

# Carbon stewardship: land management decisions and the potential for carbon sequestration in Colorado, USA

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## Abstract

Land use and its role in reducing greenhouse gases is a key element of policy negotiations to address climate change. Calculations of the potential for enhanced terrestrial sequestration have largely focused on the technical characteristics of carbon stocks, such as vegetation type and management regime, and to some degree, on economic incentives. However, the actual potential for carbon sequestration critically depends on who owns the land and additional land management decision drivers. US land ownership patterns are complex, and consequently land use decision making is driven by a variety of economic, social and policy incentives. These patterns and incentives make up the ‘carbon stewardship landscape’—that is, the decision making context for carbon sequestration. We examine the carbon stewardship landscape in the US state of Colorado across several public and private ownership categories. Achieving the full potential for land use management to help mitigate carbon emissions requires not only technical feasibility and financial incentives, but also effective implementing mechanisms within a suite of often conflicting and hard to quantify factors such as multiple-use mandates, historical precedents, and non-monetary decision drivers.

**Keywords:** stewardship, carbon sequestration, land tenure, land cover, land management, decision making, GIS, Colorado, United States

## 1. Introduction

Land use practices affect the global distribution of carbon through agriculture and forestry, contributing as much as 20% of global carbon emissions. Traditional methods of agriculture such as clearing land and plowing, and certain forest harvest practices lose carbon to the atmosphere (CCSP 2007). If these methods are changed, or lands are allowed to revegetate, soils and above-ground biomass can recover over time, enhancing carbon sequestration on land at relatively low cost (Kinsella 2002, Heath *et al* 2003, Lal *et al* 2003, Sperow *et al* 2003, Paustian *et al* 2006, Richards *et al* 2006). For these reasons, many climate change policies including the Kyoto Protocol, US Congress’ American Clean

Energy and Security Act of 2009 (HR 2454), and regional or state-level policies in the US (e.g. the Western Climate Initiative and Colorado Climate Action Plan) promote land management as a means to mitigate greenhouse gas emissions by removing carbon from the atmosphere. Thus far, estimates of the potential for future additional carbon sequestration on land have been calculated primarily as a function of the technical characteristics of the land or a theoretical price on carbon. These descriptors, however, do not tell the full story of the potential for carbon sequestration on managed land as they leave out a fundamental mediator of carbon storage—the decision context of the landowner. The pattern of ownership and influences on decision making make up the ‘carbon stewardship landscape’, or how decision making will ultimately control carbon sequestration.

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The technical potential for enhancing carbon sequestration on agricultural, range, forest and degraded lands depends on land use history, current practices, soil, climate, humidity, vegetation, among other factors (IPCC 2006, CCSP 2007, USDA 2008). In the US, the potential for enhancing carbon storage in agricultural soils alone has been estimated from 70 to 221 million metric tonnes (MMT) per annum over several decades, i.e. until saturation (Paustian *et al* 2006). Until then, changes in agricultural practices technically have the potential of offsetting 5–14% of US baseline 2004 emissions (Paustian *et al* 2006). Forest lands represent another 214 MMT of additional potential sequestration (USDA 2008).

The economic trade-offs between existing practices and the practices required to store carbon may further constrain the potential to enhance carbon sequestration (Antle *et al* 2007). For example, adopting no-till practices results in additional carbon storage over conventional tillage and can earn land managers additional income from the sale of carbon offsets. However, no-till may result in additional costs (i.e. new equipment) or reduced land productivity for a period of time that will affect the landowner's profit (Richards *et al* 2006, New Energy Finance 2009). Economists can estimate the necessary incentive—the price per ton of carbon—to induce farmers to take on these different practices by generating assumptions about profit maximization and other economic drivers. According to some models at a price of \$10/ton, 1–44 MMT of additional carbon could be stored in US lands; however, if that price goes up to \$50/ton, 10–70 MMT might be stored (Lewandowski *et al*, McCarl and Schneider, both as cited in (Paustian *et al* 2006).

We suggest that in order to estimate the actual or realized potential for land management to contribute to climate mitigation, we must consider not only the technical and economic potential, but also who owns the land and what influences land owners' decisions. For example, ownership category and subsequent management practices can play a strong role in determining above-ground biomass and landscape dynamics, which in turn are linked to carbon stocks and fluxes (Zheng *et al* 2010).

In the United States and elsewhere a complex variety of individual landowners and managers, responding to a host of decision drivers, determine the overall pattern of land use and the consequent carbon storage (Lambin *et al* 2001, Lubowski *et al* 2006, Richards *et al* 2006, Dilling 2007, Hersperger and Bürgi 2009). A large portion of land nationwide (37%) is owned and managed by the public sector, by either federal agencies or states and local governments. Private individuals and corporations own most of the rest of the land (60%), with a small fraction (1%) owned by tribes (Lubowski *et al* 2006). Public lands in particular must accommodate a wide variety of uses from mineral and timber extraction to species and habitat preservation. Further, public land agencies are not homogeneous—they have varying cultural histories and policy mandates. Private landowners range from those that manage less than a few hundred acres to large corporations that manage hundreds of thousands of acres. Economic factors are strong drivers of decisions by private landowners, but diverse non-monetary benefits or traditions often influence land

management decisions as well (Lambin *et al* 2001, Koontz 2001).

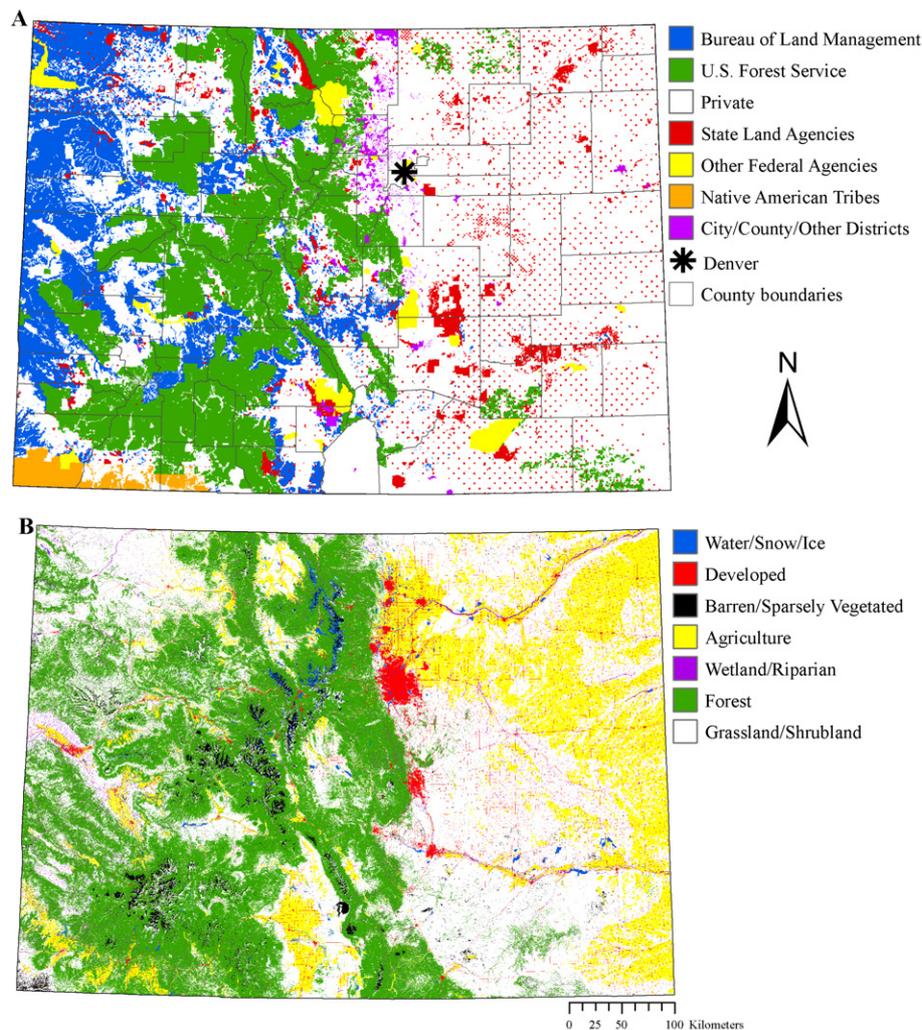
Land managers thus face complex decisions for enhancing terrestrial carbon sequestration (Richards *et al* 2006). Even with a price and formal trading regime for carbon—however achieved—the distribution and diversity of land management decision makers will require a mix of policies targeting public lands agencies and other policies targeting private landowners.

To characterize the carbon stewardship landscape in order to better inform the opportunities and constraints for carbon sequestration, we can combine data on ownership, decision influences including policies, and carbon stocks and fluxes. We conducted a case study of carbon stewardship focusing on the US state of Colorado where the wide variety of ownership categories reflects those of the larger US. Here we present the results of combining GIS spatial data on land ownership with vegetation cover, as well as with carbon sequestration estimates found in the published literature. We examine some of the diverse decision drivers within two private sector land uses (e.g. farmers and ranchers) and three public land management agencies (e.g. BLM, USFS and State), and then we assess implications for policy and carbon cycle science research.

## 2. Methods

We created a geographic information system (GIS) to analyze existing vegetation and land ownership data in Colorado and to combine vegetation data with published estimates of vegetation carbon stock and flux in order to evaluate the state's carbon stewardship. We used Colorado Ownership, Management and Protection Version 7 (COMaP) (Theobald *et al* 2008) and LANDFIRE Existing Vegetation Type data (US Geological Survey 2008) in our GIS. We reclassified the COMaP data to create seven stewardship classes: (1) Bureau of Land Management (BLM), (2) US Forest Service (USFS), (3) Private, (4) State, (5) Other Federal, (6) Native American, and (7) City/County/Other Districts. For land cover, we grouped the original LANDFIRE data into seven land cover classes: (1) water/snow/ice, (2) developed, (3) barren/sparsely vegetated, (4) agriculture, (5) riparian/wetland, (6) forest, and (7) grassland/shrubland. We defined agriculture (4) as irrigated land, dryland crops, hay and pasture and forest (6) as combined deciduous and coniferous forests and woodland areas. We joined the grassland and shrubland classes (7) because both land covers are used primarily for livestock grazing in Colorado. We recognize that land cover is not the same as land use (e.g. that grassland and agriculture are land cover and land use, respectively) but for simplicity we follow the classification conventions established in the LANDFIRE database and refer to them as land cover.

We reviewed the literature and compiled carbon stock and flux estimates from published studies and reports as well as from an unpublished report by Conant *et al* (2007). Although we sought measurements specific to Colorado, we had to rely on calculations from the western and contiguous US when Colorado specific data were not available. Estimates that evaluated both vegetation and soil carbon were preferred, but we also considered soil carbon measurements when combined vegetation and soil carbon values were not available. We



**Figure 1.** (A) Land ownership patterns for the state of Colorado from the CoMAP database v7, compiled from 1995 to 2008 datasets by Theobald *et al* (2008) and (B) land cover aggregated into seven main classes from the USGS LANDFIRE database (2008 version) for the state of Colorado.

**Table 1.** Area of land cover type in Colorado, and the range of published literature estimates we used in our GIS analysis for carbon flux and stock; positive flux estimates represent sources and negative flux values are land sinks.

Land cover type (Area (Mha))	Flux range (Mg C ha <sup>-1</sup> yr <sup>-1</sup> )	Stock range (Mg C ha <sup>-1</sup> )
Water/snow/ice (0.20)	—	—
Riparian/wetland (0.53)	0.61 <sup>a</sup> to -0.24 <sup>b</sup>	198.60 <sup>a</sup> –1540.49 <sup>a</sup>
Barren/sparsely vegetated (0.56)	—	—
Developed (0.70)	-0.31 <sup>a</sup> to -3.83 <sup>c</sup>	6.32 <sup>d</sup> –47.58 <sup>c</sup>
Agriculture (4.05)	0 <sup>a</sup> to -0.22 <sup>e</sup>	16.62 <sup>c</sup> –95.10 <sup>a</sup>
Forest (8.43)	-0.57 <sup>e</sup> to -1.21 <sup>e</sup>	102.38 <sup>f</sup> –224.83 <sup>a</sup>
Grassland/shrubland (12.50)	0.03 <sup>d</sup> to -0.07 <sup>d</sup>	47.77 <sup>c</sup> –107.44 <sup>a</sup>

<sup>a</sup> CCSP (2007). <sup>b</sup> Chimmer and Cooper (2003).

<sup>c</sup> Kaye *et al* (2005). <sup>d</sup> Conant *et al* (2007). <sup>e</sup> Pacala *et al* (2001).

<sup>f</sup> Goodale *et al* (2006).

converted all published carbon data into megagrams of carbon (Mg C) and all area measurements into hectares (ha). Negative flux values represent carbon sequestered in vegetation and soils

(sinks) whereas positive values correspond to carbon released to the atmosphere (sources) (table 1). Table 1 includes only the citations with either the highest or lowest estimate in our literature sample.

To assess Colorado’s carbon stewardship we applied a range of the estimated carbon stocks and fluxes obtained from carbon literature to our GIS. In our analysis of carbon stock and flux, we opted not to consider the water/snow/ice and barren/sparsely vegetated classes. Note that these estimates do not include fluxes from the use of fossil fuel in managing the land.

### 3. Who is managing carbon on the land?

#### 3.1. Mapping the landscape

Colorado is a western US state of approximately 26.96 million hectares (Mha) in size. The ownership pattern is reflective of the US as a whole with Colorado’s majority ownership held by the private sector (57%) and federal government agencies (mainly US Forest Service and Bureau of Land Management)

**Table 2.** Range of estimates of fluxes and stock of carbon summarized by landowner category in Colorado (in Tg C yr<sup>-1</sup> and Tg C respectively; negative fluxes are net uptake of carbon). In a GIS we merged the published range of carbon stock and flux estimates (table 1) with our land cover and land ownership data files.

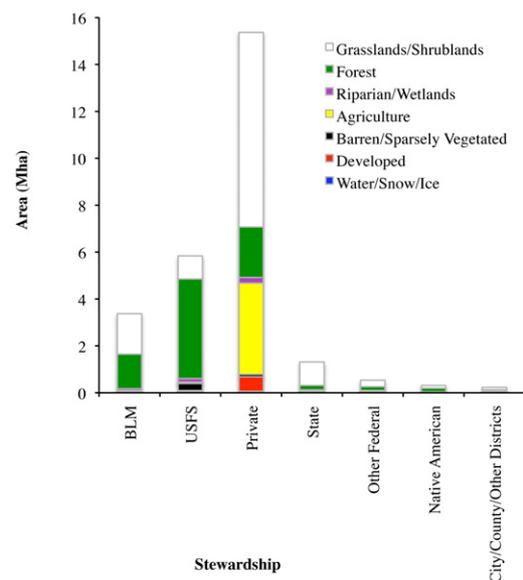
Landowner	Area (Mha)	Flux range (Tg C yr <sup>-1</sup> )	Stock range (Tg C)
Private	15.37	-1.02 to -6.48	733–2150
USFS	5.84	-2.31 to -5.33	512–1296
BLM	3.37	-0.74 to -1.97	250–645
State	1.31	-0.07 to -0.39	71.8–187
Other Federal	0.54	0.08 to -0.26	32.7–88.1
Native American	0.31	0.08 to -0.21	22.3–54.6
City/county/other districts	0.23	-0.03 to -0.15	13.7–43.3

having the second largest stake (37%) (figure 1(A); Lubowski *et al* 2006). Grassland/shrubland (including land used for grazing livestock) is the state’s primary land cover (46%) followed by forests (31%) and agriculture (15%); with minor amounts of other land cover types (figure 1(B)). Colorado tends to be substantially drier on average than the US within each of these land categories, and the US has proportionately more crop land (20%) and less grassland, pasture, and range (26–37%) (Lal *et al* 2003, Lubowski *et al* 2006).

### 3.2. Private lands

The 15 million hectares of private lands in Colorado fall primarily into three land cover types: grasslands, agriculture and forests. Colorado private lands contain almost half of the state’s carbon stocks (733–2150 Tg C; table 2) and these lands sequester from 1 to 6.5 Tg C per annum, slightly less than their proportionate area in the state as a whole, as carbon stocks per ha are relatively low on grasslands and agricultural lands when compared with forests (table 1). In Colorado, cultivated crop land represents 36% of total agricultural land (approximately 4 million hectares, figure 2). Although about 35% of Colorado farms have irrigated cropland, only 20% of total cropland in the state is irrigated (USDA NASS 2009). No-till carbon-offset projects require irrigation (in the few Colorado counties that are currently eligible to earn this type of offset (CCX 2010)). The financial incentive associated with various offset project options in addition to external influences such as energy policy (e.g. incentives for biofuel production) also strongly influence whether specific practices may be implemented on private or public lands. For example, no-till projects generally earn a lower sequestration rate (ton/acre/year) than grassland planting projects (New Energy Finance 2009, CCX 2010). Many land managers avoid changing management practices because of: (i) existing low financial incentive (e.g. carbon price <\$1.00 per ton—CCX (2010)); (ii) restrictions on management decisions during the contract period, lasting five or more years; and (iii) poorly understood impacts on agricultural production (Dilling and Failey 2010).

Private owners also manage the majority of grasslands and shrublands in the state (66%), using the land primarily for grazing (Conant *et al* 2007). In theory, grazing lands or rangelands represent a large land area that could benefit from



**Figure 2.** The amount of landcover type (in Mha) within each ownership category in Colorado. Note that all agricultural land is privately held, while the federal government in this state predominantly manages forests. Figure generated by overlaying GIS ownership and land cover datasets.

management practices to increase carbon sequestration (Follett and Reed 2010). In practice, however, several challenges surround rangeland management for carbon sequestration, from the short residence time of carbon in many rangeland soils to climate conditions to heterogeneity and lack of measurement capability (Neff *et al* 2009, Brown *et al* 2010). For example, during the first few years of the 21st century drought stressed the state’s grasslands and they became a source of carbon emissions (Conant *et al* 2007). Implementing rangeland management projects in arid or semi-arid environments has technical and economic challenges (Conant *et al* 2001) and little research has evaluated the potential for management practices to affect sequestration on rangelands and pasture lands (Morgan *et al* 2010). The composition of private landowners is also undergoing rapid demographic and cultural shifts as owners age, and some properties that are sold may be converted to other uses, potentially affecting carbon storage (Brunson and Huntsinger 2008).

To illustrate the importance of considering not only technical and economic factors when calculating the potential for increased carbon sequestration on private land, consider the federal Conservation Reserve Program (CRP) in the United States that was established to incentivize landowners to convert highly erodible or environmentally sensitive cropland to other uses. While not its focus, the CRP likely has contributed to the observed increase in soil carbon in agricultural lands in the US (Eve *et al* 2002). The CRP has been a success: in some regions, the CRP enrolls as much as 54% of eligible agricultural lands (Parks and Schorr 1997). When calculating the potential of a program, adoption rates matter. Financial incentives are often a strong motivating factor in the decision to enroll in CRP, but a suite of other factors influence such decisions (e.g. perceptions about flexibility of land use in

the future, other opportunity costs, behavior of neighbors, environmental attitudes, characteristics of the land, and even the design and timing of the program incentive) (Parks and Schorr 1997, Sengupta *et al* 2005, Jack *et al* 2008, Pocerwicz *et al* 2008, Suter *et al* 2008, Lubowski *et al* 2008, Greiner *et al* 2009).

Only 25% of Colorado's forests are privately owned and these private forests contain 12% of the state's carbon stock (representing 220–483 Tg C). Current US forest carbon-offset projects target private landowners who can manage timber harvests or reforest land. The rest of the forests in Colorado, and therefore a good portion of the carbon stock, are owned by public agencies and are not therefore being targeted for deliberate carbon management by market incentives.

### 3.3. Public lands

Compared to private lands, public lands in Colorado include more forested area and less grasslands/shrublands area (figure 2), and represent >50% of the carbon stocks (902.5–2314 Tg C) and fluxes for the state ( $-3.31$  to  $-8.31$  Tg C yr<sup>-1</sup>; negative numbers represent sequestration on land). The federal government manages over 9 million hectares in Colorado, primarily the US Forest Service (USFS) and the Bureau of Land Management (BLM) agencies. Private sector ranchers also graze livestock over a large portion of public federal lands through leasing, with historical use going back for generations. Nearly 75% of Colorado's forests are managed by public land agencies with the USFS (50%) and the BLM (17%) the two primary federal forest managers (figure 2). Including privately held land, forests hold Colorado's largest carbon stock, ranging 862.93–1895.03 Tg C, and sequester the greatest flux, ranging from  $-4.80$  to  $-10.20$  Tg C yr<sup>-1</sup>. Across the US, public timberlands account for 30% of the total US timber production volume and represent substantial potential gains for carbon sequestration with appropriate incentives (Depro *et al* 2008). The Council on Environmental Quality (CEQ) within the Executive Office of the President (which coordinates US federal environmental policy across agencies) has recently called for public comment on assessing protocols to manage carbon on federal lands (Sutley 2010). As of 2010, however, public land managers frequently face more pressing demands such as fire management, recreation, species preservation, and resource extraction (Dilling and Failey 2010).

Two separate federal government departments manage the BLM and the USFS, the Department of Interior and the Department of Agriculture, respectively. Although both BLM and USFS directives now refer to multiple uses of the land, the two agencies were established for different reasons and developed unique cultural histories. The Forest Service formed to manage land for timber with the goal of land conservation to obtain a sustained yield of timber products; on the other hand, the BLM and its precursors were established to give away lands for homesteading and to manage grazing lands that remained in the public realm (Loomis 1993). Still today these two agencies differ in their 'structure, responsiveness to stakeholders, political power, use of science, funding and organizational culture' (Koontz and

Bodine 2008). Even within agencies and their constituencies, multiple sets of sometimes conflicting values and objectives for land management are evident (Martin and Steelman 2004).

The USFS and the Department of Interior have stated goals regarding carbon accounting, voluntary participation in carbon markets, and managing for carbon sequestration; however, other priorities such as resource use, tourism, fire and wildlife preservation currently take precedent over considerations of carbon emissions and potential sequestration in land use proposals and 'on the ground' decision making (US Department of the Interior 2008, USDA 2008, Dilling and Failey 2010). Some evidence indicates that land managers primary missions (e.g. reducing erosion, mitigating fire risk, and producing lumber) can be compatible with carbon management practices (CCSP 2007, Hurteau *et al* 2008, North *et al* 2009). However, maximizing multiple objectives such as biodiversity and carbon is not always possible (Krcmar *et al* 2005). Moreover, practical considerations may preclude carbon management in some areas. For example, approximately 18% of Colorado's public forest land is largely unmanaged wilderness, and the majority of Colorado's forests are located in the mountainous western and central parts of the state (figure 1(B)) making carbon management practices that require access potentially more difficult (or economically impossible) to implement in this rugged terrain.

Furthermore, Colorado's largest carbon stocks and sinks may be the most vulnerable. Pine beetle outbreaks and the onslaught of other arboreal diseases (e.g. Sudden Aspen Decline) may shift Colorado's forest stock through rapid tree mortality (Robbins 2008, Klutsch *et al* 2009). Fire is well known to be a major risk for carbon stocks in Western States (Wiedinmyer and Neff 2007, Hurteau *et al* 2009). For these reasons, Colorado, like British Columbia, may experience a substantial decline in its forests' ability to offset carbon emissions in the near-term (Kurz *et al* 2008).

Finally, state government agencies manage 5% of Colorado's land containing a potential carbon stock of 71.8 to 187 Tg C and a flux ranging  $-0.07$  to  $-0.39$  Tg C (table 2). The Colorado State constitution requires the state Land Board, like others in the West, to seek maximum revenue from its lands. In general, state lands therefore act more like profit-maximizing private entities. State land agencies experience fewer legal constraints, have generally less stakeholder involvement than federal agencies, and can be less responsive to environmental concerns (Koontz 2007, Davis 2008). State bureaucracies can also be heterogeneous with management functions widely dispersed across state governments compared to federal land agencies (Ellefson *et al* 2002).

## 4. Conclusions

To more accurately characterize the potential for enhanced carbon sequestration on land through changes in land use and management, we must look not only to technical and economic factors, but to the complexity of the ownership and the decision making context. Work thus far in the carbon arena has focused largely on the technical potential, with some studies

examining the effects of varying price signals on sequestration (Richards *et al* 2006, Antle *et al* 2007). New techniques to characterize land use decision making that combine qualitative and quantitative modeling may be useful in developing more accurate estimates of realized potential (e.g. Sengupta *et al* 2005, Pocewicz *et al* 2008).

Our review of Colorado's carbon stewardship landscape first reveals a complicated pattern of ownership and vegetation types. The 'carbon stewardship landscape' adds in all other factors that affect sequestration, e.g. diverse incentives that do not yet consider carbon sequestration. This polydimensional landscape represents a challenge for both research and policy focused on terrestrial carbon sequestration as well as implementation. More than half of the carbon stock in Colorado is managed by public agencies of various types—the policy options available to manage these stocks are quite different from the current incentives to manage carbon storage on private lands. The potential role of public lands in sequestering additional carbon through management has been recognized, but processes and procedures that require carbon storage have not been implemented. Moreover, the impact of the multiple competing uses for public lands on carbon storage is uncertain, and how these trade-offs will be negotiated remains to be seen. Future efforts should consider the carbon stewardship landscape including an examination of the institutions, policies, and values at work on land in order to develop more realistic estimates and, ultimately, more effective policies for carbon sequestration.

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