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GRASSLAND MANAGEMENT AND CONVERSION INTO GRASSLAND: EFFECTS ON SOIL CARBON

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Abstract. Grasslands are heavily relied upon for food and forage production. A key component for sustaining production in grassland ecosystems is the maintenance of soil organic matter (SOM), which can be strongly influenced by management. Many management techniques intended to increase forage production may potentially increase SOM, thus sequestering atmospheric carbon (C). Further, conversion from either cultivation or native vegetation into grassland could also sequester atmospheric carbon. We reviewed studies examining the influence of improved grassland management practices and conversion into grasslands on soil C worldwide to assess the potential for C sequestration. Results from 115 studies containing over 300 data points were analyzed. Management improvements included fertilization (39%), improved grazing management (24%), conversion from cultivation (15%) and native vegetation (15%), sowing of legumes (4%) and grasses (2%), earthworm introduction (1%), and irrigation (1%). Soil C content and concentration increased with improved management in 74% of the studies, and mean soil C increased with all types of improvement. Carbon sequestration rates were highest during the first 40 yr after treatments began and tended to be greatest in the top 10 cm of soil. Impacts were greater in woodland and grassland biomes than in forest, desert, rain forest, or shrubland biomes. Conversion from cultivation, the introduction of earthworms, and irrigation resulted in the largest increases. Rates of C sequestration by type of improvement ranged from 0.11 to 3.04 Mg C·ha^{-1} yr^{-1}, with a mean of 0.54 Mg C·ha^{-1}·yr^{-1}, and were highly influenced by biome type and climate. We conclude that grasslands can act as a significant carbon sink with the implementation of improved management.

Key words: carbon sequestration; cultivation; grassland management; grasslands; grazing management; pasture; soil carbon; soil organic matter.

INTRODUCTION

Much of the earth's grasslands are over used and poorly managed (Oldeman 1994), and significant amounts of native forest, shrubland, and woodland have been converted to grassland (DeFries et al. 1999). Grassland over use and land conversion into grasslands are driven by the demand for forage production since significant portions of world milk (27%) and beef (23%) production occur on grasslands managed solely for those purposes (Sere et al. 1995). Grasslands have high inherent soil organic matter (SOM) content that supplies plant nutrients, increases soil aggregation, limits soil erosion, and also increases cation exchange and water holding capacities (Miller and Donahue 1990). Thus, maintenance of SOM is a key factor in the sustainability of grassland ecosystems.

Soil organic matter in temperate grasslands averages 331 Mg/ha, and grasslands contain 12% of the earth's SOM (Schlesinger 1977). Grassland SOM can be strongly influenced by management. Historically, intensive cultivation has resulted in the transfer of 993 Tg of SOM to the atmosphere in the form of CO_2 in the United States alone, much of which was lost from native grasslands (Kern 1994). Soil organic matter losses due to conversion of native grasslands to cultivation are both extensive and well documented (Haas et al. 1957, Schlesinger 1986, Davidson and Ackerman 1993, Kern and Johnson 1993), and losses due to over grazing and poor pasture management have also been observed (Fearnside and Barbosa 1998, Abril and Bucher 1999). However, historical SOM losses can potentially be reversed, and atmospheric carbon (C) sequestered, with good agricultural management. In the United States, agricultural conservation practices such as reduced tillage, improved fertilizer management, elimination of bare fallowing, the use of perennials in rotations, and the use of cover crops can potentially sequester large amounts of atmospheric C (Paustian et al. 1997). Similarly, areas converted from cultivation and maintained under well managed permanent grassland, as pastures or rangelands, constitute potential C sinks. Within established pastures, soil C can be increased by eliminating disturbances to the soil and by increasing primary production.

A variety of management techniques have evolved to increase forage production for livestock, which also have the potential to increase SOM. Improved management includes fertilization, irrigation, introduction of earthworms, intensive grazing management, and sowing of favorable forage grasses and legumes. As forage production increases, an ancillary benefit may

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be increased sequestration of atmospheric carbon. Indeed, Gifford et al. (1992) noted that improved pasture management is an important consideration when computing the national C budget for Australia.

The objective of this study was to examine the influence of grassland management and conversion into grassland on soil C, based on published data. We surveyed the potential for C sequestration following management improvement and following conversion of both native and cultivated lands to pasture land. Factors influencing C sequestration potentials were investigated across different regions and through different forms of improved management. Finally, we evaluated how time, sampling depth, and soil characteristics relate to sequestration rates of atmospheric C, and how climate can influence management-induced changes in soil carbon.

METHODS

Survey data

We compiled data from the literature on the influence of grassland management and land use conversion to grassland on soil carbon. In order for data to be useful for this analysis, studies examining land management must have been designed so that management was the primary factor influencing soil carbon. A variety of management practices were reported, including fertilization, intensity of grazing management, introduction of earthworms, introduction of legumes and grasses, and irrigation. Management was designated as improved if adoption generally resulted in increased forage production. For example, fertilization, irrigation, sowing legumes, and introduction of grasses or earthworms were all considered management improvements. Grazing was designated as improved management if an ungrazed site was present for comparison with grazed sites. Occasionally, a range of grazing treatments was compared without an ungrazed control (9% of grazing studies). For these cases, the moderate stocking rate was considered improved management since low stocking rates may under utilize forage resources and high stocking rates may be abusive, both leading to decreased production (Milchunas and Lauenroth 1993). If more than one fertilizer treatment was evaluated within a study, each was compared with an unfertilized control plot. Land conversions from cultivation to perennial grassland were included in the analysis. Conversion of native land, rangeland, or pasture to cultivation were not included in this study, as those data have been reviewed elsewhere (see Davidson and Ackerman 1993, Paustian et al. 1997, Lal et al. 1998).

Literature searches were performed using the Cambridge Scientific abstracts database (CAB Abstracts 1999) with keywords relating to rangeland, pasture, or grassland management, and soil organic matter or soil carbon. Of the more than 400 articles in English, Spanish, French, and German evaluated, 115 articles contained data comparing soil C for different management practices, resulting in 336 experimental treatments. Many of the papers reported data for multiple depths, permitting a soil C by depth comparison with nearly 400 points from 44 of the articles. In addition to soil C, information on latitude, longitude, soil texture, duration of treatment, mean annual temperature (MAT), mean annual precipitation (MAP), measurement techniques, experimental design, and primary production were recorded when present. Summary information about each data point is available in the Appendix.

Studies included in this review generally used three different approaches to examine the influence of management on soil carbon. The most common method was to examine paired plots, whereby two proximate sites differing only in management were compared. Experiments designed to carry out planned comparisons were also common. The third, least common, approach compared soil samples collected some time in the past with subsequent measurements made within the same farm or field following a change in management. All three approaches require consistent measurement techniques, established differences between treatments, a well-documented site history, and unambiguous information about all pertinent aspects of the experimental design and results. Maintaining uniformity between plots is especially important for paired plot comparisons since soil characteristics can influence land use and land management decisions.

Soil C measurement techniques and methods of reporting soil C data varied substantially. Soil C was usually oxidized by combustion or wet oxidation and measured by titration, conductivity, or chromatography. When data on soil organic matter (SOM) or percent of material lost on ignition were reported, we assumed that SOM was 58% C (Nelson and Sommers 1982). Data were often reported as percent C by weight with no indication of the bulk density of the soil. Soil C concentration data without accompanying information about soil bulk density are less useful in making either regional extrapolations or estimates of soil C storage potential. Since data were reported both with and without bulk density measurements, data were standardized by calculating both the annual percent change following management improvement or conversion and the ratio of soil C under improved grassland management with that under unimproved management, native vegetation, or cultivation. This requires the assumption that bulk densities were uniform between comparative sites; this assumption was evaluated when possible.

Mean annual temperature (MAT) and precipitation (MAP) were obtained from a $0.5° \times 0.5°$ grid cell climate map developed for use in the POTSDAM project (Schimel et al. 1996). Potential evapotranspiration (PET) was calculated using mean monthly temperatures, the annual heat index, and a latitudinal correction factor (Thornthwaite 1948). Native vegetation for each

FIG. 1. Global distribution of study sites.

site was obtained either from the reference or from a 1° × 1° vegetation map generated by Matthews (1983).

Statistical analyses

Of the 336 data points used for this analysis, just over 10% reported some measure of central tendency. Though much of the data were accompanied by descriptions of experimental design, including number and treatment of replicates, most of them reported whether differences between means were significant without presenting any measure of central tendency. Limited meta-analysis was performed using only data points with some measure of central tendency. The standardized mean difference (SMD) and standard error of this difference were calculated for each study, enabling an estimate of the overall SMD and its standard error using meta-analytic methods (Cooper and Hedges 1994). Random effects meta-analysis was used to account for heterogeneity between studies.

Regression analyses were performed using SAS (SAS 1985) to evaluate the influence of MAT, MAP, PET, the ratio of MAP to PET (P:E), latitude, and soil texture (percent sand and clay) on soil C response variables. Stepwise regression analyses were performed relating C sequestration rates to climatic variables.

RESULTS

Qualities of the studies surveyed

Studies from 17 countries (Fig. 1) were included in this review, but 87% of the studies were from Australia, the United Kingdom, New Zealand, Canada, Brazil, and the United States which contain just 26% of the world's grassland area (Matthews 1983). Study sites ranged from 57° N to 46° S, with an average latitude of 38.0° from the equator (Table 1). Most studies were located above 30° latitude (264 of 336 data points), while a much smaller portion (15%) took place in the tropics (Fig. 1). This was reflected in MATs, which ranged from −1.4°C to 26.8°C, though mean and median MATs were 12.6°C and 10.2°C, respectively (Table 1). Mean annual precipitation ranged from 140 mm to 3700 mm, with an average of 1040 mm (Table 1). The majority of measurements took place on unique study sites, but there were eight occurrences of data reported for the same study sites over different periods of time. Often many treatments were compared in the same study area, resulting in 336 data points from 115 separate articles. Many studies used experimental treatments to control conditions (46%), but slightly more (49%) evaluated across-the-fence type comparisons.

TABLE 1. Summary of environmental variables from the studies used in this analysis.

Variable	Mean	Median	Minimum	Maximum
Mean annual temperature (°C)	12.6	10.2	−1.4	26.8
Mean annual precipitation (mm)	1040	810	140	3700
Latitude	38.0	38.9	1.7	57.3
Depth (cm)	32.5	15.0	2.0	800
Duration (yr)	23.7	18.0	1.0	200

TABLE 2. Number of studies and number of data points summarized by type of management change implemented.

Treatment	Studies	Data points	Percentage of total
Irrigation	1	2	0.6
Earthworm introduction	2	3	0.9
Improved grass species	4	7	2.1
Introduction of legumes	8	12	3.6
Conversion: native to pasture	17	49	14.6
Conversion: cultivation to pasture	23	51	15.2
Improved grazing	31	80	23.8
Fertilization	40	132	39.3

Less than 5% of the studies re-sampled the same field after some duration.

Soil samples were collected at depths ranging from 2 cm to 800 cm, with a mean of 32.5 cm (Table 1). Soil samples were collected from only one depth for nearly two-thirds of the studies. The shortest treatment duration was one year and the longest treatment lasted 200 yr. While the mean duration was 23.7 yr, the median was 18.0 yr, because treatment duration was <40 yr for 81% of the studies (Table 1).

The most common types of improvement were fertilization, improved grazing management, and conversion to pasture from native and cultivated lands, accounting for >90% of all studies (Table 2). There was some regional variation in the type of fertilizer applied and type of grazing animals. In New Zealand and Australia, most of the studies examined the effects of superphosphate, and sheep were more common grazers than cattle. Fertilization studies in the United States and the United Kingdom most often evaluated the influence of nitrogen and manure application on cattle pastures. Studies examining the influence of sowing grasses took place in a wide range of environments, and included over seeding pastures with new varieties, the influence of endophyte-infected vs. endophyte-free fescue, and the introduction of African grasses on Colombian savannas. Studies examining the sowing of legumes and the introduction of earthworms were less common (Table 2). Experiments investigating the influence of conversion from native land to pasture were carried out in Australia, Brazil, Costa Rica, Mexico, New Zealand, and Zimbabwe, and conversions from native grassland, woodland, forest, and shrubland were studied. Conversion of native land to pasture always included clearing of native vegetation, and often included additional treatments such as fertilization or sowing of grass or legumes.

Changes in soil carbon with management

Soil carbon increased following management improvements for 76% of studies reporting changes in C content and for 65% of studies reporting C concentration only (Figs. 2 and 3). The average change for content data was an increase of 20% and the average for concentration data was a 29% increase. For studies that showed an increase in soil C, soil C concentration in-

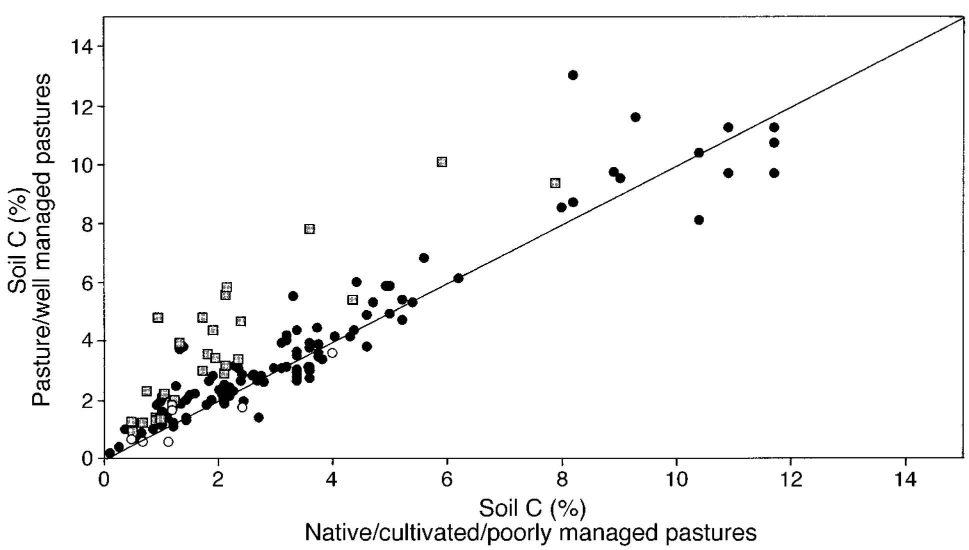

FIG. 2. Soil carbon concentration for improved vs. unimproved pastures (closed circles), or grassland vs. cultivated fields (gray squares) or native vegetation (open circles). Soil carbon concentration increased for points above the line and decreased for points below the line. All data are in percentage carbon.

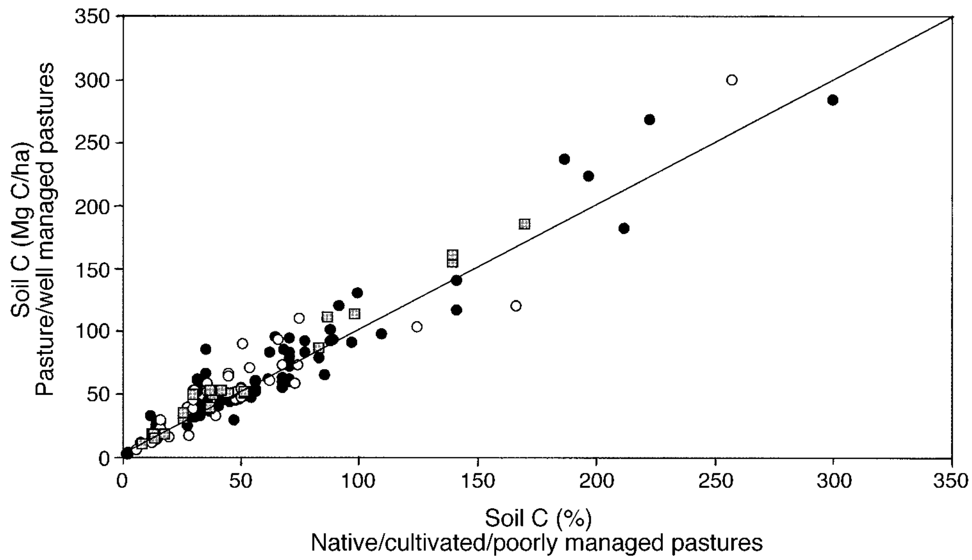

FIG. 3. Soil carbon content for improved vs. unimproved pastures (closed circles), or grassland vs. cultivated fields (gray squares) or native vegetation (open circles). Soil carbon content increased for points above the line and decreased for points below the line. All data are in Mg C/ha.

crease averaged 51% and soil C content increased by an average of 31%. The 20% of the studies with the smallest increases averaged 3.8% for soil C concentration data and 4.0% for soil C content data, while the average increase for the 20% with the largest increases was 154% and 76% for soil C concentration and content data, respectively. For those studies with a net loss of C with improved management, content and concentration data decreases both averaged very close to 12.0%. Soil C increased for nearly two-thirds of the studies examining native land conversions and for all but one (98%) of the studies evaluating cultivation to pasture conversions. Slightly more than half of the studies evaluated reported values in soil C per unit surface area or contained enough information to calculate soil C per unit surface area. No attempt was made to correct for bulk density since studies occurred on a wide variety of soils under various types of management. Bulk density tended to increase following conversion from cultivation (1.3%), native vegetation (10.6%), and earthworm introduction (4.8%). Overall, grazing resulted in slightly decreased (−0.4%) bulk density (Rawes 1981, Bauer et al. 1987, Manley et al. 1995).

Thirteen studies (40 data points) reported a mean and standard error and were included in the meta-analysis. The randomized effects estimate of the standardized mean difference (SMD) was 5.11 (Fig. 4). Of the studies evaluated, the SMD was positive for 63%, negative for 29%, and zero for 8% (Fig. 4). Only 56% of the studies evaluating conversion from native land had positive SMDs, while 62% of the grazing studies and 100% of the fertilization studies had positive SMDs (Fig. 4).

Soil C content and concentration increased, on average, for all types of management improvement and both types of land use conversion (Fig. 5). The largest response, an annual increase of 5.4%, was observed following irrigation, but conditions unique to this particular study, like the initially low fertility, allophanic soils, and the development of a highly decomposable surface mat of organic matter, make it unlikely to reflect C sequestration potential following irrigation in other regions or for longer periods of time (Rixon 1966). Conversion from cultivated land to pasture had the next largest response, with a mean annual increase in C concentration of nearly 5% and >3% annual increase in soil C content (Fig. 5). The mean response for earthworm introduction was also an increase of nearly 4% per year (Fig. 5), though only two studies examined the influence of earthworms on soil C and both took place on allophanic soils which have a high capacity for organic matter stabilization (Parfitt et al. 1997). Sowing legumes and grasses led to an mean annual increase of 2.0% and 2.3%, respectively, but the mean for grasses was largely driven by the large changes reported with the introduction of deep-rooted African grasses in Colombian savanna (Fisher et al. 1994). After removing this source, the mean annual increase resulting from sowing improved or endophyte-free grass species fell to 1%. Soil C concentration and content did not agree well for changes following sowing grasses, likely since there was just one concentration study. Changes in grazing management and fertilization led to annual increases of 2.9% and 2.2%, respectively (Fig. 5). Soil C in over grazed sites decreased by a mean of 0.19 $Mg\ C\cdot ha^{-1}\cdot yr^{-1}$ compared to moderately grazed sites. Conversion of native land to pasture resulted in the smallest annual increase, 1.9% and 1.6% for C content and concentration, respectively (Fig. 5).

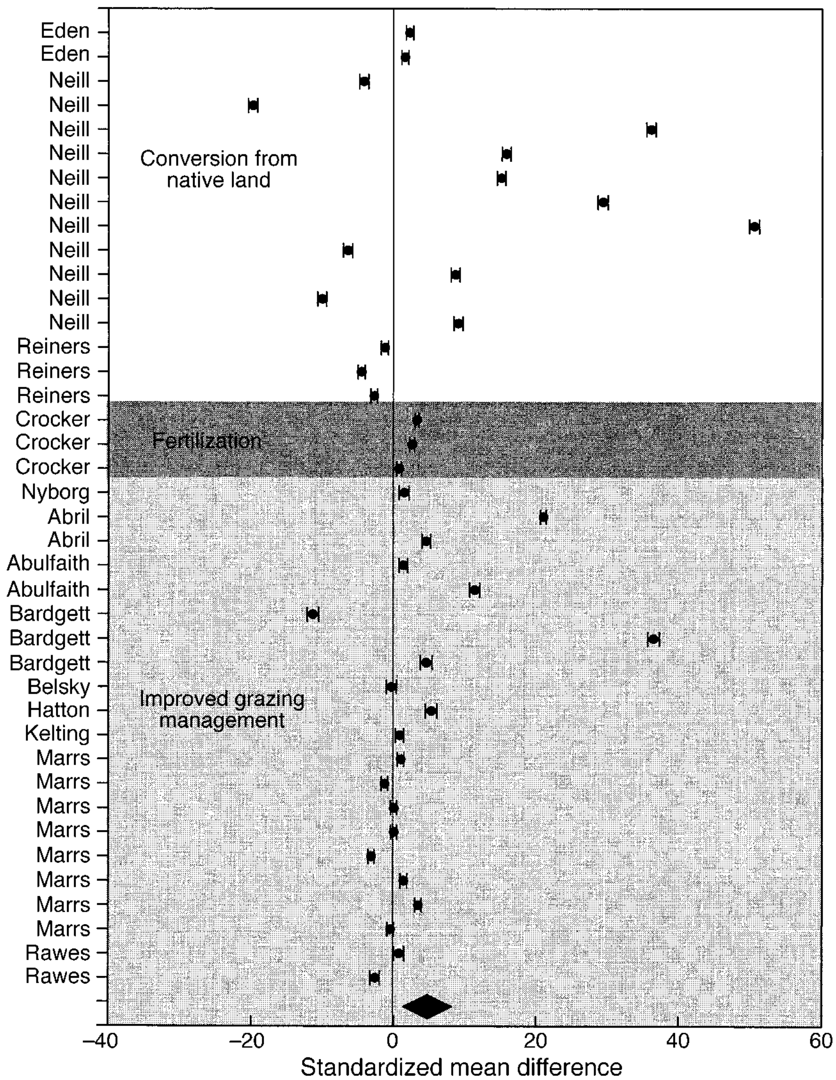

FIG. 4. Ladder plot for studies reported with sample size and some measure of central tendency, listed by lead author (Bardgett refers to Bardgett et al. [1993]). The position and size of the diamond reflect the randomized effects estimate and 95% confidence intervals.

Data for conversion from native land reflect changes in soil C only, not changes in biomass carbon.

Changes in soil C content and concentration and rates of soil C accumulation followed similar patterns, decreasing with depth (Fig. 6). Sample depth explained 15% (7.0% and 8.5% for values reported as C concentration or C content alone, respectively) of the variation in the ratio of soil C in improved grasslands to soil C in unimproved grassland, or native vegetation or cultivated fields, using a hyperbolic decay formula (Fig. 6). The mean annual increase in soil C content for soil samples collected in the top 10 cm was 37%, with concentration increases averaging 20%. For samples collected between 10 cm and 20 cm, the mean soil C content increase was 20% and values reported as concentrations increased 30%, though these values were heavily influenced by results of manure addition studies. When results from Mugiwra (1976) were excluded, soil C concentration increased by an average of only 9.0% total. Increases for samples collected below 20 cm averaged 1.3% and 2.4% per year and totaled 9.4% and 13.6% for content and concentration, respectively. A major exception to the trend of decreased C storage with depth was a study examining the introduction of African grasses to Brazilian savanna (Fisher et al. 1994). Total soil C content in the top 10 cm increased by almost 15%, but soil C increased nearly 30% between 20 cm and 100 cm, and total C sequestration per unit depth was relatively uniform for all depths sampled (Fisher et al. 1994).

Fig. 7 shows the relationship between management-induced changes in soil C and time. The regression line

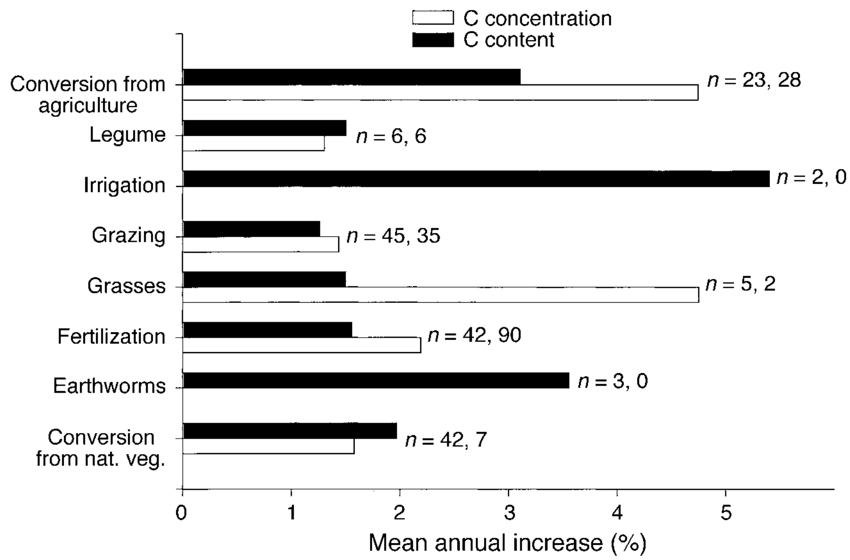

FIG. 5. Mean annual increase in soil carbon concentration (white bars) and content (black bars) calculated as the ratio of improved soil carbon to unimproved soil carbon divided by time and summarized by type of management improvement. The number of studies reporting data as carbon content and carbon concentration, respectively, are shown.

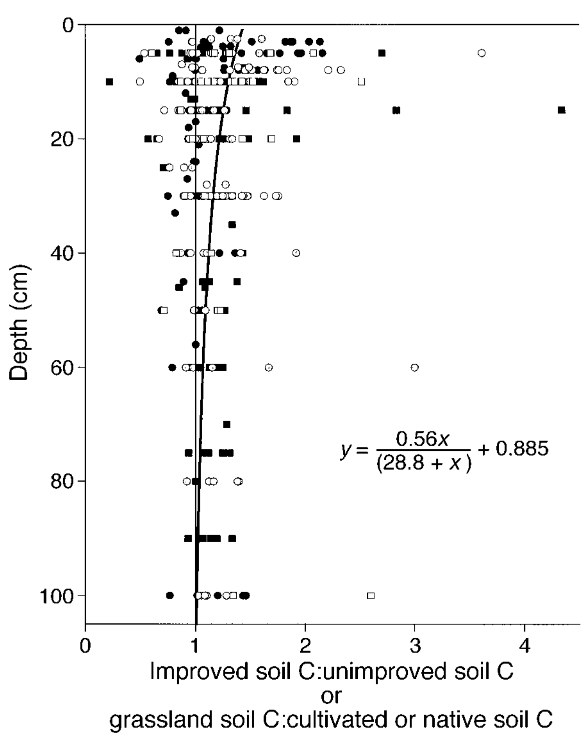

FIG. 6. Relationship between the ratio of improved soil carbon to unimproved soil carbon (closed symbols), or grassland to cultivated field (gray symbols) or native vegetation (open symbols), and depth for both carbon concentration (squares) and content (circles). The regression relationship was based on all data, though only samples collected above 100 cm in depth are shown.

in the figure is based on all of the data, though only studies lasting <85 yr are shown. Duration of treatment explained only a small amount of the variability in soil C response to changes in management (r^2 = 0.12, 0.11, 0.08 for all, content, and concentration values, respectively), and appears to be heavily influenced by low ratios during later years. The annual rate of soil C content increase in improved grasslands compared to unimproved grasslands averaged by decade decreased over the first five decades from 0.88 to 0.17 Mg $C \cdot ha^{-1} \cdot yr^{-1}$. Soil C concentration data followed a similar trend decreasing from 0.1% to 0.001% C per year over the first four decades. Trends in subsequent decadal means for both content and concentration values were unclear because of the limited number of studies. Soil C peaked at a mean increase of nearly 42% for both C content and concentration after the fourth decade (Fig. 7).

Regression analyses revealed that rates of C sequestration were significantly influenced by climatic variables, but not strongly related to soil textural variables (Table 3). For all types of management improvement, rates of C sequestration were slightly positively related to the ratio of mean annual precipitation (MAP) to potential evapotranspiration (PET) (Table 3). When broken down into management groups, regressions explained 61%, 42%, and 85% of the variability for fertilization, improving grazing management, and sowing grasses, respectively (Table 3). The effects of sowing grasses on soil C were largely controlled by the distribution of study locations since those reporting values in Mg C/ha were limited to Colombia and the United States; effects were very high in Colombia, with high PET, and substantially lower at a cooler United States

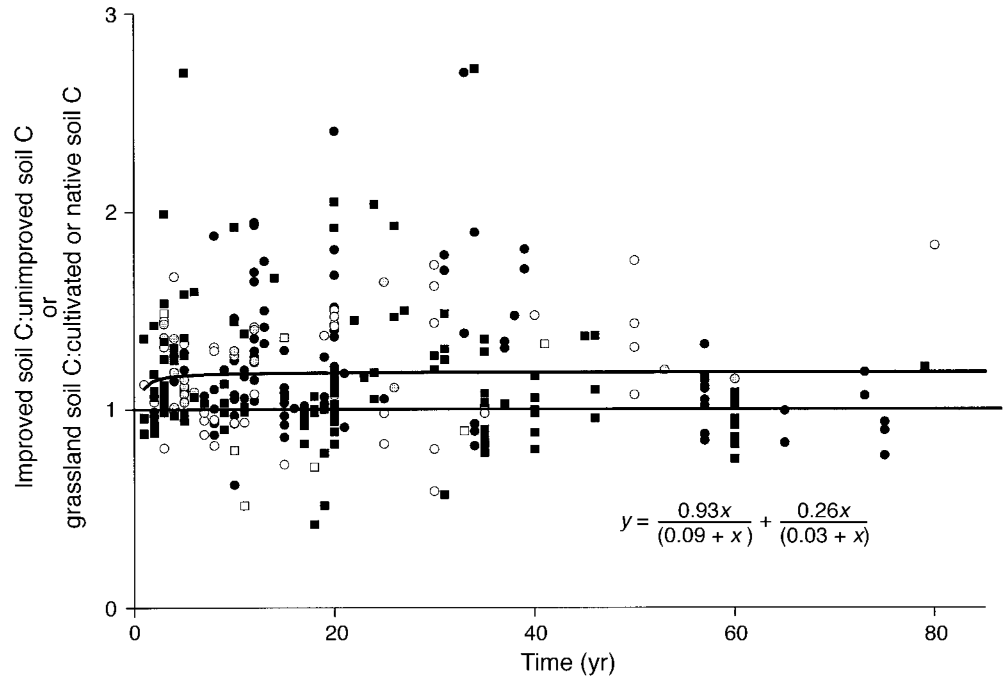

FIG. 7. Relationship between the ratio of improved soil carbon to unimproved soil carbon (closed symbols), or grassland to cultivated field (gray symbols) or native vegetation (open symbols), and time for both carbon concentration (squares) and content (circles). The regression relationship was based on all data, though only data for the first 85 yr are shown.

study site with much lower PET. Effects of land conversion on soil C were not strongly related to any climate variables.

The response of soil C concentration and content to improved management or land conversion both varied according to major biome type (Fig. 8a, b). Sites located in shrubland had the smallest average annual increases for C content data while desert and shrubland biomes has the smallest average soil C concentration changes. Sites located in native grassland and woodland biomes (including savannas) averaged the largest increases in soil C concentration, while average changes in soil C content were largest in grasslands and woodlands. The average influence of fertilization on percent change in soil C concentration was roughly 50% greater in forest than in grassland biomes, and 50% larger again in woodland biomes (Fig. 8b). The influence of grazing management on soil C concentration varied among areas with different native biomes, ranging from slight decreases to mean annual increases of >7% (Fig. 8b); soil C content behaved similarly (Fig. 8a). Changes in soil C content for all treatments ranged from slight decreases to increases of nearly 6% per year (Fig. 8a). Soil C concentrations were even more variable with increases up to >8% per year (Fig. 8b). Biome type influenced rates of C sequestration averaged across all management changes, ranging from a low of 0.1 Mg C·ha^{-1}·yr^{-1} in rain forest biomes, to 0.3 Mg C·ha^{-1}·yr^{-1} for desert and forest sites, to as much as 1.0 Mg C·ha^{-1}·yr^{-1} for native grassland and woodland regions.

Rates of sequestration of atmospheric C are summarized by type of management improvement or land use conversion in Table 4. Introduction of earthworms, sowing of improved grass species, and sowing legumes had very high rates of C storage (Table 4), though the number of observations was limited and results were influenced by unique conditions including allophanic soils and somewhat controversial results (Davidson et al. 1995). Conversion from cultivated land to grassland

TABLE 3. Statistics for regression analyses of carbon sequestration rates (Mg C·ha^{-1}·yr^{-1}) on latitude and four climate variables.

Management	r^2	P	MAT	MAP	PET	P:E	Latitude
All	0.09	0.005	n	n	n	+	n
Fertilization	0.61	0.005	−	−	n	n	−
Grazing	0.42	0.05	+	−	−	+	n
Grass sown	0.85	0.01	n	n	+	n	n

Notes: MAT = mean annual temperature; MAP = mean annual precipitation; PET = potential evapotranspiration; P:E = MAP : PET ratio. Positive (+) and negative (−) relationships and exclusion (n) from regression relationships are indicated.

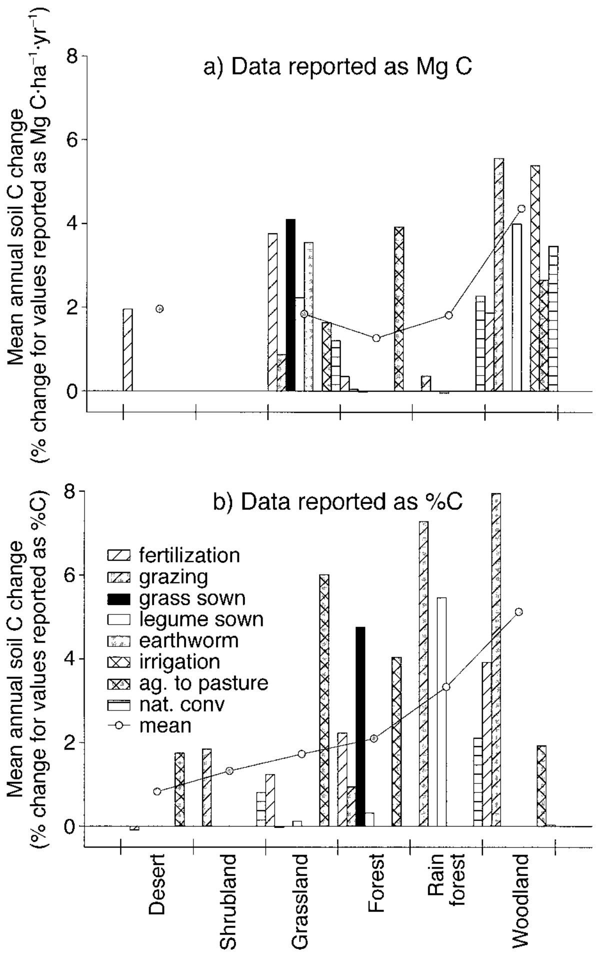

FIG. 8. Effects of management/land-use change on soil carbon summarized by native vegetation type. The weighted mean for each native vegetation type is indicated by points; bars illustrate changes in management/land-use within each native vegetation type.

also had high sequestration rates, likely due to prior soil C depletion following cultivation. Carbon sequestration rates for other management types were substantially lower, resulting in an overall mean sequestration rate of 0.54 Mg C·ha^{-1}·yr^{-1} (Table 4). When results of Fisher et al. (1994) were excluded, sowing legumes and grasses sequestered only 0.10 and −0.12 Mg C·ha^{-1}·yr^{-1}, and the mean of all studies dropped to 0.43 Mg C·ha^{-1}·yr^{-1}.

DISCUSSION

Our results suggest that management influences grassland soil carbon in all types of environments. Management improvements and land use conversions intended to increase forage production usually increased soil carbon. This study shows that climatic variables, native vegetation, depth, time, and original soil C all affect rates of soil C change, but on average, management improvements and conversion into pasture lead to increased soil C content and to net soil C storage.

Conversion from native land cover to pasture led to increased soil C content for nearly 70% of the studies examining conversion, most of the which (75%) took place in areas with rain forest as the native vegetation. Though more than half of the rain forest conversion studies (60%) resulted in increased soil C content, net ecosystem C balance (where reported), decreased substantially due to the loss of large amounts of biomass carbon. Indeed, the largest increase observed in tropical rain forests was 43 Mg C/ha over 23 yr (Trumbore et al. 1995). The global mean biomass in tropical rain forests is 200 Mg C/ha (Schlesinger 1991); thus, with soil C sequestration of 43 Mg C/ha, only ~21.5% of C lost with biomass removal would be replaced with soil C after 23 yr. Fearnside and Barbosa (1998) reviewed the effects of conversion of tropical forest to pasture in Brazil and found that soil C in the top 20 cm increased only for well managed pastures; soil C decreased following conversion if pastures were poorly managed. It should be noted that a very small portion of tropical pastures (~5%) are well managed (Fearnside and Barbosa 1998).

In addition to increasing forage production, sowing grasses and legumes often results in increased belowground production (Robinson and Jacques 1958, Prasad and Mukerji 1980, Crawford et al. 1996). This leads to increased belowground C inputs and can result in increased soil carbon. Furthermore, the introduction of legumes can increase soil nitrogen, resulting in superior

TABLE 4. Carbon sequestration rates and number of data points summarized by type of management change.

Management	Data points	C sequestration (Mg C·ha^{-1}·yr^{-1})
Irrigation	2	0.11
Fertilization	42	0.30
Improved grazing	45	0.35
Conversion: native to pasture	42	0.35
Conversion: cultivation to pasture	23	1.01
Introduction of legumes	6	0.75
Earthworm introduction	2	2.35
Improved grass species	5	3.04
All types	167	0.54

soil fertility, further increasing aboveground and belowground production (Watson 1963, Vallis 1972, Boddey et al. 1997). Sowing improved species led to greater primary production in the only study in which primary production was measured in addition to soil C concentration (Watson 1963). It appears likely that sowing improved species, both grasses and legumes, increases total plant–soil system C, thus sequestering atmospheric carbon.

Grassland fertilization has been used for centuries to increase forage production (e.g., Johnston et al. 1980). Fertilization results in increased belowground production as well as aboveground production (Russell and Williams 1982), which can both lead to increased soil carbon. Fertilization resulted in increased production, when it was measured, with increases ranging from 41% to 109% (Lambert et al. 1996). Soil C increases were generally greater with higher levels of fertilization, though this was not always the case (Hassink 1994). Interestingly, changes in soil C following fertilization were strongly negatively related to mean annual temperature (MAT) and latitude, largely a result of the strong influence of fertilization on soil C at high latitude locations in the United Kingdom, United States, and Canada.

The addition of manure to soil can also lead to increased production, leading to increased sequestration of atmospheric carbon. However, the direct addition of manure makes if difficult to estimate atmospheric C sequestration since a portion of increased soil C is attributable directly to the addition of manure C to the soil. Thirteen of the 17 treatments examining the influence of manure on soil C and production reported significantly increased forage production; nine of 14 reported increases in soil C concentration, and all three reporting soil C content had increased soil carbon. For those studies with increased forage production and increased soil C, it is reasonable to conclude that some portion of the increase in soil C may be due to increased vegetation inputs. However, the studies with increased soil C and increased production gave no indication of the relative influence of production and manure addition on changes in soil carbon. Long et al. (1975) observed that soil C concentration did not increase measurably until after three years of manure application, and then soil C concentration increased from 0.27% to 0.37%. Mugiwra (1976) found that slurry applications >44 Mg/ha did not further increase aboveground plant production, but did result in continually increasing soil C content, suggesting that additional soil C increases with application rates >44 Mg/ha were due entirely to manure C inputs. Thus, a portion of the change in soil C concentration may be caused by increased inputs derived from increased production, yet a substantial but variable portion is a direct result of the addition of C in the form of manure. It is interesting to note that average C sequestration rates in fields receiving inorganic fertilizers (0.29 Mg $C \cdot ha^{-1} \cdot yr^{-1}$) were very similar to those in fields receiving organic fertilizer (0.28 Mg $C \cdot ha^{-1} \cdot yr^{-1}$).

Under certain conditions, grazing can lead to increased annual net primary production over ungrazed areas, particularly with moderate grazing in areas with a long evolutionary history of grazing and low primary production (Milchunas and Lauenroth 1993). Approximately 65% of the articles examining the impacts of grazing on soil C occurred in areas with a long evolutionary history of grazing and relatively low productivity. Thus, for the majority of the studies reviewed, increased soil C may be the result of increased production, and overall, grazing tended to increase soil C most in warm dry regions, especially those with high potential evapotranspiration. Indeed, average annual rate of soil C content increase was 7.7% for studies with a long history of grazing, but those not meeting this criteria lost an average of 1.8% per year. However, in one study characterizing this type of system, Schuman et al. (1999) found that root C decreased 7–15% as a result of grazing, but soil C content still increased. When production decreases as a result of grazing, soil C content could still potentially increase if decreased aboveground plant inputs to the soil are offset by manure inputs, if changes in species composition result in greater root:shoot ratios and increased belowground inputs, or if grazing results in lower standing stocks of biomass, but increased production and turnover. Of the studies examining different intensities of grazing, 29% found lower soil C content for moderate compared with heavily grazed sites, and soil C increased by an average of 0.19 Mg C/ha for studies comparing those different grazing intensities.

Soil C and percent change in soil C following changes in management or land use were very weakly negatively related ($r = 0.03$; $P < 0.05$). Thus, large changes were slightly more likely for soils with low initial C and slightly less likely for soils with high carbon. This is both expected, since low C soils may have a higher capacity for C storage, and potentially misleading, since large percent changes can skew results. For example, studies evaluating the effect of irrigation on grassland soil C were limited to two studies published in one article (Rixon 1966). Mineral soil C decreased slightly for one of the experimental treatments examined by Rixon (1966), but in both cases a mat of highly decomposable organic matter developed on the surface of the soil. The development of this organic mat significantly increased the amount of soil C for both of the experimental treatments, but it is not certain how pertinent these results are to other regions and whether C buildup will continue.

Most of the studies reviewed lasted fewer than 20 years. Due to the variability in response to management types, and the fact that only a few of the studies took measurements over multiple periods of time, it is difficult to determine how long soil C will continue to increase with improved management. Regressing soil

C increases with time suggested that soil C tends to approach equilibrium quickly. However, this may be misleading due to the large number of short-term studies and confounding factors such as climate, soils, and initial soil C. Moreover, some long-term studies indicate that soil C increases can continue nearly linearly for as long as 40–60 years (Williams and Donald 1957, Russell 1960, Barrow 1969, Johnston et al. 1980, Russell and Williams 1982, Potter et al. 1999). A study by Hoogerkamp (1973) indicates that soil C content of young pastures tends to reach levels observed in old pastures, regardless of initial soil C. Our data indicate that there is substantial variability in rates of sequestration over time, but it appears that net increases in soil C may persist for at least 40 yr. Although some of the C sequestered in soil is likely to be easily decomposable with a short lifetime (Hsieh 1992), much is found in highly decomposed, recalcitrant substances or occluded within stable aggregates with a long residence time on the order of decades or centuries (Ross and Hughes 1985, Oades et al. 1988, Guggenberger et al. 1995, Chan 1997).

For studies with samples from multiple depths, mean soil C sequestration in the top 10 cm, normalized per centimeter of depth, was 0.03 Mg $C \cdot ha^{-1} \cdot yr^{-1} \cdot cm^{-1}$. This is much higher than the 0.01 Mg $C \cdot ha^{-1} \cdot yr^{-1} \cdot cm^{-1}$ calculated for the 10–20 cm and 20–50 cm layers. Between 50 and 100 cm of depth, soil C sequestration was 0.008 Mg $C \cdot ha^{-1} \cdot yr^{-1} \cdot cm^{-1}$ and below 100 cm in depth was $<$0.001 Mg $C \cdot ha^{-1} \cdot yr^{-1} \cdot cm^{-1}$. These results suggest that 64% of soil C sequestered is located in the top 50 cm in most cases, and that C sequestration estimates will be increased by $<$1% for every meter sampled below one meter. Soil C sequestration estimates generated in this study may underestimate actual C sequestration potential since average sample depth for studies included in this review was only 32.2 cm. In some cases, significant amounts of soil C can be gained or lost at depths below one meter following land use or land management conversion, particularly in the tropics (e.g., Fisher et al. 1994, Trumbore et al. 1995).

Though meta-analysis was performed only for a subset of the data, results support overall conclusions. The majority of the studies evaluated using meta-analysis had positive standardized mean differences (SMDs), or increased soil carbon. Furthermore, the results indicated that the overall SMD was positive, suggesting an increase in soil C (Fig. 4). It should be noted that, of all studies, only a small portion (35%) reported whether management-induced changes in soil C were significant, and 65% of those reported nonsignificant differences. Thus, conclusions from this work should be viewed with caution.

Much research has recently focused on the potential for sequestration of atmospheric C in agricultural soils. Improved grassland management has received attention in Australia (Russell and Williams 1982, Gifford et al. 1992), New Zealand (Tate et al. 1997), and in the United States and Canada (Bruce et al. 1998). While Bruce et al. (1998) estimated that North American soils can sequester 0.2 Mg $C \cdot ha^{-1} \cdot yr^{-1}$, Gifford et al. (1992) estimated that Australian soils can sequester between 0.5 and 0.6 Mg $C \cdot ha^{-1} \cdot yr^{-1}$. Our results average 0.59 Mg $C \cdot ha^{-1} \cdot yr^{-1}$ for studies in North America (United States and Canada) and 0.28 Mg $C \cdot ha^{-1} \cdot yr^{-1}$ for studies in Australia. Differences between our results and those of others could arise from the fact that more articles examining a wider variety of management improvements were included in this study.

Though this study indicates that improved grassland management can sequester considerable amounts of atmospheric C, emission costs are associated with many types of grassland management. For example, Lee and Dodson (1996) modeled the influence of pasture fertilization on soil C. They found that pasture soils sequestered 0.16 Mg $C \cdot ha^{-1} \cdot yr^{-1}$ with application of 70 kg $N \cdot ha^{-1} \cdot yr^{-1}$ (Lee and Dodson 1996). However, since ~1.4 kg C are emitted per kilogram of nitrogen manufactured, net C sequestration would be reduced to 0.06 Mg $C \cdot ha^{-1} \cdot yr^{-1}$ (Lee and Dodson 1996). Nitrogen fertilizer applied to grasslands also contributor significantly to N_2O emissions (Oenema et al. 1997). Carbon and nitrogen emission costs associated with improved management must be considered when estimating C sequestration potential of grassland soils with improved management.

The overall mean rate of soil C increase for all types of management change in all areas was 0.54 Mg $C \cdot ha^{-1} \cdot yr^{-1}$. This estimate is comparable to potential C sequestration rates estimated for the Conservation Reserve Program (0.2–0.8 Mg $C \cdot ha^{-1} \cdot yr^{-1}$), the grassland Waterways program (0.5 Mg $C \cdot ha^{-1} \cdot yr^{-1}$), and adoption of no tillage (0.5–0.8 Mg $C \cdot ha^{-1} \cdot yr^{-1}$) (Lal et al. 1998). Soil C sequestration rates were influenced primarily by management history and management changes, but also by climate and native vegetation. Due to relatively high potential C sequestration rates and extensive grassland coverage, improved grassland management is potentially a substantial global sink for atmospheric carbon.

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APPENDIX

Summary information about each data point compiled from the literature is available in the form of a table reporting site coordinates, type of management change, duration, soil depth, initial and final soil C, and references. The table may be accessed in ESA's Electronic Data Archive: *Ecological Archives* A011-005.