's results (22).

The actual drying rate in the falling-rate stage is dictated by the ability of the soil profile to deliver water to the evaporation zone, a factor which was evaluated in the soil temperature experiment previously described. However, evaporation rates at water contents in the constant rate stage (greater than 8% soil water) are greater than evaporation rates in the falling rate stage, because the conductive properties of the soil profile are no longer of major importance (37). Thus, when

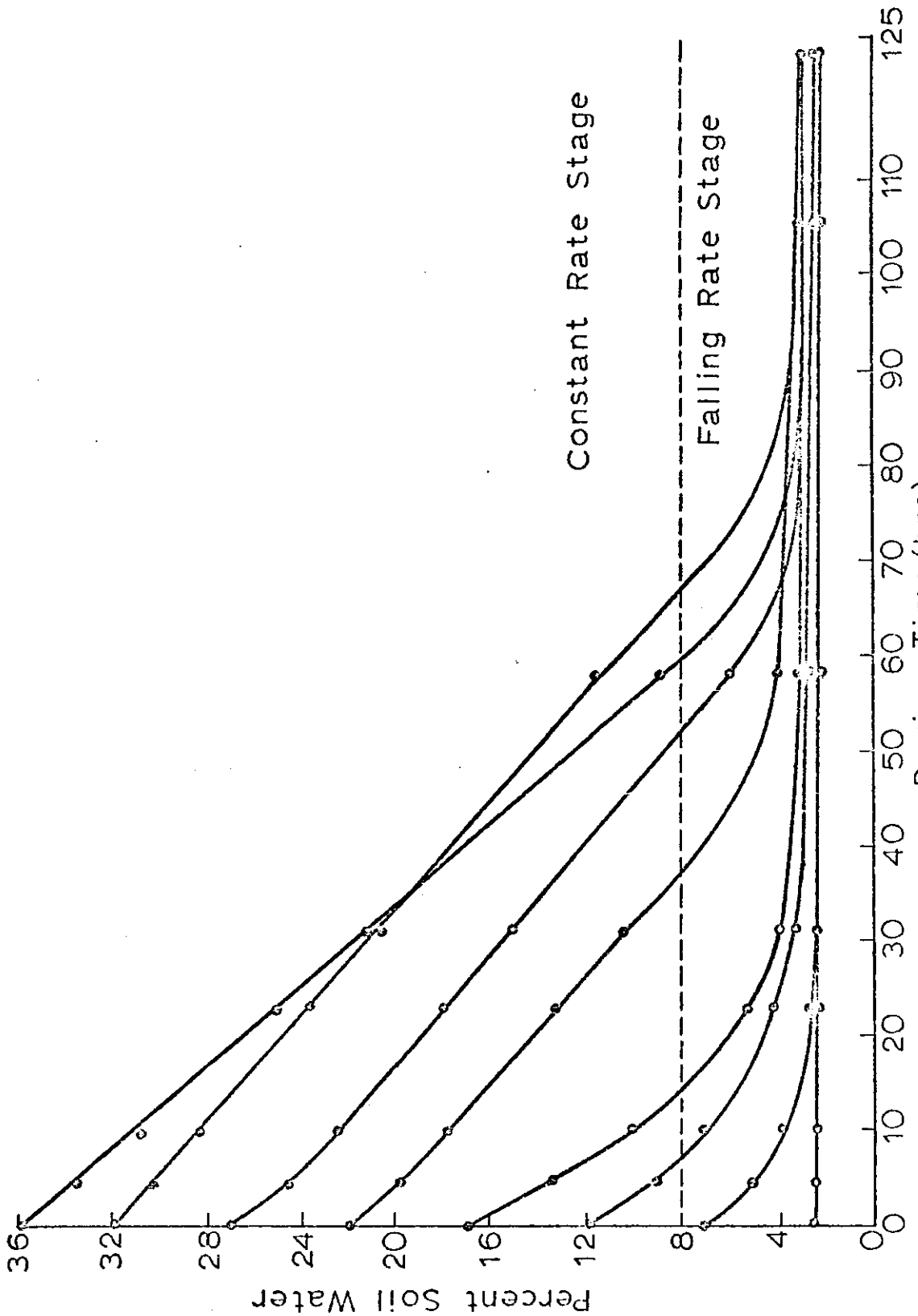

Fig. 8. Effect of initial soil water content on rate of water loss of soil.

Table 13. Multiple regression analysis of the soil drying rate (percent soil water evaporated/hour) as a function of independent variables related to the soil water content (M) at the start of the drying period (47 observations).

Independent variables and constant of multiple regression equation	Value of regression coefficient or constant	Coefficient of determination (R^2)	
		Increase/variable	Cumulative increase
Log Log (M x 100)	3.80702	.9216	.9216
1/M	.56136	.0022*	.9238
$(M - 18)^3$	.00002	.0021*	.9259
M^2	- .0015	.0003*	.9262
Constant	-1.57378	-----	-----

* Non-significant contributions to regression equation.

the soil water content of the experimental soil is above 8%, the drying rates predicted from soil temperature must be increased by a constant rate stage correction factor. The latter factor was calculated by dividing the drying rate predicted for a particular soil water content (from the regression equation in Table 13) by the regression-predicted drying rate at 8% soil water. Figure 9 shows how this correction factor varies with soil water content.

A third laboratory experiment was designed to determine the influence of simulated rain events on the water content of soil in decomposition containers 15 min after water additions. The data presented in Table 14 demonstrate that simulated rain events less than 2.5 mm do not wet an air-dry soil beyond a depth of 2 cm. This fact has important ecological significance when considering microbial activity in soil, since most of the precipitation events that occur at the Pawnee Site are less than 2 mm (75).

The parabolic relationship between the increase in the soil water content at the 0-2 cm depth and increased simulated rainfall is apparent from Table 14 and is shown in Figure 10, where a quadratic regression equation for the data is given. Since the largest hourly rain event under field conditions was 13.5 mm, the quadratic regression equation was not used to predict a decrease in soil water content with a precipitation event greater than 16 mm.

Description of soil water model

A mathematical model, entitled DECOM 1, was used to predict changes in blue grama carbon loss rates in the decomposition containers under field conditions. This model contained an exponential soil water loss

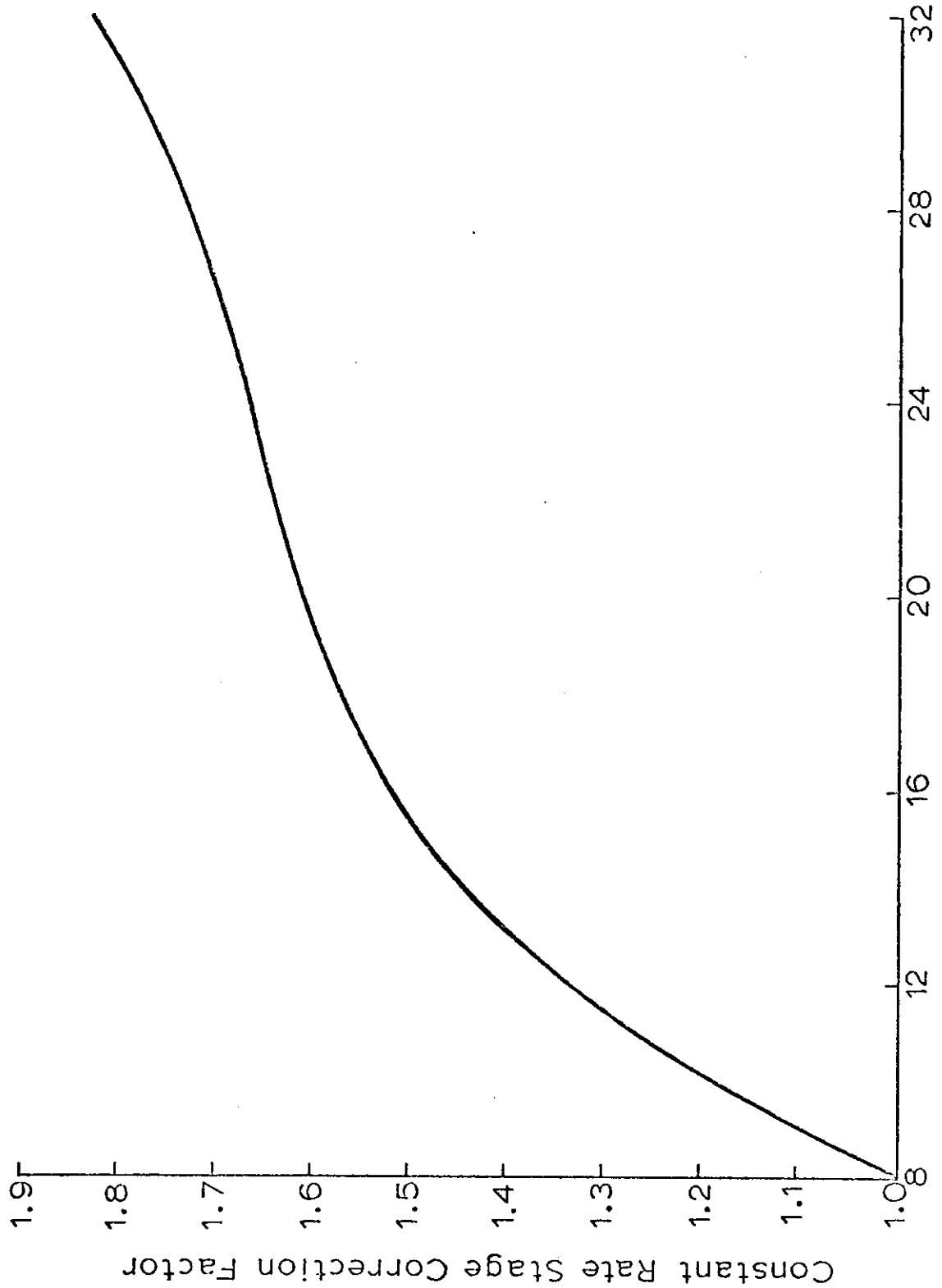

Fig. 9. Calculated values for constant rate stage correction factor as a function of soil water content.

Table 14. Influence of simulated rain events of various sizes on depth of wetting and increased water content of soil in container.

Size of simulated rain event (mm)	Measured wetting depth (cm)	Increase in % soil water at 0-2 cm depth
1.25	1	3.53
2.50	2	6.90
3.75	3	10.67
6.25	4	15.85
8.75	5	18.40
12.50	7	21.37
18.75	11	22.47

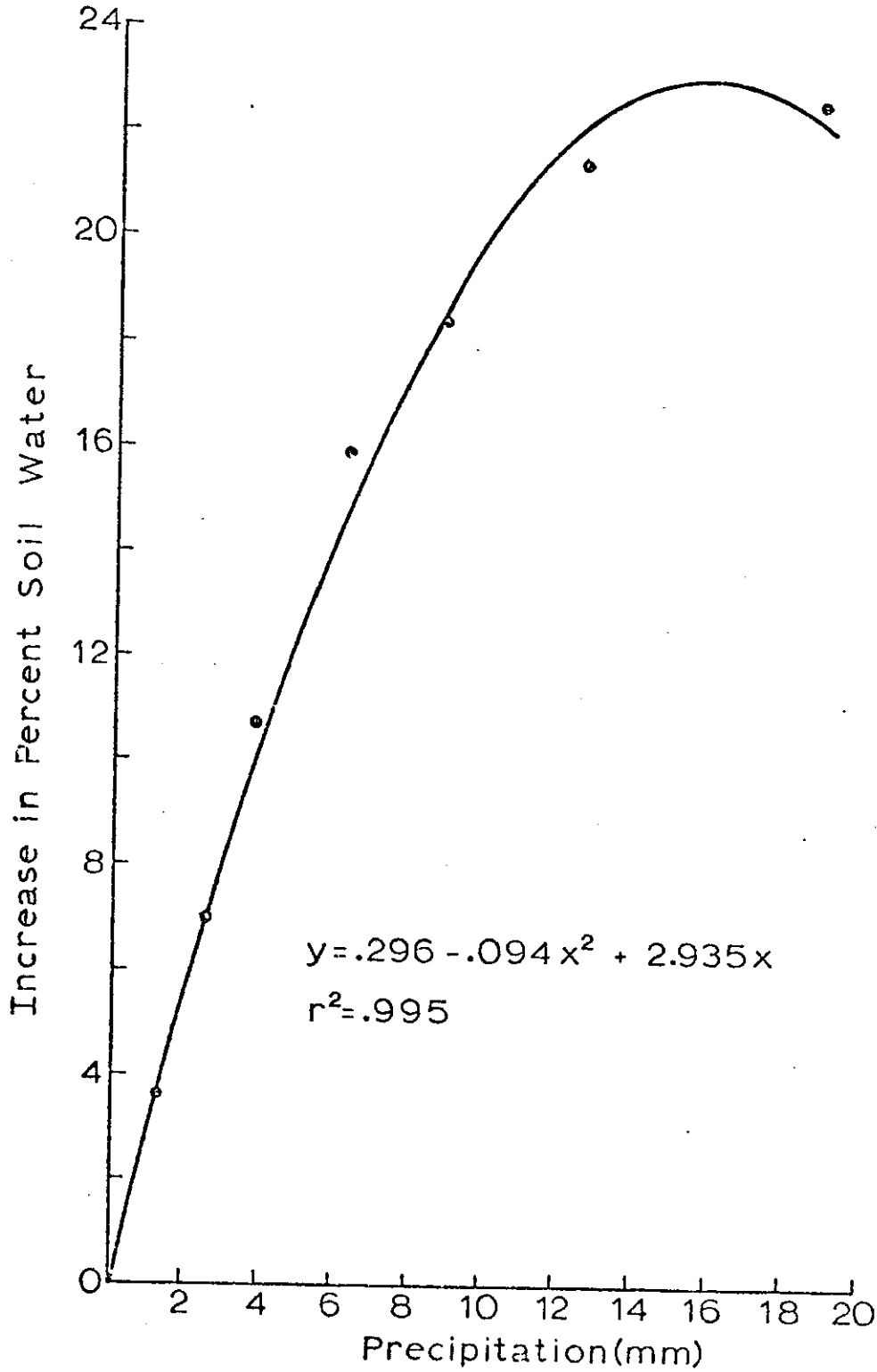

Fig. 10. Relationship of soil water content to simulated precipitation events of various sizes.

submodel, which predicted the water fluctuations for soil at 0-2.5 cm depth. Given the inputs of hourly rain gauge data, soil temperature at the 0-2.5 cm depth in the containers, time, and the soil water content at the start of a week, hourly soil water values were predicted using the following equation:

$$M_{t+1} = (M_t + RAINADD_t)e^{-b}$$

The predicted percent soil water for hour t+1 (M_{t+1}) is expressed as a function of the percent soil water at time t (M_t), the increase in percent soil water due to a preciptiation event at time t ($RAINADD_t$), and the soil drying rate (b) evaluated at time t. The value used for M_t for the first hour of a weekly period is an average of 5 measurements taken in the decomposition containers in the field for that hour and successive M_t values are predicted using an iterative solution of the model.

The value for $RAINADD_t$ is calculated from the quadratic regression equation shown in Figure 10:

$$RAINADD_t = .296 - .094\ RAIN_t^2 + 2.935\ RAIN_t$$

Thus, the increase in the percent soil water is calculated from mm rain occuring at hour t ($RAIN_t$). $RAINADD_t$ is set equal to zero in the absence of a rain event at time t.

The hourly drying rate of the soil in the containers (b) is expressed as a function of soil temperature at time t and a constant rate phase correction factor. The soil drying rate is first calculated from the soil drying rates given in Table 12 using the following soil temperature (Tp) criteria:

(1) b = 0 if Tp is less than $0^{o}C$

(2) b = -.001476 x Tp if Tp is equal to $0^{o}C$ or less than or equal to $5^{o}C$

(3) b = -.00608 - .0026 x Tp when Tp is from $6^{o}C$ to $30^{o}C$

(4) b = .0151 - .0097 x Tp when Tp is from $31^{o}C$ to $40^{o}C$

(5) b = .3641 - .01412 x Tp + .00011 x Tp^{2} when Tp is from $41^{o}C$ to $61^{o}C$.

Using this set of criteria, the assumption is made that the values of the soil drying rates between measured drying rates at specific temperatures can be interpolated linearly from $0^{o}C$ to $40^{o}C$ and curvilinearly from $41^{o}C$ to $61^{o}C$. When the percent soil water is greater than 8%, the soil drying rate (b) is increased by multiplying b by the constant rate phase correction factor (CORR), expressed according to the regression equation given in Table 13 as:

$$CORR = (-1.5738 + 3.80702\ LogLog(M_t x100) + .56136/M_t + .00002 \times (M_t-18)^3 - .00015 \times M_t^2)/.228909$$

The only overall restraint put on the soil water submodel was that soil water content could not increase beyond 32%. This value was chosen as a result of soil water measurements taken inside the decomposition containers on April 21, 1971 after a 12.7-mm rain event.

Evaluation of soil water model

The soil water submodel predicted water levels within 3 standard deviations of values measured in the field on 20 out of 51 weekly sampling dates. The predictions of soil water content on the 51 sampling dates are presented in Table 15, whereas Figure 11 shows the predictions on a daily basis. To evaluate the model, a linear regression

Table 15. Predicted and measured soil water contents in field decomposition containers on various sampling dates.

Sampling date	Measured % soil water* (± 3 standard deviations)		Predicted average % soil water
4/08/71	3.73	(0.0 , 8.02)	-----
4/15/71	1.96	(.79, 3.13)	1.08
4/22/71	30.13	(21.25, 39.01)	30.99
4/29/71	17.16	(14.31, 20.01)	19.41
5/06/71	19.34	(17.24, 21.44)	22.44
5/13/71	13.84	(9.19, 18.49)	12.57
5/20/71	6.19	(2.98, 9.40)	3.71
5/27/71	10.76	(8.48, 13.04)	10.28
6/03/71	6.34	(2.56, 10.12)	5.36
6/10/71	.92	(.14, 1.70)	1.67
6/17/71	1.99	(1.12, 2.86)	5.97
6/24/71	2.58	(0.0 , 5.46)	.05
7/01/71	1.06	(.73, 1.39)	.03
7/08/71	1.48	(1.18, 1.78)	.03
7/15/71	1.37	(.71, 2.03)	.02
7/22/71	6.40	(3.10, 9.70)	7.16
7/29/71	5.25	(3.57, 6.93)	7.37
8/05/71	.92	(.65, 1.19)	.66
8/12/71	.37	(.22, .52)	.02
8/19/71	1.54	(.79, 2.29)	.01
8/26/71	1.95	(1.77, 2.13)	2.54
9/02/71	1.53	(1.23, 1.83)	.20
9/09/71	14.76	(13.95, 15.57)	18.84
9/16/71	5.66	(4.37, 6.95)	1.69
9/23/71	11.53	(6.76, 16.30)	19.57
9/30/71	6.00	(2.85, 9.15)	2.37
10/06/71	6.12	(2.43, 9.81)	9.09
10/13/71	3.14	(1.58, 4.70)	1.34
10/20/71	8.33	(5.30, 11.36)	4.88
10/27/71	3.52	(2.38, 4.66)	4.17
11/03/71	6.04	(4.57, 7.51)	13.27
11/10/71	3.98	(1.73, 6.23)	6.71
11/17/71	4.05	(1.23, 6.87)	5.82
11/24/71	4.54	(2.98, 6.10)	3.03
12/01/71	3.34	(2.47, 4.21)	6.92
12/08/71	4.92	(2.13, 7.71)	6.07
12/15/71	2.42	(1.52, 3.32)	4.53
12/22/71	2.52	(1.53, 3.51)	2.14
12/29/71	1.78	(.82, 2.74)	1.80
1/05/72	2.78	(2.30, 3.26)	1.55
1/12/72	1.63	(.64, 2.62)	2.39
1/19/72	5.52	(2.67, 8.37)	13.04

Table 15. (Continued)

Sampling date	Measured % soil water* (± 3 standard deviations)		Predicted average % soil water
1/26/72	3.51	(2.13, 4.89)	5.10
2/02/72	2.23	(.82, 3.64)	3.48
2/09/72	2.47	(1.66, 3.28)	2.10
2/16/72	2.16	(1.44, 2.88)	2.91
2/23/72	1.49	(1.07, 1.91)	1.39
3/01/72	1.72	(1.39, 2.05)	.79
3/08/72	1.53	(1.38, 1.68)	.80
3/15/72	1.09	(.94, 1.24)	.49
3/22/72	1.81	(1.36, 2.26)	5.90
3/29/72	7.50	(5.19, 9.81)	8.91

* Average of five replicate determinations.

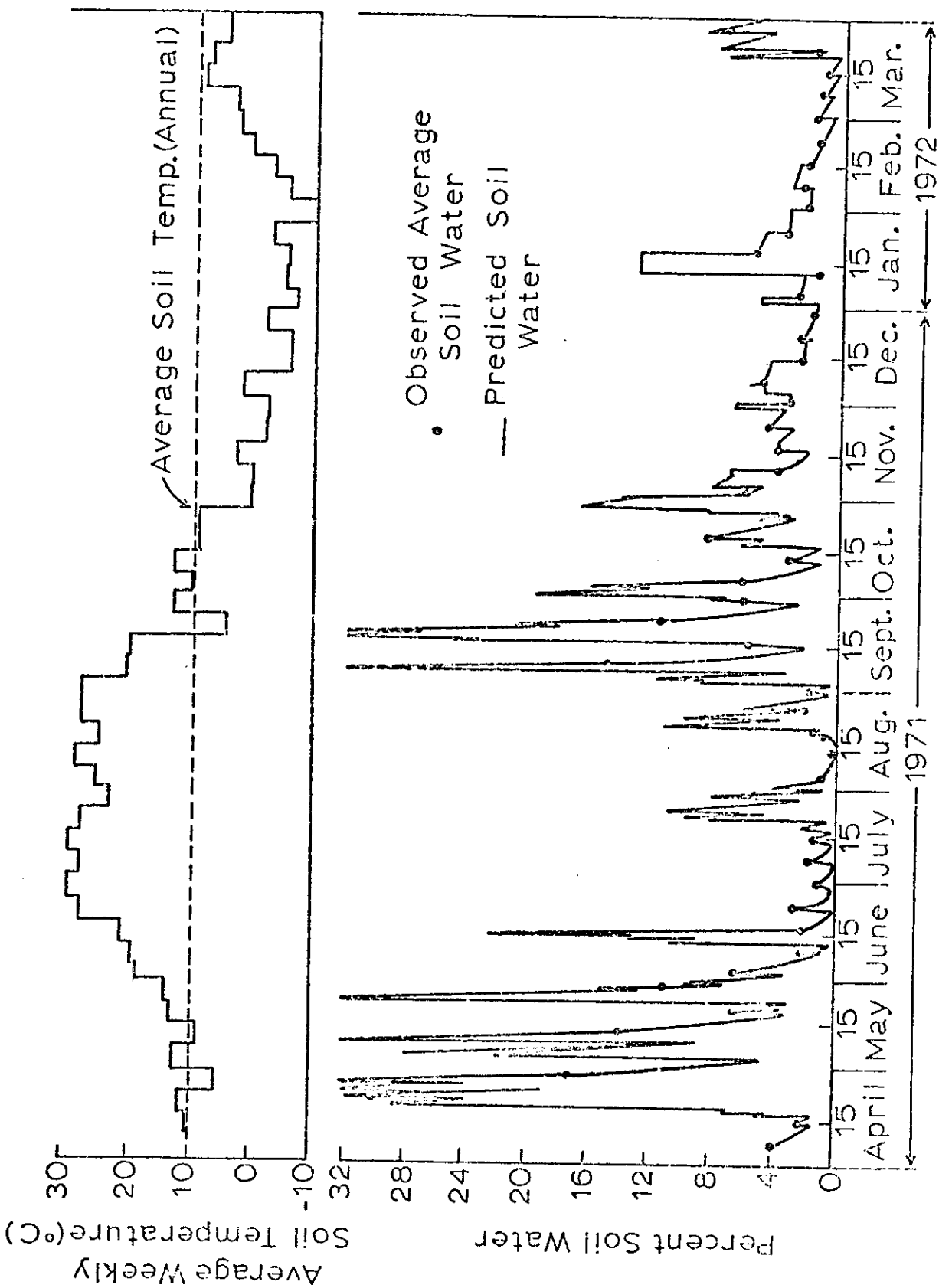

Fig. 11. Measured temperatures and water contents and predicted water contents of soil in decomposition containers in the field.

was performed, expressing the predicted percent soil water (D) as a function of measured water contents (MW) for these 51 observations. The resulting regression equation, D = 1.10 MW + .09, had a coefficient of determination of .852.

The regression results indicate a good relationship between predicted and observed soil water content in the decomposition containers, due to the small value of the slope and y-intercept of the latter equation, as well as the high value of r^2. This analysis also indicates that the average prediction of the soil water model will be slightly higher value than the measured soil water content. Erroneous rain gauge data for periods of time when snow occurs are known to result in values of predicted soil water contents by RAINADD that are overestimates (Table 15).

Variations in wind speeds are known to influence evaporation processes in the field. Chang indicated that decreases in air temperature resulted in an increased contribution of wind to evaporation rates (13). Thus during periods of cold weather, high wind speed could have increased evaporation rates in the field over those measured in the laboratory experiments, and subsequently predicted by the soil water model.

Another factor that could be influential in making predictions is related to the fact that the soil drying rates (b) were experimentally determined after applying a 12.55 mm simulated rain. Thus, when the field containers received a greater water addition than this, the soil below the top 2.5 cm soil layer could supply less water to the upper soil layer. This would result in higher values for field drying rates than would be predicted in the model. However, if the subsoil was dry, as

often occurs in the summer, the opposite situation would occur: the field soil would dry more slowly than predicted.

Thus, future work in this modeling area should involve an evaluation of wind speed on evaporation processes in cold weather, as well as the effects of rain events of different sizes on soil drying rates. The model could be applied to soils in other ecosystems if the soil drying rates were predicted as changes in tension with time, provided the other hydrologic experiments were executed for the soil.

In view of the highly simplistic nature of this model, compared with more sophisticated models such as Penman's model (62), it was surprising that the model yielded useful approximations of soil water. These hourly predictions of soil water content were used to predict decomposition rates of labeled blue grama under field conditions.

D. Blue Grama Degradation under Controlled Conditions in the Laboratory

To develop a mathematical model expressing plant decomposition as a function of environmental variables, an experiment was designed to measure blue grama carbon losses under controlled laboratory conditions. Mixtures of soil and labeled blue grama were placed in closed 500-ml Erlenmeyer flasks and incubated at various temperatures (3°-60°C) and soil water contents (2.6-35%). The labeled carbon dioxide produced in the incubation vessels was trapped in an absorption solution, which was subjected to scintillation counting. Oxygen determinations of the atmosphere in the incubation vessels were performed to evaluate oxygen consumption rates in the vessels.

The results of laboratory experiments characterizing blue grama radiocarbon loss rates as a function of time, temperature and soil water

content are presented in Appendix C. To use this information in a model to predict accurately rates of plant radiocarbon loss, it was necessary to develop a multiple regression equation which expressed mathematical relationships between rates of carbon loss and these three variables.

Previously determined relationships between soil respiration rates and either temperature (Figure 2) or soil water content (4,53,65,85) indicated that quadratic transformations of these variables could be useful in describing decomposition in the present experiment. In an initial attempt to develop multiple regression equation, the rate of radiocarbon loss, expressed as percent labeled carbon loss per hour, was expressed as a function of soil temperature (^{o}C), percent soil water and time (hr): soil temperature (Tp), Tp^2, soil water content (M), M^2, and the log of time. Since the latter regression equation exhibited a coefficient of determination of only .313, further data analysis of these interrelated variables was undertaken.

Two modeling approaches were available to further develop a relationship between the measured carbon loss rates of blue grama and the independent variables. In the direct approach, advance knowledge regarding variable interrelationships was utilized as fully as possible to select transformations that are known to accurately describe data relationships. Since sufficient advance knowledge was not available for use in the present study, the indirect modeling approach was used to develop a significant relationship between environmental factors and blue grama decomposition rates. In this approach, a limited array of transformations is used on the data, and these transformed variables are

statistically screened for those variables that best decrease the variance about regression.

Thus, the laboratory data were divided into six soil-temperature groups and either the radiocarbon loss rate or the log of the radiocarbon loss rate of each soil temperature group was expressed as a function of 13 transformed variables related to percent soil water and time (hr). When the carbon loss rates were expressed as a function of these transformed variables, independent variables which contributed significantly to the prediction of carbon loss for one temperature, were not related to carbon loss at other temperatures.

Due to the latter inconsistant results, log carbon loss rate was used to develop a relationship between decay rates and soil water and time (Table 16). The five variables that seemed to contribute most significantly to the relationships between log carbon loss rate, soil water, and time were: log of soil water content (M), log log (Mx100), time (t), log t, and (log t)x(log M).

The final regression equation was developed by expressing log of the radiocarbon loss rate (log D) as a function of the latter five variables plus variables related to soil temperature using 485 laboratory observations. The results of this final multiple regression equation are shown in Table 17, and the coefficient of determination for this model is 0.866, a considerable improvement over the results of the initial regression equation.

The influence of soil moisture, expressed as percent soil water (M), on log D is expressed in the equation by two variables: loglog(Mx100) - log(Mx100). Increases in M from 2% to 12.6% result in a dramatic increase in log D, which has a maximum value at 12.6% soil

Table 16. Increase in coefficient of determination (R^2) when log carbon loss rate (percent carbon loss/hour) is expressed as a function of variables related to decomposition time and soil water content for six soil temperature groups.

Independent variables	Increase in coefficient of determination (R^2) due to independent variable entered/soil temperature group					
	3°C	10°C	25°C	40°C	50°C	60°C
t*	.113	0	.074	.006	.007	0
$t^3/10^6$	.034	.003	.001	.001	0	.006
log t	0	0	0	0	0	.575
log log (100 x t)	0	.002	.002	.003	.002	0
$(t)^{\frac{1}{2}} + (t+1)^{\frac{1}{2}}$	.030	0	0	0	0	.001
M+	0	0	0	0	0	0
log M	.165	.214	.230	.087	0	0
log log (100 x M)	.511	.726	.653	.598	.510	.343
$M^2/10^6$	.002	0	0	0	.035	0
$(M)^{\frac{1}{2}}$	0	0	.025	.007	0	0
$(M)^{\frac{1}{2}} + (M+1)^{\frac{1}{2}}$	.040	0	0	0	.001	.007
$(t \times M)/10^6$	.001	.002	.001	0	.011	0
log t x log M	.006	0	0	.289	.386	.014
Total R^2	.902	.977	.986	.990	.958	.946
No. of observations	76	77	78	94	90	91

* T = no. of hours from initiation of decomposition; + M = percent soil water (oven dry weight basis).

Table 17. Regression coefficients and coefficients of determination of the regression of log decomposition rate (percent carbon loss/hr) versus independent variables related to decomposition time, soil temperature and soil water content.

Independent variables and constant of multiple regression equation	Value of regression coefficient or constant	Standard error of estimate	Coefficient of determination (R^2)	
			Increase/variable entered	Cumulative increase
Log Log (% soil water x 100)	92.01488	.740	.500	.500
(Log(time x 100)) x (Log(% soil water x 100))	.15749	.594	.179	.679
Log(% soil water x 100)	-12.89981	.529	.067	.746
$(1.8 - \text{Log(soil temp.)})^2$	3.44651	.464	.059	.805
Soil temperature x Log(time x 100)	- .01840	.418	.038	.843
Log Log (soil temperature x 100)	60.14738	.403	.011	.854
Time	- .00238	.386	.012	.866
Constant	-38.56569	----------	---	---

water content. If M is increased beyond 12.6%, the value of log D is decreased slightly. The value of 12.6% soil water content, which corresponds to a tension of .33 bars for this soil, was previously found to result in maximum soil respiration rates in laboratory experiments with other soils from the Pawnee Site (70).

The influence of temperature, defined in ^{o}C (Tp), on log D is expressed in the multiple regression equation as a combination of two variables: $(1.8-\log Tp)^2 + \log\log(Tpx100)$. This functional construct defines a relatively large increase in log D with increases in temperature below $30^{o}C$; temperatures above $30^{o}C$ result in relatively smaller log D increases.

The decomposition time variable (t) occurs both as an individual independent variable and in moisture and temperature interaction terms in the multiple regression equation. Decomposition rates in experiments cited in the literature (43,61) have been shown to decrease exponentially with time, just as the contribution of the t variable indicates in the present experiment. However, the t variable is probably acting as a surrogate of substrate or biomass in the multiple regression equation, i.e., as decomposition processes proceed, the decomposition rate of the total plant material is decreased, due in part to a disappearance of easily-degraded substrates (1,54).

The regression model predictions (presented in Figures 12 and 13) indicate the relationships of radiocarbon loss rates to soil water content, time and temperature on a dynamic basis. Figure 12 shows the response of the radiocarbon loss rate to soil water additions as a function of time. From Figures 12 and 13 a picture can be formed of the response of blue grama carbon loss rates to varying temperature.

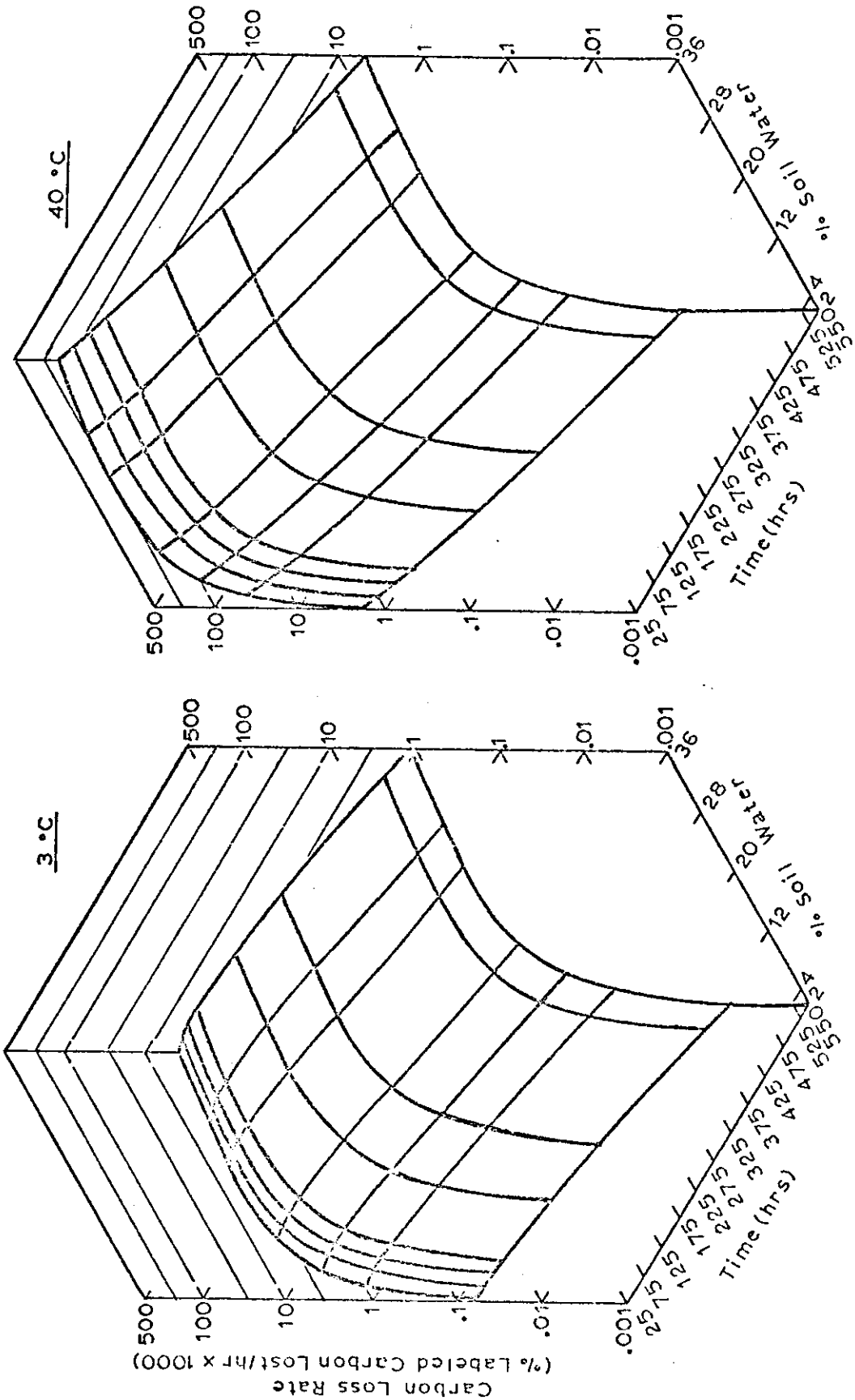

Fig. 12. Relationship of regression predictions of carbon loss rate (expressed on a log basis) of blue grama to percent water and time for soil incubated at 3°C and 40°C in the laboratory.

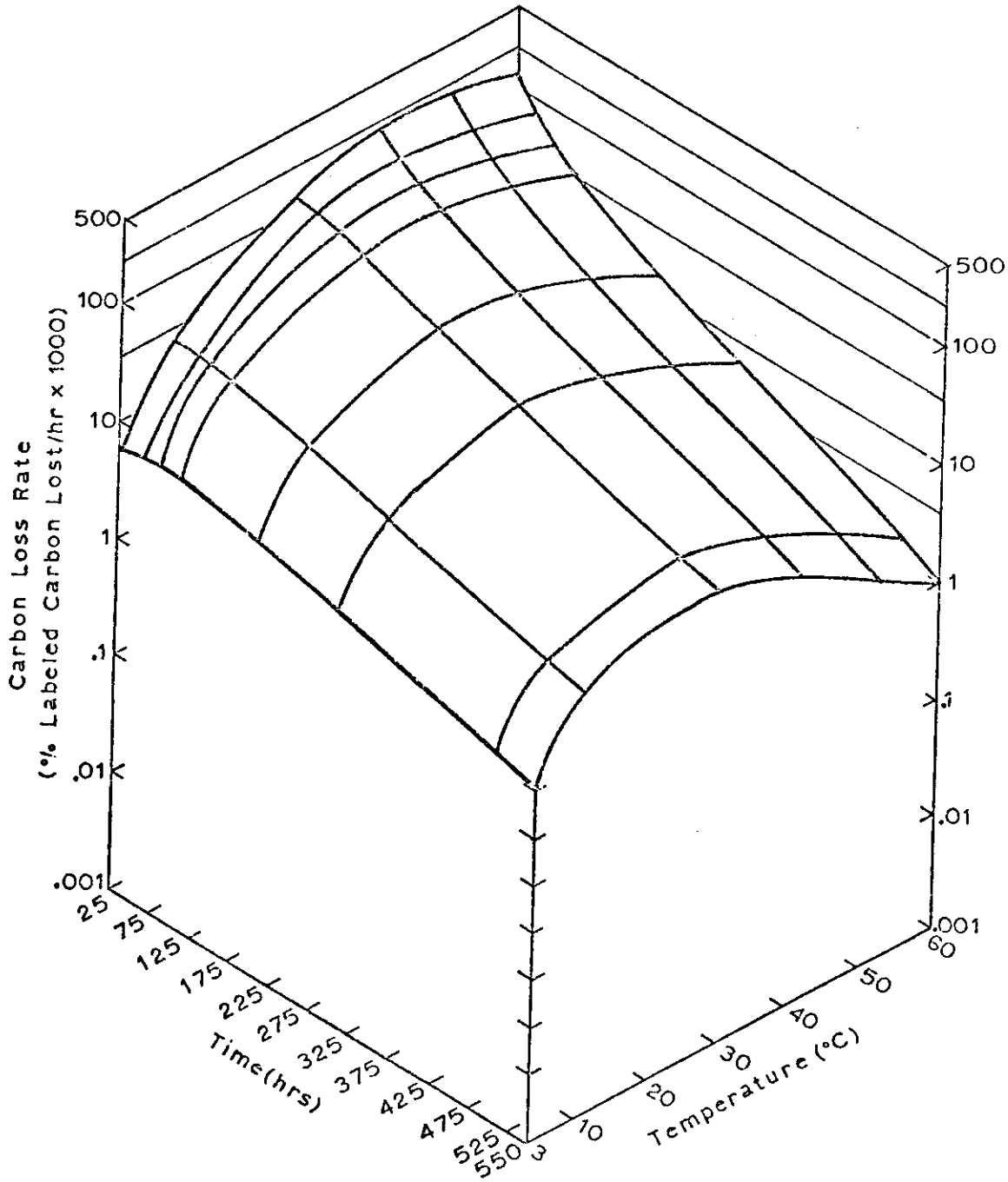

Fig. 13. Relationship of regression predictions of carbon loss rate (expressed on a log basis) of blue grama to temperature and time for soil incubated in the laboratory at 10% water content.

Determinations of the gaseous oxygen concentrations in the laboratory decomposition vessels were used to evaluate the possibility that oxygen became limiting in the respiration experiments. Results of oxygen determinations performed on a representative set of decomposition vessels are presented in Table 18. In one vessel the initial oxygen concentration was 21% and then decreased to 4.2% during the first week of incubation. Estimates from the literature on the effect of oxygen level on respiration indicate that carbon loss is uneffected by oxygen concentrations down to about 2.5% (60). However, although oxygen may not have been limiting in these experiments, this does not preclude an influence of increased carbon dioxide levels on radiocarbon loss rates. Assuming a respiratory quotient of 1, for example, the carbon dioxide concentration may have increased from .03% initially to 16.8% over the week's incubation period, as oxygen concentrations dropped from 21 to 4.2%. Since much smaller changes in the concentrations of carbon dioxide are known to affect microbial activity in soil (20), decomposition rates could have been inhibited in the vessels by the accumulation of CO_2.

E. Modeling Decomposition Processes in Field Experiments

Results and statistical evaluation of decomposition simulation

A mathematical model capable of describing rates of blue grama decomposition under field conditions was developed from laboratory decomposition studies (Appendix E). This model, entitled DECOM 1, contained the previously-described soil water submodel, which was used to predict hourly soil water content in the field decomposition containers. Once the hourly soil water prediction is calculated in

Table 18. Gaseous oxygen concentrations of respiratory vessels containing mixtures of soil and radioactive blue grama herbage.

% Soil water (oven dry weight basis)	% Oxygen in vessels at various soil temperatures*			
	3°C	25°C	50°C	60°C
2	20.3	21.8	20.3	18.6
5	19.7	17.5	15.3	16.3
10	19.3	14.3	5.3	13.2
20	18.6	14.0	5.1	4.2
25	18.5	12.8	6.4	5.4
36	18.5	13.2	9.4	5.6

* Incubation time: 7 days.

DECOM 1, the percent carbon loss of blue grama herbage (D) is estimated as a function of hourly soil water (M_t), hourly soil temperature (Tp) and time (t). This is accomplished in DECOM 1 by using the results of the multiple regression equation given in Table 17:

$$\log D_t = -38.5657 + 92.015\ \text{loglog}(M_t x100)$$
$$+.1575\ (\log(t x100))\ x\ (\log(M_t x100))$$
$$-12.89981\ \log(M_t x100) + 3.4465\ (1.8-\log Tp)^2$$
$$+ 60.1474\ \text{loglog}(Tp x100) - .00238t$$

The antilog of D is then calculated, giving the rate of blue grama carbon loss per hour. The sum of these hourly values of D are expressed as a cumulative carbon loss (CD) which increases with simulation time in DECOM 1.

The overall constraints placed on the decomposition aspects of DECOM 1 relate to predictions of the rate of carbon loss from the multiple regression model. Since time (t) is a variable in the latter model and the laboratory experiments lasted 560 hr, extrapolation beyond this time was handled by assuming that carbon loss rates beyond 560 hr were equal to those at t=560. The other two constraints on use of this equation are that the carbon loss rate is set equal to zero at soil temperatures less than 0°C and at soil water contents less than 1.00%. Measured carbon loss rates at temperatures close to 0°C and soil water contents approaching 1% soil water indicated that this is a valid assumption.

An initial computer simulation of DECOM 1 resulted in cumulative blue grama carbon loses that were three times smaller than the carbon losses measured under field conditions. This observation was made

for every sampling date tested in Experiments 1 and 3. The results of the blue grama carbon loss predictions from DECOM 1, which now included multiplication of the carbon loss rate by 3, are given in Table 19, by sampling date, and in Figure 14 on a daily basis. To compare DECOM 1 cumulative carbon loss predictions (DP) with carbon losses measured in the field (CM) a series of linear regression equations was developed. Using all of the observations in Table 19, the linear regression equation, DP = .07 + .99 CM, had a coefficient of determination of .957. The pattern of carbon loss in Experiment 1 was not predicted as well by DECOM 1 (Figure 14); the regression equation for this set of data, DP = -.89 + 1.01 CM, had an r^2=.531. However, the regression equation for Experiment 3 data, DP = .19 + .99 CM, had an r^2=.996. In considering the coefficients of determination in these three equations, it should be noted that the r^2 of .531 was significant at the 5% level, and the other two coefficients of determination were significant at the 1% level.

A final version of DECOM 1 was implemented to determine the effect of changing the predictions of the soil water submodel on the cumulative carbon loss (CD) predictions. Average soil water values were used as before, but two other values were also utilized: average percent soil water $\pm$ 3 standard deviations of the average water content. These three measured soil water values were then used to predict three different rates of carbon loss at each hourly DECOM 1 iteration. The cumulative carbon losses of Experiment 1 on March 29, 1972, using average soil water content, average soil water content minus 3 standard deviations, and average soil water content plus 3 standard deviations were found to be 59.43, 55.51 and 64.17%, respectively. The same procedure was followed

Table 19. DECOM 1 predictions and measured losses of blue grama radiocarbon on various sampling dates.

Sampling date	Measured percent radiocarbon loss	Predicted percent radiocarbon loss
Experiment 1		
5/20/71	42.26	42.26
6/15/71	50.95	47.30
7/16/71	54.38	47.97
8/12/71	56.68	49.72
9/16/71	52.71	53.84
10/13/71	55.80	57.53
11/17/71	55.86	58.69
1/12/72	56.22	58.79
3/29/72	54.31	59.42
Experiment 3		
5/20/71	0	0
6/15/71	28.02	28.61
7/16/71	30.74	29.28
9/16/71	34.15	35.15
11/17/71	40.00	40.01
3/29/72	42.15	40.74

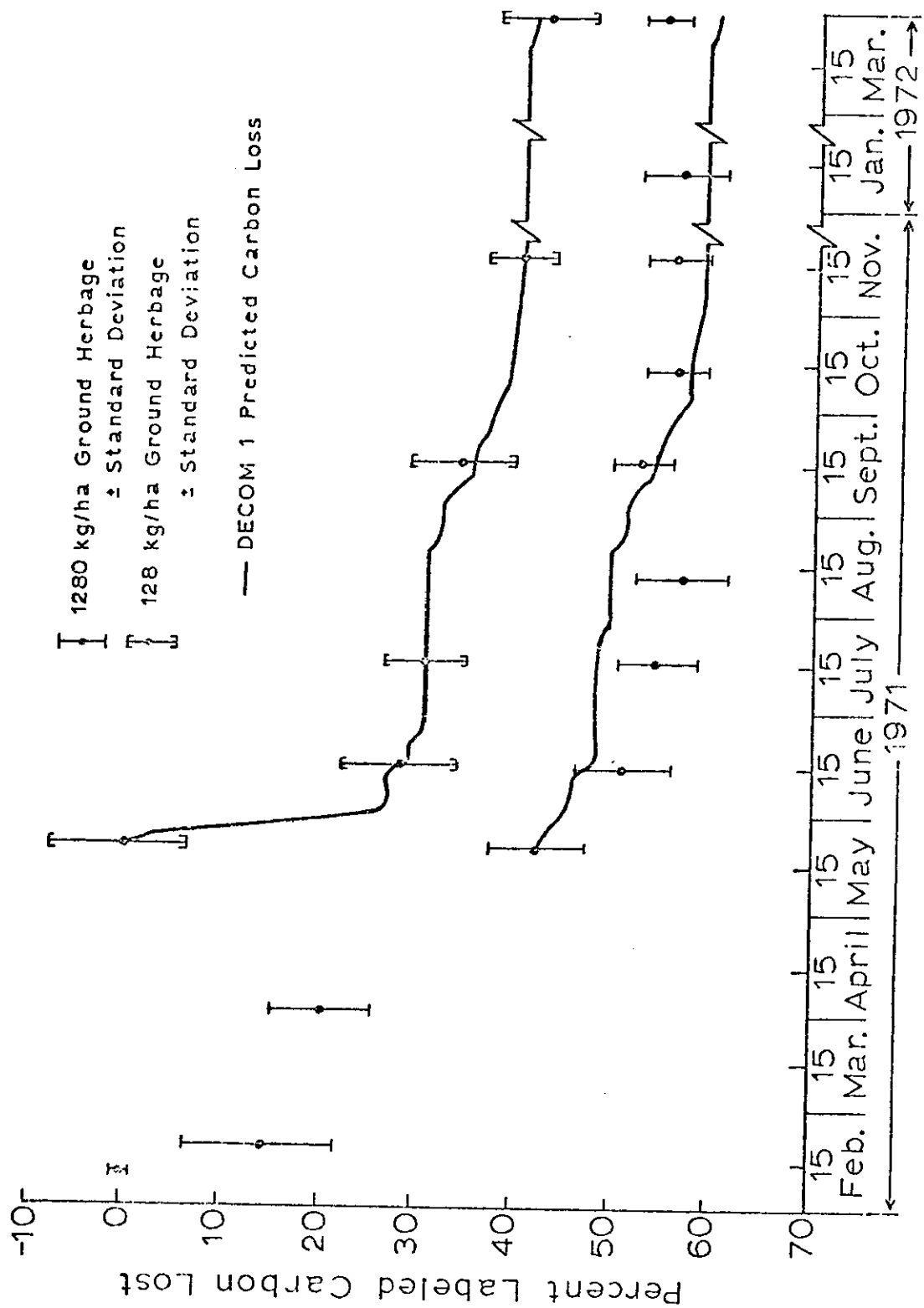

Fig. 14. Seasonal fluctuations in labeled carbon loss of blue grama in field decomposition containers as predicted by DECOM 1.

for the Experiment 3 simulation, resulting in cumulative carbon losses of 40.74, 33.43, and 49.94%. These results indicate that the predicted rates of carbon loss in DECOM 1 are sensitive to changes in soil water predictions, but differences of 3 standard deviations from the average soil water content will not result in a threefold increase in carbon loss rates predicted by DECOM 1.

Discussion of decomposition modeling efforts

A decomposition model with a high degree of sophistication and short time-scale resolution would have to consider environmental, substrate and decomposer-population factors as forcing functions. Among the most important environmental factors are soil temperature, water content, and fertility status. Measurements of temperature and water content are needed at frequent intervals in the upper part of the soil profile, especially for zones with large accumulations of roots or other organic materials. Substrate factors include the quantity, chemical composition, and physical form of the material available for decomposition in a given time period. Fluctuations in active decomposer populations should be taken into account. The contributions of individual decomposer groups to the total decomposition process might be characterized. The latter would help to insure success of the model predictions in different ecosystems with varying decomposer populations.

Mathematical models describing decomposition processes in nature have been developed from both laboratory and field experiments (2,7,48, 49,50,54,66,84,88). In the present investigation data generated from laboratory studies were used to develop a model capable of predicting rates of blue grama decay under field conditions. Decomposition experiments under field conditions can also provide information for

use in mathematical models, which relate the influence of fluctuating environmental conditions to degradation processes. Such experiments might employ labeled substrates for short-term (hourly) studies. Observed field decomposition rates could then be expressed as functions of environmental factors such as temperature and moisture and used to predict decomposition rates in the field. Since so little short-term, field-oriented research has been carried out in this area, there is not enough information available to evaluate whether this field approach would be superior to the laboratory approach.

The blue grama decomposition rates measured in the present laboratory experiments were too low to predict accurately those observed in the field. It was necessary to multiply these laboratory values by 3 to obtain a good prediction. The reason for this discrepancy is probably due to a combination of factors. The laboratory measurements of respiration were performed under conditions of constant temperature and soil water content, which obviously do not occur under field conditions. Fluctuating temperature alone can result in a 5-fold increase in decomposer activity (21), let alone fluctuations of soil water content. It is also possible that decomposition endproducts (including CO_2) accumulated in the respiration flasks and that these decreased the rates of carbon loss. A third possibility is that the predicted soil water estimates were such that an error in calculating carbon loss rates was introduced. The latter explanation seems unlikely, however, since increasing the soil water predictions by 3 standard deviations still does not account for the 300% increase in blue grama decomposition as predicted by DECOM 1.

The DECOM 1 predictions of decay patterns represent several improvements over pre-existing decomposition models. Olson (57) expressed decay rates in his model as a fixed amount of annual production, whereas carbon loss rates in DECOM 1 are related to the environmental factors of soil water and temperature. Many other models predict cumulative degradation of plant materials solely as a function of time (43,61). Such models would be insensitive to variations in environmental parameters on a short-term basis. Witkamp's decomposition model (84) was developed for a forest ecosystem and expresses soil respiration rates as functions of the temperature and moisture content of litter. However, in the forest ecosystem studied, water was not limiting as at the Pawnee Site. Thus, DECOM 1 has been tested over a wider range of environmental conditions.

DECOM 1 has several limitations that restrict its usefulness in predicting rates of decomposition. Since the model has only been used in connection with one year's field data, it has not been thoroughly evaluated. In addition, DECOM 1 does not consider changes in decomposer biomass as an independent variable in predicting decay patterns. Thus, predictions of decay rates in soils with decomposer activities greatly different from that in the soils used in the present study might lead to faulty predictions. Another limitation is related to the fact that DECOM 1 is insensitive to chemical and physical differences in the plant materials undergoing decomposition. Thus, the possibility exists that native blue grama which differs in its chemical or physical characteristics from the labeled blue grama used in the present study might exhibit a decay pattern slightly different from that predicted by this decomposition model.

The model has merit in uncovering gaps in our understanding of the quantitative influence of environmental factors on decomposition rates in the field. Also, since relatively few decomposition models have been developed for grassland ecosystems, DECOM 1 represents a starting point for modeling efforts in this area.

Further work in modeling might involve more extensive development of DECOM 1 with the inclusion of additional laboratory decomposition and soil water data. The model's sensitivity to changes in environmental factors should be studied to judge whether this additional data results in improved model forecasting abilities. Other laboratory techniques for evaluating decomposition rates might be employed. Additional research is needed to determine the effect of fluctuating environmental conditions on decomposition rates. Since fluctuations in temperature and soil water content influence decay processes, such studies would seem to be more meaningful than decomposition experiments carried out under constant conditions. Finally, additional work is needed on the soil water model, in the absence of suitable field data. The influence of rain events of different sizes on the drying rates of soils in the upper soil layer should be studied in more detail, as well as the influence of wind on the predictions of the soil water submodel of DECOM 1.

SUMMARY

A series of field experiments were designed to determine the decomposition rates of carbon-14 labeled Bouteloua gracilis plant materials at the Pawnee Site, the intensive study area of the U. S. International Biological Program Grassland Biome. Laboratory studies were undertaken to evaluate relationships among blue grama degradation rates, temperature, percent soil water and time. A mathematical model was used to integrate laboratory and field experiments related to blue grama decomposition rates and changes in soil water content.

Routine procedures were developed for the determination of radiocarbon and total carbon in soil samples amended with carbon-14 labeled blue grama herbage. A Coleman Nitrogen Analyzer was modified to combust soil or plant samples, using commercial oxygen as the carrier gas and Cuprox as the combustion catalyst. The radioactive combustion endproducts were bubbled through absorption solution in a test tube and the radiocarbon content of an aliquot of this absorption solution was determined using a scintillation counter.

Preliminary experiments were designed to determine the efficiency of recovery of the radiocarbon in samples combusted in the Nitrogen Analyzer. Essentially all of the labeled carbon dioxide of combusted samples were found to be absorbed in the one test tube of the absorption solution. A 2 x 3 factorial completely randomized experiment was designed to determine the effect of varying the length of the Nitrogen Analyzer combustion and combustion-sweep times on radiocarbon recovery in combusted soil samples. The results of this experiment indicated that the

combustion-sweep cycle needed to be extended by two minutes beyond the preset Nitrogen Analyzer settings in order to achieve efficient radiocarbon recovery. A third experiment indicated that there was no significant effect of varying ratios of radioactive to nonradioactive sample carbon on radiocarbon recoveries.

Field decomposition containers amended with 128 kg/ha and 1280 kg/ha of ground blue grama herbage on February, 1971, exhibited 57 and 54% losses of labeled blue grama carbon in 412 days, whereas ground blue grama root material only lost 26 and 37% of its radiocarbon in this same time interval at amendment levels of 384 and 1920 kg/ha. No significant differences in carbon loss rates were found due to amendment level of plant material, but root material decomposed significantly slower than blue grama herbage. Blue grama buried in February lost 56% of its labeled carbon in 335 days compared with 42% carbon loss in 314 days suffered by the blue grama buried in May. Herbage segments decomposed slower than ground blue grama herbage, eventually resulting in carbon losses of 37 and 57%, respectively in 412 days. Blue grama segments placed on the soil surface suffered a 50% loss of carbon in 412 days, a loss which was significantly less than that for ground vegetative material mixed into the soil, and significantly more than for plant segments mixed into the soil. However, there was no statistically significant effect of the addition of fresh blue grama herbage on the rate of carbon loss of partially degraded, labeled blue grama herbage.

Soil samples amended with ground blue grama herbage were incubated in the laboratory at various temperatures (3^{o}-60^{o}C) and water contents (2.6-36%). Determinations were performed on labeled carbon dioxide evolved by these samples for a period of approximately a month, and

the results used to develop a multiple regression equation to predict rates of carbon loss. This multiple regression equation predicted the log percent carbon loss as a function of seven variables related to percent soil water (M), soil temperature (Tp) and time (t): log(Mx100), loglog(Mx100), loglog(Tpx100), log(tx100) x log(Mx100), t, $(1.8-\log Tp)^2$, and Tp x log(tx100).

Three laboratory experiments were designed to measure the influence of soil temperature, soil water content, and simulated precipitation events on changes in soil water content in decomposition containers. A 12.5-mm simulated rain was applied to soil in decomposition containers subsequently dried at 5^{o}, 20^{o}, 30^{o}, 40^{o}, 50^{o} and 60^{o}C and soil water determinations performed on the top 2.5 cm of soil in the containers at various times. Exponential regression equations were developed equating percent soil water at time t to initial percent soil water multiplied by e^{-bt}, where b is the drying rate of the soil at a given temperature. A second experiment consisted of applying simulated rain events to soil in containers and subsequently determining the increase in percent water. The results of the latter experiment resulted in a quadratic regression model which predicted the increase in percent water (RAINADD) as a function of the size of the precipitation event. A third experiment was designed to measure the effect of soil water content of 2.5 cm of soil on soil drying rates, independent of soil water supply below 2.5 cm. Soil samples received additions of water to establish soils at a range of water contents from 2 to 36%, and evaporation rates were expressed as a function of variables related to percent soil water at initiation of evaporation period. The later regression

equation was divided by the predicted evaporation rate at 8% water to derive a constant rate phase correction factor.

A mathematical model, DECOM 1, was designed to integrate the hydrologic and decomposition information gathered in laboratory and field experiments. DECOM 1 contains an exponential soil water loss submodel of the form $M_{t+1} = (M_t + RAINADD_t)e^{-b}$, where percent soil water at hour t+1 is predicted from the percent soil water at time t (M_t), the increase in percent soil water due to a precipitation event at time t ($RAINADD_t$), and the soil drying rate (b). Observed weekly soil water data is utilized and M_{t+1} is predicted using an iterative model solution for all other hours of the week. $RAINADD_t$ used rain gauge data to predict increases in soil water. The soil drying rate at time t is calculated from hourly soil temperature data using the results of the laboratory evaporation experiment. The soil drying rate is equal to b if soil water is less than 8% soil water, but larger soil water values are increased by the constant rate phase correction factor. The average DECOM 1 predicted soil water content (D) was related to measured percent water (MW) by the regression equation, $D = 1.10\ MW + .09$, which had a $r^2 = .852$.

After the hourly soil water prediction is calculated in DECOM 1, the houly percent carbon loss of blue grama herbage (D) is estimated as a function of this hourly soil water prediction, hourly soil temperature data, and time, and are summed with time to estimate the cumulative percent carbon loss (CD). The estimates of D are calculated in DECOM 1 by using the multiple regression model, derived in the laboratory decomposition experiment and multiplying these estimates by a correction factor of 3. To evaluate the decomposition predictive capabilities of

DECOM 1, the (DP) were expressed as a function of the carbon losses measured in field experiments (CM). This resulted in a regression equation, DP = .07 + .99 Cm, with an r^2 = .957, indicating a significant correlation between field measurements and DECOM 1 predictions of blue grama carbon loss rates.

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APPENDICES

APPENDIX A

Radiological Considerations

RADIOLOGICAL CONSIDERATIONS

The use of radioactive label in a natural ecosystem raises questions about the potential hazards involved. Some questions that arise would include:

1. How could the carbon-14 label distribute itself outside of the containers?
2. What will happen to the label as a function of time?
3. What hazards exist for man?
4. Will the site contain radioactive contamination when all of the labeled samples are removed?

Definite answers to many of these questions cannot be given since these questions form part of the justification for the study. However, in making calculations and approximations the "worst possible situation" will be portrayed relative to radiation hazards.

Taking the precautions outlined previously, no radioactive material should escape from the containers during transport of the samples. However, once the containers are placed in the soil it will be possible for carbon-14 labeled material to escape through the tops and bottoms of the containers. Carbon-14 labeled carbon dioxide will be respired by soil microorganisms decomposing the radioactive plant material in the soil, and this gas will exist in a vertical concentration gradient favoring movement of carbon dioxide into the atmosphere. The water-soluble components of the radioactive plant material in the soil could be transported via rainfall through the soil and pass through the bottom of the container.

Having considered these potential carbon-14 escape routes from the containers, realistic escape routes can be arrived at only by consider-

considering what happens to the carbon-14 as a function of time. When a total of 20 millicuries of carbon-14 is put out in the soil at the Pawnee Site, approximately 50% of this activity will be given off to the atmosphere above the containers as carbon dioxide during the first year and an additional 25% during the second year. The remainder of the carbon-14 label will be found typically in high molecular weight organic compounds, which are relatively resistant to decomposition and movement in the soil. The small amount of water-soluble plant material in the carbon-14 labeled soil amendments (20 milligrams of carbon-14 labeled water-soluble material per container at the highest amendment rate) are so susceptible to microbial degradation that very little chance will be afforded for downward movement with rain water additions to the sample container. Even if some of this labeled fraction got out of the container, it would be quickly respired as carbon-14 labeled carbon dioxide and be included with the rest of the carbon dioxide given off.

The worst hazards that could exist for man can be calculated from a knowledge of the rate of exchange of air over the containers and the rate of release of the carbon-14 labeled carbon dioxide in microbial decomposition processes. Assuming that all 1300 containers were placed exactly side by side, they would occupy a total area of 19.5 square meters. Considering a height of two meters directly over this area (the height of a man), there is a volume of air of 39 cubic meters, or 3.9×10^7 milliliters that must be considered. If the wind speed on a calm day was only one mile per hour, or 26.82 meters per minute, and the distance across the plot was 4.42 meters (assuming the containers would be arranged in a square area in the field), the air over the

containers would be renewed 26.82/4.42 or 6.07 times per minute. Thus, the rate of exchange of air over the sample containers would be equal to 3.9×10^{7} milliliters total volume times 6.07, or 2.37×10^{8} milliliters permminute. If the maximum decomposition rate was 10 millicuries per year or 1.90×10^{-2} microcuries per minute, then the maximum concentration of labeled carbon dioxide would be approximately equal to the decomposition rate divided by the rate of exchange of air over the containers, or 1.90×10^{-2} microcuries per minute divided by 2.37×10^{8} milliliters per minute, or 8.02×10^{-11} microcuries per milliliter.

According to the Colorado State Department of Public Health, the Maximum Permissible Concentration of carbon-14 labeled carbon dioxide in air for uncontrolled areas is 1.0×10^{-6} microcuries per milliliter. Thus, the maximum predicted concentration of 8.02×10^{-11} microcuries per milliliter is well below this maximum permissible concentration. Although it would be presumptuous to say that the arguments presented above are without error, it is believed that any error in the presentation would tend toward an even "more safe" situation.

Long-term radiological contamination of the site must be considered after all of the sample containers have been removed from the site at the end of the two year study. An extreme situation would occur if the 1300 samples contained a total of 26 grams of water-soluble labeled plant material initially and all of this material could get through the bottom of the containers undecomposed. If this labeled plant material had a specific activity of 10 microcuries per gram and a decomposition rate of 90% per month, there would only be 2.6×10^{-23} g of water-soluble material left after two years, the rest of the carbon-14 label having gone off as labeled carbon dioxide. This corresponds to the negligible

carbon-14 contamination level of 2.6×10^{-22} microcuries spread out over the total container area of 19.5 square meters.

Supplementary Radiological Considerations

1. Field Treatments.

The carbon-14 labeled plant material (specific activity = 7 uCi g dry wt) will be added at two rates: 0.2 g (1.4 uCi) and 2 g (14 uCi) per container. The labeled material will be incorporated into the upper 4 cm of soil in each container. This would represent a soil weight of approximately 800 g. Beneath this treated soil in each container will be 12 cm of unamended soil.

The maximum total quantity of C-14 at the site at any one time will not exceed 1800 uCi.

2. Storage of Carbon-14 Treated Soil.

After removing the containers of carbon-14 treated soil from the field, these will be placed in plastic bags whcih are impermeable to CO_2 and returned immediately to the laboratory. For long-term storage of soil samples, the plastic bags of soil will be placed in large metal cans and kept in a cold room at -32°F. The atmosphere of the cans will be monitored by placing a CO_2 absorbent in them and assaying this for C-14 at regular intervals.

3. Analysis of Carbon-14 Treated Soil.

Composite samples will be prepared from subsamples from each container. These will be analyzed for total carbon-14 using a combustion technique in which CO_2 is released from small soil samples (0.5 g) and trapped in ethanolamine. The combustion of soil samples will be carried out in a specially designed instrument which is located in the A.R.S. Soil Nitrogen Laboratory in Fort Collins. The ethanolamine solutions will be counted using a liquid scintillation spectrometer in the Agronomy Department. The total quantity of isotope in the laboratory at any one time will not exceed 250 uCi.

4. Disposal of Soil.

At the termination of the experiment all soil samples containing carbon-14 will have been disposed of by means of standard CSU radioactive wastes disposal procedures. The soil will be placed in suitable containers and prepared for burial by Radiation Control Office.

All carbon-14 labeled soil will be removed from the Pawnee site and disposed of at the termination of the experiment.

APPENDIX B

Radiocarbon Determinations and Statistical Analyses for Field Experiments

Appendix B

Table 1. Radiocarbon determinations and statistical analyses for field experiment 1. (1280 kg/ha amendment level)

Sampling date	Total days from amendment date	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
2/19/71	8	2	81.16	85.73	7.70 (11)
		3	84.39		
		4	86.56		
		5	90.81		
4/01/71	49	6	77.11	79.63	5.23 (15)
		7	84.44		
		8	80.80		
		9	80.43		
		10	75.37		
5/20/71	98	11	62.26	57.74	4.95 (11)
		13	56.51		
		14	58.42		
		15	53.34		
6/15/71	124	16	52.60	49.05	4.64 (15)
		17	43.20		
		18	52.85		
		19	48.26		
		20	48.35		

Table 1. (Continued)

Sampling date	Total days from amendment date	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
7/16/71	155	21	51.27	45.62	4.16 (15)
		22	48.05		
		23	45.43		
		24	42.92		
		25	40.44		
8/12/71	182	26	49.88	43.32	4.72 (14)
		27	37.38		
		28	44.64		
		29	42.01		
		30	42.26		
9/16/71	217	31	46.72	47.29	2.89 (15)
		32	46.58		
		33	49.17		
		34	45.48		
		35	48.49		
10/13/71	244	36	43.32	44.20	2.96 (15)
		37	42.20		
		38	48.36		
		39	41.90		
		40	45.22		

Table 1. (Continued)

Sampling date	Total days from amendment	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
11/17/71	279	42	44.34	44.14	3.12 (7)
		44	43.47		
		45	44.53		
1/12/72	335	46	48.59	43.78	4.36 (12)
		47	46.18		
		48	41.05		
		49	39.31		
3/29/72	412	51	46.83	45.69	2.04 (15)
		52	45.80		
		53	43.81		
		54	44.11		
		55	47.89		

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Table 2. Radiocarbon determinations and statistical analyses for field experiment 1. (128 kg/ha amendment level)

Sampling date	Total days from amendment date	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
2/19/71	8	81	97.49	98.97	6.02 (12)
		83	106.17		
		84	94.48		
		85	95.41		
4/01/71	49	87	69.36	69.31	4.78 (11)
		88	76.69		
		89	67.91		
		90	65.74		
5/20/71	98	91	55.16	53.06	5.57 (14)
		92	59.10		
		93	51.35		
		94	52.85		
		95	46.84		

Table 2. (Continued)

Sampling date	Total days from amendment date	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
6/15/71	124	96	56.71	50.98	5.30 (15)
		97	48.42		
		98	45.92		
		99	54.65		
		100	49.31		
7/16/71	155	101	54.83	49.92	3.60 (12)
		103	47.74		
		104	48.78		
		105	48.39		
8/12/71	182	106	45.35	44.11	2.45 (12)
		107	43.15		
		108	41.85		
		109	46.17		
9/16/71	217	111	46.57	45.79	3.91 (15)
		112	47.34		
		113	46.97		
		114	42.71		
		115	45.48		

Table 2. (Continued)

Sampling date	Total days from amendment date	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
10/13/71	244	116	50.73	46.19	3.47 (15)
		117	45.32		
		118	46.13		
		119	42.98		
		120	45.82		
11/17/71	279	121	51.32	46.13	5.02 (15)
		122	49.38		
		123	42.02		
		124	46.66		
		125	41.27		
1/12/72	335	126	45.61	43.77	2.89 (15)
		127	41.01		
		128	43.63		
		130	44.87		
3/29/72	412	131	45.72	43.02	3.05 (14)
		132	41.77		
		133	44.63		
		134	40.30		
		135	43.27		

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Table 3. Radiocarbon determinations and statistical analyses for field experiment 2. (1920 kg/ha amendment level)

Sampling date	Total days from amendment date	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
2/19/71	8	241	85.09	84.90	8.67 (13)
		242	89.48		
		243	90.19		
		244	80.36		
		245	76.36		
4/01/71	49	246	75.90	77.19	7.53 (11)
		247	85.38		
		249	71.88		
		250	78.35		
5/20/71	98	251	76.17	71.84	9.15 (13)
		252	75.45		
		253	64.13		
		254	59.94		
		255	82.40		
6/15/71	124	257	70.36	66.56	4.60 (12)
		258	64.58		
		259	63.56		
		260	67.77		

Table 3. (Continued)

Sampling date	Total days from amendment date	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
7/16/71	155	261	62.41	62.04	4.37 (14)
		262	62.81		
		263	60.18		
		264	67.04		
		265	57.93		
10/13/71	244	277	58.18	62.71	4.78 (12)
		278	66.55		
		279	62.89		
		280	63.28		
3/29/72	412	291	62.56	62.90	4.53 (14)
		292	67.27		
		293	62.16		
		294	62.17		
		295	61.82		

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Table 4. Radiocarbon determinations and statistical analyses for field experiment 2. (384 kg/ha amendment level)

Sampling date	Total days from amendment date	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
2/19/71	8	322	93.59	95.42	7.80 (8)
		323	89.27		
		324	101.76		
		325	97.18		
4/01/71	49	326	84.00	75.62	8.22 (12)
		327	70.20		
		329	79.10		
		330	69.31		
5/20/71	98	331	79.32	72.26	5.79 (14)
		332	67.11		
		333	69.90		
		334	70.58		
		335	75.49		
6/15/71	124	336	70.75	70.86	6.13 (12)
		337	74.44		
		338	71.85		
		340	66.51		

Table 4. (Continued)

Sampling date	Total days from amendment	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
7/16/71	155	341	70.93	69.70	4.23 (10)
		342	68.18		
		343	71.80		
		344	72.38		
		345	65.34		
10/13/71	244	356	78.92	70.43	7.36 (14)
		357	67.77		
		358	66.40		
		359	71.40		
		360	66.94		
3/29/72	412	371	71.31	73.58	6.53 (13)
		372	75.59		
		373	76.26		
		374	76.22		
		375	70.22		

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Table 5. Radiocarbon determinations and statistical analyses for field experiment 3. (128 kg/ha amendment level)

Sampling date	Total days from amendment date	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
5/21/71	1	402	97.80	100.9	7.18 (7)
		403	99.82		
		404	93.23		
		405	108.91		
6/15/71	26	407	70.72	71.98	6.09 (8)
		408	67.03		
		410	77.79		
7/16/71	57	411	73.62	69.26	4.25 (15)
		412	67.95		
		413	67.79		
		414	69.73		
		415	67.28		
9/16/71	119	422	62.30	65.85	5.50 (9)
		423	71.34		
		424	63.90		

Table 5. (Continued)

Sampling date	Total days from amendment	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
11/17/71	181	432	58.97	60.00	3.60 (12)
		433	60.32		
		434	57.39		
		435	63.32		
3/29/72	314	441	58.93	57.85	4.96 (15)
		442	54.10		
		443	53.94		
		444	63.35		
		445	58.98		

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Table 6. Radiocarbon determinations and statistical analyses for field experiment 4. (128 kg/ha amendment level)

Sampling date	Total days from amendment date	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
2/19/71	8	596	93.54	89.99	5.44 (6)
		597	84.65		
		598	90.75		
		599	95.56		
6/04/71	113	601	57.20	51.99	4.53 (27)
		602	53.03		
		603	56.28		
		604	50.50		
		605	47.45		
		606	48.89		
		607	47.93		
		609	50.31		
		610	56.43		

Table 6. (Continued)

Sampling date	Total days from amendment date	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
11/17/71	279	621	39.79	41.53	2.77 (26)
		623	42.40		
		624	37.93		
		625	43.94		
		626	43.14		
		627	41.70		
		628	40.04		
		629	42.25		
		630	42.96		
Samples amended with radioactive and nonradioactive blue grama:					
11/17/71	279	691	33.35	36.90	3.27 (25)
		692	37.83		
		693	38.67		
		694	39.63		
		696	35.71		
		697	33.33		
		698	38.45		
		699	34.08		
		700	40.79		

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Table 7. Radiocarbon determinations and statistical analyses for field experiment 5. (128 kg/ha amendment level of labeled herbage)

Sampling date	Total days from amendment date	Container number	Percent retention of labeled carbon: Container mean	Sampling date mean	Standard deviation (total observations)
2/19/71	8	762	101.38	95.13	7.04 (6)
		763	89.78		
		764	90.06		
		765	86.76		
4/01/71	49	766	89.72	92.93	6.78 (10)
		767	96.72		
		768	85.71		
		769	99.32		
5/20/71	98	772	65.10	65.51	5.71 (10)
		773	60.12		
		774	69.80		
		775	69.91		
3/29/72	412	811	62.84	60.93	5.44 (9)
		812	62.03		
		813	63.18		
		814	47.11		

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Table 8. Radiocarbon determinations and statistical analyses for field experiment 6. (128 kg/ha amendment level)

Sampling date	Total days from amendment date	Container number	Percent retention of labeled carbon		
			Container mean	Sampling date mean	Standard deviation (total observations)
2/19/71	2	922	88.42	91.86	5.44 (9)
		923	100.80		
		924	90.66		
		925	87.93		
4/01/71	43	926	87.45	92.21	5.00 (8)
		928	89.16		
		929	95.69		
		930	95.70		
5/20/71	92	931	67.35	72.32	4.97 (15)
		932	70.20		
		934	75.46		
		935	76.25		
3/29/72	406	971	46.93	49.92	3.20 (10)
		972	48.40		
		973	51.16		
		974	51.20		

APPENDIX C

Carbon Loss Rates of Radioactive Blue Grama Herbage and Water Content of Soil Samples Incubated at Various Temperatures in the Laboratory

Appendix C

Table 1. Carbon loss rates of radioactive blue grama herbage and water contents of soil samples incubated at 3°C.

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
0	168	84	1	.0000176	2.00
0	219	110	2	.0000178	2.00
0	219	110	3	.0000191	2.00
0	219	110	4	.0000155	2.00
168	332	250	1	.0000161	2.00
219	523	371	2	.0000046	2.00
219	523	371	3	.0000096	2.00
219	523	371	4	.0000083	2.00
332	500	416	1	.0000092	2.00
500	568	534	1	.0000148	2.00
523	968	746	4	.0000000	2.00
0	168	84	1	.0042937	5.00
0	219	110	2	.0049272	5.00
0	219	110	3	.0055648	5.00
0	219	110	4	.0047791	5.00
168	332	250	1	.0062206	5.00
219	523	371	2	.0028980	5.00
219	523	371	3	.0025835	5.00
219	523	371	4	.0027210	5.00
523	968	746	2	.0000581	5.00
523	968	746	3	.0000537	5.00
523	968	746	4	.0000541	5.00
0	168	84	1	.0096847	10.00
0	219	110	2	.0054943	10.00

Table 1. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
0	219	110	3	.0067078	10.00
0	219	110	4	.0052017	10.00
168	332	250	1	.0054104	10.00
219	523	371	2	.0025107	10.00
219	523	371	3	.0030786	10.00
219	523	371	4	.0026026	10.00
332	500	416	1	.0057978	10.00
500	568	534	1	.0087468	10.00
523	968	746	3	.0000937	10.00
523	968	746	4	.0000832	10.00
0	168	84	1	.0115619	20.00
0	219	110	2	.0066565	20.00
0	219	110	3	.0065570	20.00
0	219	110	4	.0072067	20.00
168	332	250	1	.0063116	20.00
219	523	371	2	.0026760	20.00
219	523	371	3	.0027156	20.00
219	523	371	4	.0028078	20.00
332	500	416	1	.0051215	20.00
500	568	534	1	.0053450	20.00
523	968	746	4	.0000685	20.00
0	168	84	1	.0118864	25.00
0	219	110	2	.0065380	25.00
0	219	110	3	.0072493	25.00
0	219	110	4	.0076307	25.00

Table 1. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
168	332	250	1	.0064321	25.00
219	523	371	2	.0024533	25.00
219	523	371	3	.0028458	25.00
219	523	371	4	.0029670	25.00
332	500	416	1	.0051622	25.00
500	568	534	1	.0054562	25.00
523	968	746	4	.0000566	25.00
0	168	84	1	.0105755	36.00
0	219	110	2	.0068317	36.00
0	219	110	3	.0077599	36.00
0	219	110	4	.0078718	36.00
168	332	250	1	.0059206	36.00
219	523	371	2	.0025658	36.00
219	523	371	3	.0028748	36.00
219	523	371	4	.0028081	36.00
332	500	416	1	.0047982	36.00
500	568	534	1	.0047568	36.00
523	968	746	4	.0002940	36.00

Appendix C

Table 2. Carbon loss rates of radioactive blue grama herbage and water contents of soil samples incubated at 10°C.

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
0	168	84	1	.0000455	2.00
0	221	111	2	.0000401	2.00
0	221	111	3	.0000417	2.00
0	221	111	4	.0000386	2.00
168	332	250	1	.0000216	2.00
221	391	306	2	.0000268	2.00
221	391	306	3	.0000269	2.00
221	391	306	4	.0000240	2.00
332	500	416	1	.0000158	2.00
391	503	447	2	.0000241	2.00
391	503	447	3	.0000198	2.00
391	503	447	4	.0000164	2.00
500	568	534	1	.0000356	2.00
0	168	84	1	.0099043	5.00
0	221	111	2	.0135844	5.00
0	221	111	3	.0148065	5.00
0	221	111	4	.0118738	5.00
168	332	250	1	.0103515	5.00
221	391	306	2	.0129403	5.00
221	391	306	3	.0110400	5.00
221	391	306	4	.0093300	5.00
332	500	416	1	.0053613	5.00

Table 2. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
391	503	447	2	.0091267	5.00
391	503	447	3	.0069940	5.00
500	568	534	1	.0038388	5.00
0	168	84	1	.0210377	10.00
0	221	111	2	.0217602	10.00
0	221	111	3	.0058064	10.00
0	221	111	4	.0208312	10.00
168	332	250	1	.0248279	10.00
221	391	306	2	.0271344	10.00
221	391	306	3	.0271151	10.00
221	391	306	4	.0264824	10.00
332	500	416	1	.0236245	10.00
391	503	447	2	.0166912	10.00
391	503	447	3	.0164521	10.00
391	503	447	4	.0166028	10.00
500	568	534	1	.0181670	10.00
0	168	84	1	.0210611	20.00
0	221	111	2	.0171225	20.00
0	221	111	3	.0012134	20.00
0	221	111	4	.0157444	20.00
168	332	250	1	.0243729	20.00
221	391	306	2	.0246444	20.00
221	391	306	3	.0260733	20.00
221	391	306	4	.0238128	20.00
332	500	416	1	.0270659	20.00

Table 2. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
391	503	447	2	.0244368	20.00
391	503	447	3	.0260784	20.00
391	503	447	4	.0254453	20.00
500	568	534	1	.0186153	20.00
0	168	84	1	.0180128	25.00
0	221	111	2	.0168124	25.00
0	221	111	3	.0186936	25.00
0	221	111	4	.0183939	25.00
168	332	250	1	.0148442	25.00
221	391	306	2	.0249655	25.00
221	391	306	3	.0279834	25.00
221	391	306	4	.0242527	25.00
332	500	416	1	.0203720	25.00
391	503	447	2	.0242472	25.00
391	503	447	3	.0263233	25.00
391	503	447	4	.0291681	25.00
500	568	534	1	.0211155	25.00
0	168	84	1	.0188468	36.00
0	221	111	2	.0217147	36.00
0	221	111	3	.0198362	36.00
0	221	111	4	.0188333	36.00
168	332	250	1	.0152568	36.00
221	391	306	2	.0310489	36.00
221	391	306	3	.0261561	36.00

Table 2. (Continued)

Duration of decomposition period (hours)		Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
Start	Finish				
221	391	306	4	.0227354	36.00
332	500	416	1	.0227419	36.00
391	503	447	2	.0293822	36.00
391	503	447	3	.0312880	36.00
391	503	447	4	.0294163	36.00
500	568	534	1	.0253096	36.00

Appendix C

Table 3. Carbon loss rates of radioactive blue grama herbage and water contents of soil samples incubated at 25°C.

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
0	168	84	1	.0001290	2.00
0	221	111	2	.0001282	2.00
0	221	111	3	.0000957	2.00
0	221	111	4	.0000725	2.00
168	332	250	1	.0000743	1.82
221	391	306	2	.0000606	2.00
221	391	306	3	.0000528	2.00
221	391	306	4	.0000549	2.00
332	500	416	1	.0000610	1.82
391	497	444	2	.0000262	2.00
391	497	444	3	.0000330	2.00
391	497	444	4	.0000334	2.00
500	561	531	1	.0000504	1.82
0	168	84	1	.0607279	5.00
0	221	111	2	.0611811	5.00
0	221	111	3	.0558422	5.00
0	221	111	4	.0511442	5.00
168	332	250	1	.0237112	4.64
221	391	306	2	.0237023	5.00
221	391	306	3	.0216325	5.00
221	391	306	4	.0192037	4.94
332	500	416	1	.0070056	4.52
391	497	444	2	.0094140	4.84

Table 3. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
391	497	444	3	.0085918	4.84
391	497	444	4	.0081532	4.86
500	561	531	1	.0039388	4.40
0	168	84	1	.1075038	10.00
0	221	111	2	.0920013	10.00
0	221	111	3	.0880529	10.00
0	221	111	4	.0981101	10.00
168	332	250	1	.0389767	9.60
221	391	306	2	.0279017	9.86
221	391	306	3	.0268831	9.84
221	391	306	4	.0325175	9.80
332	500	416	1	.0212528	9.48
391	497	444	2	.0195979	9.72
391	497	444	3	.0182708	9.76
391	497	444	4	.0219741	9.80
500	561	531	1	.0141152	9.32
0	168	84	1	.1008794	20.00
0	221	111	2	.0858889	20.00
0	221	111	3	.0844158	20.00
0	221	111	4	.0871203	20.00
168	332	250	1	.0425824	19.56
221	391	306	2	.0324926	20.00
221	391	306	3	.0326553	19.90
221	391	306	4	.0338100	19.88
332	500	416	1	.0154056	19.48

Table 3. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
391	497	444	2	.0153309	19.94
391	497	444	3	.0146089	19.90
391	497	444	4	.0152704	19.88
500	561	531	1	.0112173	19.26
0	168	84	1	.1111533	25.00
0	221	111	2	.0861158	25.00
0	221	111	3	.0895670	25.00
0	221	111	4	.0914688	25.00
168	332	250	1	.0487423	24.52
221	391	306	2	.0352040	24.90
221	391	306	3	.0368307	24.92
221	391	306	4	.0373396	24.94
332	500	416	1	.0172111	24.38
391	497	444	2	.0157071	24.90
391	497	444	3	.0154594	24.92
391	497	444	4	.0164249	24.88
500	561	531	1	.0121403	24.18
0	168	84	1	.1065759	36.00
0	221	111	2	.0845302	36.00
0	221	111	3	.0932640	36.00
0	221	111	4	.0914563	36.00
168	332	250	1	.0548305	35.54
221	391	306	2	.0379190	35.80
221	391	306	3	.0400715	36.00

Table 3. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
221	391	306	4	.0397275	35.70
332	500	416	1	.0202212	35.50
391	497	444	2	.0158212	35.76
391	497	444	3	.0169011	35.92
391	497	444	4	.0180904	35.64
500	561	531	1	.0134617	35.26

Appendix C

Table 4. Carbon loss rates of radioactive blue grama herbage and water contents of soil samples incubated at 40°C.

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
0	152	76	2	.0005684	2.00
0	152	76	3	.0004577	2.00
0	152	76	4	.0005426	2.00
0	168	84	1	.0005298	2.00
152	282	217	2	.0001751	2.00
152	282	217	3	.0001996	2.00
0	152	76	2	.0005684	2.00
0	152	76	3	.0004577	2.00
0	152	76	4	.0005426	2.00
0	168	84	1	.0005298	2.00
152	282	217	2	.0001751	2.00
152	282	217	3	.0001996	2.00
152	282	217	4	.0001805	2.00
168	332	250	1	.0001656	2.00
282	415	349	2	.0000942	2.00
282	415	349	3	.0001017	2.00
282	415	349	4	.0000862	2.00
332	500	416	1	.0000909	2.00
415	497	456	2	.0000667	2.00
415	497	456	3	.0000898	2.00
415	497	456	4	.0000737	2.00
500	561	531	1	.0000855	2.00
0	152	76	2	.0577110	5.00
0	152	76	3	.0664429	5.00

Table 4. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
0	152	76	4	.0716009	5.00
0	168	84	1	.0545822	5.00
152	282	217	2	.0187312	5.00
152	282	217	3	.0191285	5.00
152	282	217	4	.0205045	5.00
168	332	250	1	.0125177	4.90
282	415	349	2	.0040244	4.82
282	415	349	3	.0043833	4.80
282	415	349	4	.0046703	4.80
332	500	416	1	.0026162	4.60
415	497	456	2	.0013994	4.44
415	497	456	3	.0014930	4.48
415	497	456	4	.0014994	4.48
500	561	531	1	.0010399	4.24
0	152	76	2	.1202075	10.00
0	152	76	3	.1343568	10.00
0	152	76	4	.1537308	10.00
0	168	84	1	.1506718	10.00
152	282	217	2	.0521839	10.00
152	282	217	4	.0420067	10.00
168	332	250	1	.0548526	9.66
282	415	349	2	.0140782	9.72
282	415	349	3	.0096597	9.50
282	415	349	4	.0097828	9.68
332	500	416	1	.0118670	9.34

Table 4. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
415	497	456	2	.0044575	9.20
415	497	456	3	.0043438	9.04
415	497	456	4	.0045294	9.26
500	561	531	1	.0045426	8.82
0	152	76	2	.1378611	20.00
0	152	76	3	.1597914	20.00
0	152	76	4	.1788327	20.00
0	168	84	1	.1791887	20.00
152	282	217	2	.0345098	19.54
152	282	217	3	.0460848	19.46
152	282	217	4	.0367949	19.76
168	332	250	1	.0482717	19.70
282	415	349	2	.0139683	18.92
282	415	349	3	.0137727	18.90
282	415	349	4	.0126260	19.10
332	500	416	1	.0125831	19.42
415	497	456	2	.0083883	18.42
415	497	456	3	.0068687	18.44
415	497	456	4	.0060610	18.36
500	561	531	1	.0077996	19.10
0	152	76	2	.1707718	25.00
0	152	76	3	.1795220	25.00
0	152	76	4	.1800789	25.00
0	168	84	1	.1689525	25.00

Table 4. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
152	282	217	2	.0393390	24.84
152	282	217	3	.0395844	24.68
152	282	217	4	.0404350	24.72
168	332	250	1	.0416515	24.80
282	415	349	2	.0134214	24.20
282	415	349	3	.0138855	24.22
282	415	349	4	.0137604	24.48
332	500	416	1	.0118831	24.36
415	497	456	2	.0074915	23.80
415	497	456	3	.0073222	23.48
415	497	456	4	.0082183	24.28
500	561	531	1	.0062239	23.82
0	152	76	2	.1811131	36.00
0	152	76	3	.1726984	36.00
0	152	76	4	.1790114	36.00
0	168	84	1	.1710605	36.00
152	282	217	2	.0365588	35.66
152	282	217	3	.0350963	35.84
152	282	217	4	.0361005	35.84
168	332	250	1	.0374243	35.72
282	415	349	2	.0155758	35.40
282	415	349	3	.0149616	35.50
332	500	416	1	.0128013	35.48
415	497	456	2	.0084343	35.10
415	497	456	3	.0083482	35.08

Table 4. (Continued)

Duration of decomposition period (hours)		Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
Start	Finish				
415	497	456	4	.0144774	35.62
500	561	531	1	.0072663	34.92

Appendix C

Table 5. Carbon loss rates of radioactive blue grama herbage and water contents of soil samples incubated at 50°C.

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
0	152	76	2	.0007108	2.00
0	152	76	3	.0007299	2.00
0	152	76	4	.0008460	2.00
0	168	84	1	.0004120	2.00
152	282	217	2	.0003608	2.00
152	282	217	3	.0003890	2.00
152	282	217	4	.0003686	2.00
168	332	250	1	.0004326	2.00
282	415	349	2	.0001783	2.00
282	415	349	3	.0002067	2.00
282	415	349	4	.0002031	2.00
332	500	416	1	.0002814	2.00
415	497	456	2	.0001221	2.00
415	497	456	3	.0001426	2.00
415	497	456	4	.0001373	2.00
500	561	531	1	.0002495	2.00
0	152	76	2	.0312187	5.00
0	152	76	3	.0270833	5.00
0	152	76	4	.0307451	5.00
0	168	84	1	.0318214	5.00
152	282	217	2	.0041395	5.00
152	282	217	3	.0043249	5.00
152	282	217	4	.0039132	5.00
168	332	250	1	.0050788	4.80

Table 5. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
282	415	349	2	.0007873	5.00
282	415	349	3	.0007353	5.00
282	415	349	4	.0007867	5.00
415	497	456	2	.0004225	4.22
415	497	456	3	.0003962	4.16
415	497	456	4	.0004825	4.26
0	152	76	2	.1280513	10.00
0	152	76	3	.0899975	10.00
0	152	76	4	.1712281	10.00
0	168	84	1	.1615319	10.00
152	282	217	2	.0340264	10.00
152	282	217	3	.0293444	10.00
152	282	217	4	.0360793	10.00
168	332	250	1	.0315431	9.84
282	415	349	2	.0030163	9.76
282	415	349	3	.0024003	10.00
282	415	349	4	.0030723	10.00
332	500	416	1	.0032242	9.84
415	497	456	2	.0016333	9.46
415	497	456	3	.0013456	9.10
415	497	456	4	.0017906	8.76
500	561	531	1	.0020482	8.84
0	152	76	2	.0755040	8.92
0	152	76	3	.1806191	20.00
0	152	76	4	.1803718	20.00
					20.00

Table 5. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
0	168	84	1	.1682861	20.00
152	282	217	3	.0492152	19.70
152	282	217	4	.0570198	19.78
168	332	250	1	.0387030	19.80
282	415	349	2	.0087393	19.60
282	415	349	3	.0070744	19.54
282	415	349	4	.0071828	19.66
332	500	416	1	.0050861	19.80
415	497	456	2	.0049930	19.20
415	497	456	3	.0034269	19.02
500	561	531	1	.0025970	18.92
0	152	76	2	.0577767	25.00
0	152	76	3	.1193044	25.00
0	152	76	4	.1131684	25.00
0	168	84	1	.1596551	25.00
152	282	217	3	.0329258	24.80
152	282	217	4	.0275084	24.72
168	332	250	1	.0430345	24.66
282	415	349	3	.0092523	24.64
282	415	349	4	.0083922	24.62
332	500	416	1	.0060838	24.62
415	497	456	2	.0037108	24.06
415	497	456	3	.0053530	24.08
415	497	456	4	.0044692	24.24
500	561	531	1	.0020036	24.34

Table 5. (Continued)

Duration of decomposition period (hours)		Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
Start	Finish				
0	152	76	2	.0618985	36.00
0	152	76	3	.0614346	36.00
0	152	76	4	.0659567	36.00
0	168	84	1	.0764741	36.00
152	282	217	2	.0162526	35.54
152	282	217	3	.0116194	35.80
152	282	217	4	.0166543	35.82
168	332	250	1	.0163647	35.80
282	415	349	2	.0069077	35.40
282	415	349	4	.0079713	35.56
332	500	416	1	.0040616	35.28
415	497	456	2	.0054624	34.92
415	497	456	4	.0055471	35.06
500	561	531	1	.0031145	34.62

Appendix C

Table 6. Carbon loss rates of radioactive blue grama herbage and water contents of soil samples incubated at 60°C.

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
0	152	76	2	.0011123	2.00
0	152	76	3	.0112210	2.00
0	152	76	4	.0012254	2.00
0	168	84	1	.0012076	2.00
152	282	217	2	.0004762	2.00
152	282	217	3	.0005270	2.00
152	282	217	4	.0005518	2.00
168	332	250	1	.0006977	2.00
282	415	349	2	.0002655	2.00
282	415	349	3	.0002741	2.00
282	415	349	4	.0002772	2.00
332	500	416	1	.0005947	2.00
415	497	456	2	.0001680	2.00
415	497	456	3	.0002062	2.00
415	497	456	4	.0001977	2.00
500	561	531	1	.0004712	1.89
0	152	76	2	.0144344	5.00
0	152	76	4	.0137181	5.00
0	168	84	1	.0118610	5.00
152	282	217	2	.0016150	4.94
152	282	217	3	.0017704	4.76
152	282	217	4	.0015947	4.86

Table 6. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
0	152	76	2	.0319186	10.00
0	152	76	3	.0419285	10.00
0	152	76	4	.0132791	10.00
0	168	84	1	.0474201	10.00
152	282	217	2	.0049163	9.94
152	282	217	3	.0040655	9.86
152	282	217	4	.0040419	9.72
168	332	250	1	.0048482	9.50
282	415	349	2	.0011640	9.48
282	415	349	3	.0011318	9.32
282	415	349	4	.0007622	9.56
332	500	416	1	.0013676	8.90
415	497	456	2	.0010741	8.88
415	497	456	3	.0010790	8.52
415	497	456	4	.0007601	8.90
500	561	531	1	.0013102	7.94
0	152	76	3	.1100595	20.00
0	152	76	4	.0631109	20.00
0	168	84	1	.1106838	20.00
152	282	217	2	.0107461	18.84
152	282	217	3	.0160996	19.18
152	282	217	4	.0112536	19.66
168	332	250	1	.0159961	19.44
282	415	349	3	.0025747	18.56
282	415	349	4	.0021670	19.02

Table 6. (Continued)

Duration of decomposition period (hours)		Midpoint of decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
Start	Finish				
332	500	416	1	.0013131	18.64
415	497	456	2	.0009574	17.60
415	497	456	3	.0012648	17.74
415	497	456	4	.0008427	18.28
500	561	531	1	.0008469	17.24
0	152	76	2	.0832553	25.00
0	152	76	3	.0580100	25.00
0	152	76	4	.0741262	25.00
0	168	84	1	.1146609	25.00
152	282	217	2	.0192585	24.56
152	282	217	3	.0145242	24.50
168	332	250	1	.0128344	24.60
282	415	349	2	.0034948	23.86
282	415	349	3	.0030281	23.66
282	415	349	4	.0022804	23.66
332	500	416	1	.0025732	23.86
415	497	456	2	.0014212	23.06
415	497	456	3	.0011248	22.98
415	497	456	4	.0011271	23.46
500	561	531	1	.0009386	22.46
0	152	76	2	.1034929	36.00
0	152	76	3	.0640665	36.00
0	152	76	4	.1003543	36.00
0	168	84	1	.0767600	36.00
152	282	217	2	.0171499	35.58

Table 6. (Continued)

Duration of decomposition period (hours) Start	Finish	Midpoint decomposition period (hours)	Replicate number	Average carbon loss rate for period (percent carbon loss/hr.)	Percent soil water (oven dry weight basis)
152	282	217	3	.0183204	34.98
152	282	217	4	.0175551	35.32
168	332	250	1	.0120685	35.70
282	415	349	3	.0049512	34.98
282	415	349	4	.0048852	34.36
332	500	416	1	.0042329	34.80
415	497	456	3	.0032149	34.44
415	497	456	4	.0025619	33.76
500	561	531	1	.0023361	33.60

APPENDIX D

Water Contents of Soil Samples Dried in the Laboratory at Various Temperatures

Appendix D

Table 1. Water contents of soil samples dried for various time periods at temperatures from 5°C to 60°C.

Soil temperature (°C)	Sampling time (hr from drying initiation)	% soil water (oven dry weight basis) Soil container number 1	2	3	4	5	6	7	8	9	10	Mean
5	0	22.09*	19.09	18.99	20.24	17.74	-	-	-	-	-	19.63
	24	-	-	-	-	-	12.18	12.88	12.33	13.13	13.32	12.77
	48	11.09	7.33	8.89	10.86	7.32	-	-	-	-	-	9.10
	67	-	-	-	-	-	10.06	10.94	9.55	9.11	11.04	10.14
	89	11.19	8.47	8.66	9.99	7.94	-	-	-	-	-	9.25
	115	-	-	-	-	-	7.66	9.20	7.10	5.66	7.69	7.46
20	0	16.55	17.32	17.37	19.70	20.07	-	-	-	-	-	18.20
	12	-	-	-	-	-	12.38	12.24	15.65	13.32	13.65	13.45
	25	11.27	14.06	12.38	10.75	14.26	-	-	-	-	-	12.64
	50	-	-	-	-	-	9.38	8.86	12.33	-	6.87	9.36
	78	7.32	7.22	7.83	4.85	9.74	-	-	-	-	-	7.39

Table 1. (Continued)

Soil temperature (°C)	Sampling time (hr from drying initiation)	% soil water (oven dry weight basis) Soil container number 1	2	3	4	5	6	7	8	9	10	Mean
30	0	19.90	19.96	20.37	21.33	22.09	-	-	-	-	-	20.73
	10	-	-	-	-	-	13.19	14.55	12.96	12.93	12.11	13.15
	29	13.55	14.55	15.21	13.07	14.20	-	-	-	-	-	14.12
	51	-	-	-	-	-	6.67	13.30	11.30	5.47	10.71	9.49
	77	-	-	-	-	-	6.19	8.03	7.00	3.73	8.01	6.59
40	0	17.39	18.17	17.16	17.78	18.14	-	-	-	-	-	17.73
	12	-	-	-	-	-	11.53	11.54	11.94	11.14	12.03	11.64
	36	10.66	13.00	11.68	10.81	11.38	-	-	-	-	-	11.51
	50	-	-	-	-	-	5.46	7.14	9.04	6.67	8.42	7.35
	75	1.74	2.63	2.45	2.08	1.09	-	-	-	-	-	2.16
	103	-	-	-	-	-	1.44	1.73	1.90	1.69	2.62	1.88

Table 1. (Continued)

Soil temperature (°C)	Sampling time (hr from drying initiation)	% soil water (oven dry weight basis) Soil container number 1	2	3	4	5	6	7	8	9	10	Mean
50	0	19.95	20.99	19.08	19.59	20.78	–	–	–	–	–	20.08
	7	–	–	–	–	–	10.50	12.01	9.67	9.86	12.67	10.94
	17	5.17	6.17	3.94	6.35	4.03	–	–	–	–	–	5.13
	24	–	–	–	–	–	–	3.65	2.05	–	4.02	3.24
	31	3.01	3.14	2.57	3.40	3.28	–	–	–	–	–	3.08
	42	–	–	–	–	–	1.06	1.23	1.09	1.14	1.01	1.11
60	0	17.64	18.33	18.95	16.77	19.12	–	–	–	–	–	18.16
	5.5	–	–	–	–	–	9.69	10.60	10.64	9.64	11.31	10.38
	11	6.33	7.28	9.29	4.74	7.18	–	–	–	–	–	6.96
	21	–	–	–	–	–	.42	1.09	1.10	1.07	1.49	1.03
	28	.78	.99	.80	.94	1.16	–	–	–	–	–	.93
	35	–	–	–	–	–	.78	.66	.98	.76	1.10	.86
	46	.48	–	.49	.56	.40	–	–	–	–	–	.48

* Average of two replicate determi

APPENDIX E

DECOM 1, a Computer Program for Predicting Changes in Soil Water Content and Carbon Losses of Blue Grama Herbage in Soil

```
      PROGRAM DECOM 1
     -(INPUT,OUTPUT,TAPE 1,TAPE 2,TAPE 3,TAPE 6=OUTPUT)

          DECOM 1 USES SOIL TEMPERATURE, SOIL MOISTURE, AND RAINGAUGE
      DATA TO PREDICT SOIL MOISTURE ON AN HOURLY BASIS.  THE PREDICTED
      SOIL MOISTURE VALUES, SOIL TEMPERATURE DATA AND TIME ARE THEN
      USED TO PREDICT HOW FAST C-14 LABELED BLUE GRAMA DECOMPOSES UNDER
      FIELD CONDITIONS AT THE PAWNEE SITE, AS A PERCENT OF THE MATERIAL
      ORIGINALLY AVAILABLE FOR DECOMPOSITION.(J.W. NYHAN, AUGUST 2,72.)

      DIMENSION BETA(3)
      REAL MOIST(3),HRTEM(24),DC(3),D(3)
      INTEGER TIME(4),TIME2(4),RTIME(4),RTIME2(4),DATE(3)
      LINE=60 $ IPG=0

      INITIALIZE SOIL MOISTURE FROM RAINGAUGE DATA AND SOIL MOISTURE
      DATA AT TIME T. INITIALIZE DECOMPOSITION RATE AND CUMULATIVE DECOM
      POSITION TO 0.

    1 CALL MOISTIO(TIME,TIME2,MOIST)
      IST=TIME(4)
      CALL RAINIO(RTIME,RTIME2,RAIN)
      RAINADD=0.
      DO 16 J=1,3
      D(J)=0.0
      CD(J)=0.0
   16 CONTINUE

      READ IN THE DATE AND HOURLY TEMPERATURE DATA.

      HOUR=0.0
    2 READ(3.10)DATE,HRTEM
      IF(EOF(3).NE.0.)STOP
      DO 9 I=IST,24
      RAIN=0.0
      DO 3 J=1.3
      IF(DATE(J).NE.RTIME2(J) GO TO 4
    3 CONTINUE
      IF(I.EQ.RTIME2(4))CALL RAINIO(RTIME,RTIME2,RAIN)
    4 DO 5 J-1,3
      IF(DATE(J).NE.TIME2(J))GO TO 6
    5 CONTINUE
      IF(I.EQ.TIME2(4))CALL MOISTIO(TIME,TIME2,MOIST)
    6 CONTINUE

      WRITE PAGE HEADINGS IF NECESSARY.

      IF(LINE.LT.60)GO TO 7
      IPG=IPG+1 $ LINE=6
      WRITE(6,11)IPG
      WRITE(6,12)
```

```
      WRITE(6,13)

      WRITE INITIAL OR CURRENT PREDICTIONS OF SOIL MOISTURE AND PC PLANT
      MATERIAL DECOMPOSED.

    7 WRITE(6,14)DATE,I,RAIN,RAINADD,HRTEM(I),MOIST(1),HOUR,D,CD
      LINE=LINE+1

      NOW CALCULATE DECOMPOSITION RATE D AND CUMULATIVE DECOMPOSITION CD

      HOUR=HOUR+1.00
      CALL DECRTE(MOIST,HRTEM(I),HOUR,D)
      DO 15 J=1,3
   15 CD(J)=CD(J)+D(J)

      BEGIN CALCULATIONS FOR SOIL MOISTURE PREDICTION

      IF(RAIN.GT.15.5)RAINADD=23.015
      IF(RAIN.LE.15.5)RAINADD=.295797-.0943826*RAIN**2+2.93451*RAIN
      IF(RAIN.EQ.0.)RAINADD=0.0

      CALCULATE B IN MOISTURE MODEL M(T+1)=M(T)+RAINADD*E**B

      IF(HRTEM(I).LE.61.)B=.36411-.014121*HRTEM(I)+.0001106*HRTEM(I)**2
      IF(HRTEM(I).LE.40.)B=.01513-.000965*HRTEM(I)
      IF(HRTEM(I).LE.30.)B=-.0060766-.000257263*HRTEM(I)
      IF(HRTEM(I).LE.5.)B=-.001476*HRTEM(I)
      IF(HRTEM(I).EQ.0.)B=-.001476
      IF(HRTEM(I).LT.0.)B=0.

      CALCULATE CORRECTION FACTOR FOR B RESULTING IN BETA(J).

      CALL CORRECT(MOIST.B.BETA)

      CALCULATION OF NEXT ITERATION OF SOIL MOISTURE.

      DO 8 J=1,3
      MOIST(J)=MOIST(J)+RAINADD
      IF(MOIST(J).GT.32.)MOIST(J)=32.
    8 MOIST(J)=MOIST(J)*EXP(BETA(J))

      NOW HAVE 3 PREDICTED SOIL MOISTURE VALUES - AVERAGE SOIL MOISTURE,
      +/- 3 STANDARD DEVIATION OF THE MEAN.
    9 CONTINUE
      IST=1
      GO TO 2
   10 FORMAT(2X,3I2,24F3.0)
   11 FORMAT(1H1,/,T19,*DECOMPOSITION OF C-14 LABELED BLUE GRAMA AT THE
     -PAWNEE SITE - NYHAN*,T110,*PAGE*,I3)
   12 FORMAT(//,T40,*SOIL MOISTURE AND DECOMPOSITION PREDICTIONS*)
   13 FORMAT(/T7,*TIME*,T17,*RAIN*,T24,*RAINADD*,T34,*TEMP.*,T41,*AVG.PC
```

```
     -.*,T52,*HOURS FROM*,T65,*DECOMPOSITION RATES USING*,T98,*CUMULATIV
     -E DECOMPOSITION*/T4,*YR MO DY HR  (MM.)  (PCH2O)*,T35,*(C)   SOIL
     -H2O   TIME 0*,T65,*AVG.PC H2O +3SD H2O   -3SD H2O   AVGPC H2O  +35
     -D H2O    -3SD H2O*/1X,130(*-*))
  14 FORMAT(T4.3(I2,*/*),I2,T17,F5.2,T24,F7.4,T34,F5.1,T42,F6.3,T53,F6.
     -0.T65,6(F10.7,1X))
     END


     SUBROUTINE MOISTIO(TIME,TIME2,MOIST)

     MOISTIO READ IN THE TIME(YR,MONTH,DAY,HOUR),AVERAGE PCSOIL
     MOISTURE, AND THE STANDARD DEVIATION OF MEAN SOIL MOISTURE.  THE
     OUTPUT IS AVERAGE PCMOISTURE (+/-3STDM),AND TIME WHEN THE SOIL
     MOISTURE IS KNOWN AGAIN (TIME2).

     REAL MOIST(3)
     INTEGER TIME(4),TIME2(4)
     READ(1,101)TIME,MOIST(1),STDM
     IF(EOF(1).NE.0.)STOP
     READ(1,102)TIME2
     IF(EOF(1).EQ.0.)GO TO 110
     TIME2(1)=TIME(1)
     TIME2(2)=TIME(2)
     TIME2(3)=TIME(3)+7
     TIME2(4)=TIME(4)
     GO TO 120
 110 BACKSPACE 1
 120 MOIST(2)=MOIST(1)+3.*STDM
     MOIST(3)=MOIST(1)-3.*STDM
     RETURN
 101 FORMAT(2X.4I2,2F5.2)
 102 FORMAT(2X.4I2)
     END


     SUBROUTINE RAINIO(RTIME,RTIME2,RAIN)

     RAINIO READS IN THE TIME WHEN A RAIN OCCURS (RTIME-YR,MONTH,DAY,
     AND HOUR). THE AMOUNT OF RAIN (MM), AND OUTPUTS THIS INFORMATION
     AND THE TIME OF THE NEXT RAIN (RTIME2).

     INTEGER RTIME(4),RTIME2(4)
     READ(2,201)RTIME,RAIN
     READ(2,202)RTIME2
     BACKSPACE 2
     RETURN
 201 FORMAT(2X,4I2,F4.2)
 202 FORMAT(2X,4I2)
     END
```

```
      SUBROUTINE CORRECT(RMOI,B,BETA)

      CORRECT CALCULATES A CORRECTION FACTOR FOR THE SOIL DRYING RATE
      (B) IN THE MOISTURE MODEL WHICH ACCOUNTS FOR THE FACT THAT A
      WETTER SOIL DRIES FASTER THAN A DRIER SOIL DOES.

      DIMENSION RMOI(3),BETA(3)
      DO 301 J=1.3
      RMST=ABS(RMOI(J))
      IF(RMST.LT..1)RMST=.1
      CORR=ALOG10(100.*RMST)
      CORR=ALOG10(CORR)
      CORR=-1.57378+3.80702*CORR
      CORR=CORR+.56136*(1./RMST)
      CORR=CORR+.00002*(RMST-18.)**3
      CORR=CORR-.0015*RMST**2
      CORR=CORR/.228909
      IF(RMST.LE.8.000)CORR=1.00000
      BETA(J)=B*CORR
  301 CONTINUE
      RETURN
      END


      SUBROUTINE DECRTE(RMDT,HRTEM,HOUR,D)

      DECRTE USES PCMOISTURE, SOIL TEMPERATURE AND TIME(HOURS) FROM O
      TIME TO OUTPUT THE DECOMPOSITION RATE D.  EXPRESSED AS A PERCENT OF
      THE MATERIAL PRESENT AT O TIME DECOMPOSED PER HOUR.

      DIMENSION RMOI(3),D(3)
      DO 401 J=1.3
      RMS=ABS(RMOI(J))
      IF(RMS.LT..1)RMS=.1
      RH=ABS(HOUR)
      IF(RH.LT.1.)RH=1
      IF(RH.GT.56.)RH=561.
      RT=ABS(HRTEM)
      IF(RT.LT.1.)RT=1
      HD=RH*.00238-38.56569
      HDR=ALOG10(100.*RMS)
      HD=HD-HDR*12.89981
      HLDR=ALOG10(HDR)
      HD=HD+HLDR*92.01488
      HLHR=ALOG10(100.*RH)
      HD=HD+.15749*HLHR*HDR
      HLTP=ALOG10(100.*RT)
      HLLTP=ALOG10(HLTP)
      HD=HD+60.14738*HLLTP
      HLIPP=ALOG10(RI)
      HCUR=HLTPP+1.8
      HD=HD+3.44651*HCUR**2
```

```
      HD=HD-HLHR*RT*.01840
      D(J)=10**HD
      D(J)=D(J)*3.0
      IF(RMOI(J).LT.1.000)D(J)=0.000
      IF(HRTEM.LT.1.000)D(J)=0.000
      IF(HOUR.LT.1.000)D(L)=0.000
  401 CONTINUE
      RETURN
      END
```