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Highlights

Payments for carbon can lead to unwanted costs from afforestation in the U.S. Great Plains

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- natural climate solutions include managing forests to store carbon
- payments for carbon could lead to 118.4 million acres of afforested rangeland
- payments for carbon distort the relative provision of other ecosystem service
- adaptive management explicitly accounts for co-costs and co-benefits of afforestation

Payments for carbon can lead to unwanted costs from afforestation in the U.S. Great Plains

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Abstract

As atmospheric carbon dioxide continues to exceed 415 ppm, there is an urgent need to reduce and reverse the concentration of atmospheric greenhouse gases. There is growing interest in using payments for carbon to incentive land management that stores additional ecosystem carbon. So called natural climate solutions include managing forests to store carbon in tree biomass. Under carbon market with a price of $50 per metric ton, 118.4 million acres of rangeland in the United States (U.S.) Great Plains could be afforested. Yet in the absence of a clear policy design that accounts for ecosystem services, payments for carbon distort the relative provision of other ecosystem services in the pursuit of short term carbon gains attributed to afforestation. An adaptive management framework offers one way to explicitly account for the spatially and temporally uneven co-costs and co-benefits of afforestation on the production of various U.S. Great Plains ecosystem services, including carbon storage.

1. Introduction

There is growing interest in generating payments to land management that stores additional ecosystem carbon. So called natural climate solutions [16] include managing forest, range, and crop lands to store carbon belowground in soil and aboveground in plants. Avoided deforestation, reforestation of former forest lands, and afforestation of non-forest lands are all natural climate solutions [32] that could be incentivized by revenue from carbon markets. However, afforestation (i.e., facilitating the spread of trees into historically non-forested lands) may include additional costs (i.e., "co-costs") that are not captured by carbon payment rates. In the absence of policy that accounts for ecosystem services, payments for carbon may distort the relative provision of ecosystem services in the pursuit of afforestation. Specifically, afforestation of grasslands increases the risk of uncontrollable forest fire and may modify soil carbon stocks, both of which may ultimately undermine the original objective of storing additional ecosystem carbon. Here we describe the effects of payment for carbon on afforestation rates, the subsequent modification to grassland ecosystem services in the United States (U.S.) Great Plains, and how policy can be designed for the Great Plains to account for spatiotemporaly uneven co-benefits and co-costs of afforestation [10].

2. The Co-costs of Afforestation

Rangelands in the U.S. Great Plains are vulnerable to afforestation due to low marginal cost of conversion, low opportunity costs relative to cropland use, and passive woody encroachment [14, 43, 13]. A price of $50 per metric ton of carbon could encourage the afforestation of 118.4 million acres of rangeland, 48.2 million acres of pasture land, and 79.2 million acres of cropland. In this scenario, nearly half of the carbon sequestered from afforested lands (93.7 of the 200 M tons) is attributed to rangeland conversion (fig. 1). Yet the co-costs of grassland afforestation are largely unaccounted for when calculating the price on afforestation-derived carbon in the U.S. Great Plains. In particular, afforestation increases vulnerability to catastrophic wildfire, reduces forage production, and has uncertain effects on soil carbon, which provides a more fire-resistant carbon sink than aboveground biomass like trees.

In grasslands, afforestation modifies the flow of grassland ecosystem services to society. Those services include wildfire regulation, forage for wildlife and livestock, and soil carbon storage. Along a grassland-to-forest gradient, loss of grassland ecosystem services can be sudden (i.e., nonlinear) and persistent (i.e., hysteretic) ([42]. Juniper invasions of grasslands exemplify this effect. In the U.S. Great Plains, juniper trees (*Juniperus spp.*) are rapidly expanding from their historic range into grasslands. This expansion is attributable to a lack of frequent low intensity fires and spread from planted windbreaks [13]. Grassland fires typically have flame lengths of between 0.1 to 3.4 m [15, 43], yet it is not uncommon for juniper forest crown fires to have flame lengths of well over 14 m [41]. The U.S. Forest Service specifies that wildfires with flame lengths over 3.4 m are unlikely to be suppressed. Afforestation can therefore render North American Great Plains more vulnerable to uncontrollable wildfires [2, 4, 42], a phenomenon likely to be exacerbated by climate change [12]. In 2017 alone, the US Department of Interior reports that it spent $2,918,165,000 nationwide on wildfire suppression, up from the roughly $1 billion spent annually between 2000 and 2010. The Depart-

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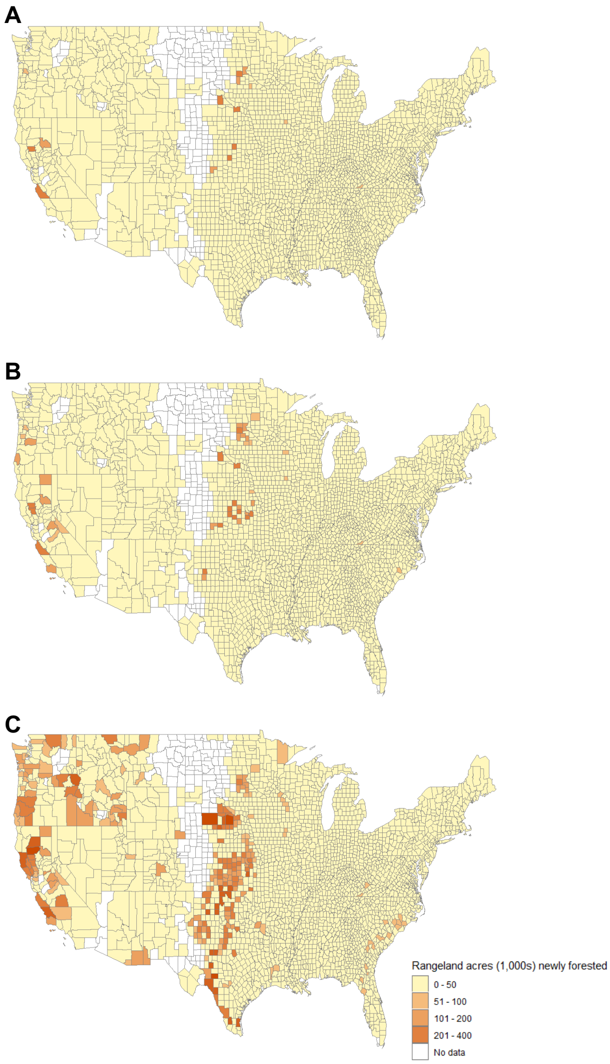

Figure 1: Rangeland acres that are candidates for afforestation under carbon markets when carbon is priced at $12 (A), $20 (B), and $50 (C) per metric ton. Reanalyzed from [14]

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ment of Commerce reports the indirect costs of wildfires, such as lost livestock forage, a depleted rural tax base, building and fence loss, and declines in tourism at between $71 to 350 billion over the past decade. In 2011, a single, 120 square mile wildfire that spanned parts of rural Nebraska and South Dakota cost $3.2 million in suppression alone. While multiple factors conspire to drive this surge in wildfire, increasing woody fuel load (i.e., brush, closed canopy forests) is a well-known driver of increasingly uncontrollable wildfires [12].

In addition to increased wildlife risk, juniper encroachment of the Great Plains is one of the leading threats to the sustainability of the region's rangelands and the economic profitability of livestock enterprises [44, 42]. In many Great Plains states, including Nebraska, public school revenue from grazing leases are already on the decline as afforestation reduces grassland forage production.

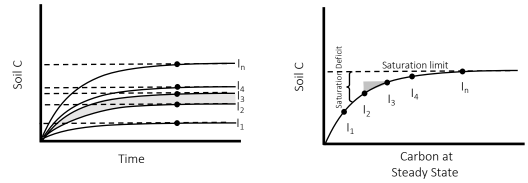

Figure 2: Soil carbon (C) dynamics described by the C-saturation hypothesis, showing the effect of different carbon input levels (I_x) on soil C over time (left panel), and at steady state (i.e., inputs and release in equilibrium) (right panel). As inputs increase, storage capacity and steady state carbon storage decrease. The greyed area shows gains in soil carbon when inputs increase. Adapted from [40].

2.1. Afforestation and ecosystem carbon

In addition to increased wildlife risks, grassland afforestation may undermine ecosystem carbon stored in the soil. Carbon gains from grassland juniper afforestation predominantly occur as perennial aboveground woody biomass [29, 25, 26, 8, 27]. This makes grassland afforestation an attractive option for rapid carbon sequestration. By contrast, grasses and forbs allocate a larger share of their annual production to the soil surface as litter [9, 45, 25] and directly to the soil through root turnover [23]. Aboveground carbon (C) in 50 year old juniper stands in the Flint Hills of the central US Great Plains were reported to contain roughly 64,090 kg C $ha^{-}1$, with 52 percent of total ecosystem carbon stored in the soil [30, 28, 25]. By comparison, adjacent tallgrass prairie cover held only an estimated 1660 kg aboveground C $ha^{-}1$ at peak growing season, but with 96 percent of total ecosystem C stored belowground [22].

Unlike the aboveground, soil carbon does not respond predictably to afforestation. A metaanlysis from Post and Kwan [33] reported that total soil C varied from -0.141 to 0.617 Mg C $ha^{-1}yr^{-1}$ in response to afforestation, with variance ascribed to tree species, soil texture, and environmental conditions. A metaanlysis from Guo and Gifford [?] reported 25 percent greater soil C gains in afforested cropland versus pastureland and a review from Paul [31] reported an increase in soil C in afforested cropland and a *decrease* on soil C in afforested pastureland.

While the effect of afforestation on soil carbon is largely unknown, there is evidence that grassland and forest soils store carbon differently. Global grassland soils store an estimated average 331 Mg C ha^{-1} [37, 11] while forested soils store an estimated average 96 Mg C ha^{-1} [24]. If a grassland soils and forest soils have different intrinsic limits to carbon storage, afforestation may ultimate reduce the capacity of former grassland soils to store carbon.

Intrinsic limits to carbon storage are understood to be the result of physico-chemical adsorption of C to clay surfaces [18], physical protection of C in soil aggregates, the biochemical complexity or recalcitrance of the C inputs themselves, and environmental limits on biological activity [3, 7]. Carbon storage limits or "saturation equilibria" have been detected to shift in some systems following changes in ecosystem processes (e.g., nutrient fertilization [36], indicating that C storage limits may be dynamic. Whether the differences in grassland and forest soil carbon levels are explained by inherently different soil carbon saturation limits in grasslands versus forests provides insight into the implications of afforestation of grasslands for C sequestration. Specifically, where afforestation reduces soil carbon storage limits and wildfire removes aboveground C, afforestation could ultimately drive an overall loss of system carbon (fig. 2). If saturation equilibria do shift in response to afforestation, the reversibility of that shift following tree-removing wildfire is similarly unknown [6].

Afforestation can effectively store carbon over short term (one to many decades). Yet those stores are ultimately vulnerable to loss from wildfire over the longer term (many decades to centuries). Historical fire-adapted forests experience periodic fires followed by stand regrowth. Those forest fires release large amounts of C-CO_2, with dead standing necromass slowly contributing additional C-CO_2 as they decompose. Eventually, post-fire regrowth of forest plants recover carbon lost to fire, creating a net neutral carbon balance over a fire-regrowth period [20, 35, 26]. When fire-regrowth successionary cycles are distributed through space and time the carbon emitted from any single fire can be modulated by regrowth occurring elsewhere in space or time [17]. An average fire in the continental US releases 213 $(\pm 50 S.D.) Tg CO_2$ yr^{-1} of carbon, and total CO_2 losses from forest fires in the US are equivalent to 4–6 percent of total anthropogenic CO_2e emissions. The typical forest fire-regrowth successionary cycle is on a scale of many decades to a century, so if fire return intervals overtake regrowth periods, or fires reach intensities high enough that regrowth does not occur, C losses will outpace the C inputs attributed to grassland afforestation. When successionary cycles of fire and regrowth (also known as "adaptive cycles" [1]) are inadvertently synchronized by simultaneous and widespread fire suppression, fuel buildup leaves the system primed for a large release of carbon from a single catastrophic wildfire season across large areas (i.e., tens of millions of acres) [39]. This synchronization is exemplified by surging western United States (US) wildfires in recent decades [12].

There is a magnitude difference of ecosystem carbon lost when a grassland (with an estimated 1660 kg aboveground C ha^{-1}, ([**?**]) versus a juniper woodland (with an estimated 64,090 kg aboveground C ha^{-1}, [**?**]) burns. Soil carbon, by contrast, does not have a predictable strength or direction of relationship to fire. Fire appears to affect soils through charcoal inputs [38] and shifts in aboveground plant communities (e.g., [34]). While grassland afforestation could be a boon to short term (decades) C sequestration, decisions about when and where to afforest must be made in the context of a non-stationary wildfire regime to secure C gains over the long term (i.e., beyond decades and centuries).

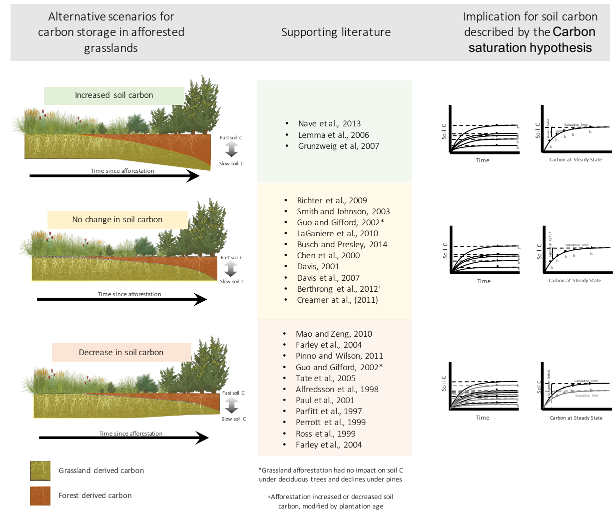

Figure 3: Alternate scenarios of afforestation on soil carbon stocks over time, with supporting literature, and the predicted change in soil carbon according to the carbon saturation hypothesis. The scenarios include gains in soil carbon (highlighted in green), no affect on soil carbon (highlighted in yellow) and declines in soil carbon (highlighted in red) in response to afforestation. Only pasture and rangeland (i.e., cropland cases omitted) afforestation cases are included in the supporting literature examples.

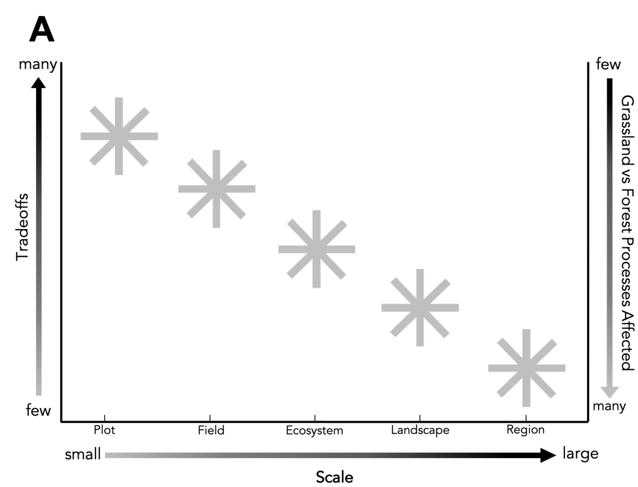

Figure 4: The tradeoffs between forest and grassland ecosystem services change at different spatial and temporal scales, as do the number of ecosystem processes affected by management. Adapted from [5]

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3. A Path Forward

In the United States, afforesting the Great Plains with juniper trees may be the most cost effective way to sequester ecosystem carbon through a market mechanism over the very short term (i.e., years to decades). Yet, ecosystem carbon storage in afforested juniper woodlands fluctuates on a scale of decades to centuries, and may even result in a net loss of carbon should soil stocks be irreversible reduced. Further,

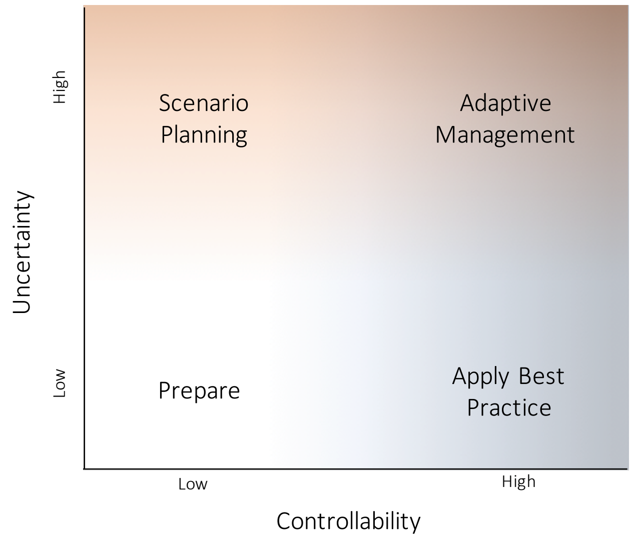

Figure 5: Adaptive management, scenario planning, preparation, and applying the best known practice are each effective approaches to managing natural resources given different uncertainty and controllability conditions.

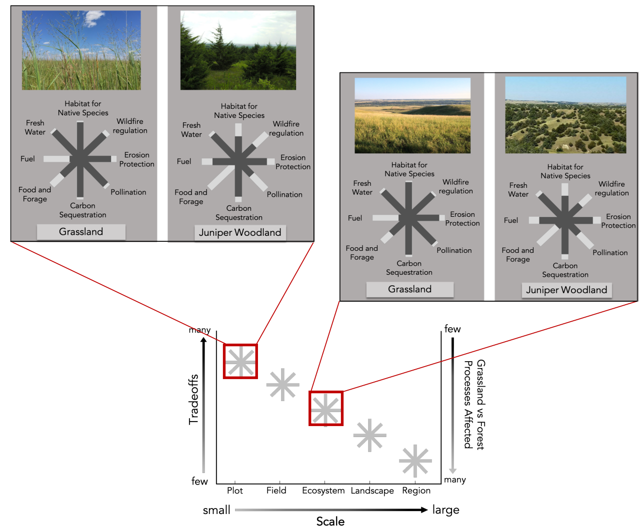

Figure 6: At the scale of a hectare plot over a single season, only a few ecosystem processes can be managed for a narrow range of services, i.e., there are many tradeoffs. At the ecosystem scale of tens to hundreds of hectares over roughly a decade, there are fewer tradeoffs and more ecosystem processes to manage to achieve multiple simultaneous ecosystem services.

policy required to mitigate and track those costs scales tend to operate on a scale of years to decades at most. An assessment of the spatial and temporal scales across which different ecosystem services emerge [10] can support policy designed mitigate unwanted outcomes (co-costs), and improve the benefits of afforestation for carbon sequestration in the U.S. Great Plains.

3.1. A Framework for Assessing Afforestation

Adaptive management is an approach to informing natural resources policy that explicitly addresses the issue of scale when managing for single primary and several ancillary objectives [21, 5]). Contextualizing a primary management objective like carbon sequestration through afforestation requires an assessment of the management action at the focal (objective), higher (constraints), and lower (explanatory) scales [19]. This approach is meant to uncover information about system relationships that could otherwise remain hidden and ultimately undermine management objectives.

Adaptive management is effective when there is a degree of both controllability and uncertainty in the system (fig 5). The mid- to long-term outcomes of grassland afforestation for carbon sequestration may meet this criteria, with controllability conferred by the design of carbon market policy, and testable uncertainty concerning system response to that policy. If there is low controllability over market design, i.e., it emerges with little to no ability to distinguish between, for example, avoided deforestation and afforestation, avoiding the unwanted risks and hazards of afforestation instead relies not on adaptive management but instead on scenario planning (fig 4). If policymakers have an objective to reduce atmospheric CO_2 by 15 percent of U.S. emission over five decades, their policy can include an investigation of how responding management modifies carbon loss to wildfire over a typical fire regime (i.e., 50-200 years), the geography of their target system (e.g., 100,000,000 ha of the Great Plains), the likely duration of the policy's reach (e.g., 5-20 years) and the expected soil carbon response (i.e., years to millennia). After this analysis is completed for carbon sequestration, it should be repeated for other valuable ecosystem services (e.g., freshwater provisioning, wildfire mitigation, spiritual benefits, etc.) gained or lost as a result of the policy. Finally, all net gains and losses in ecosystems services, including carbon storage, and other economic and social impacts should be considered together (e.g., [5]. This approach can uncover economic, social, and ecological costs of afforestation not otherwise captured by the cost of a carbon credit. To avoid unexpected and unwanted outcomes, policymakers can explicitly define the scale over which carbon market objectives should be met and over what scale carbon market risks should avoided.

4. Conclusion

To confront the challenges of global change, both grasslands and forests must be managed for critical ecosystem processes, including ecosystem carbon storage. As atmospheric carbon dioxide continues to exceed 415 ppm, improved ecosystem management can provide the critical service of reversing concentrations of atmospheric greenhouse gases. While managing forests to store additional carbon is a powerful natural climate solution, the context for where and how those forests occur is critical for avoiding costs including net loss of ecosystem carbon over the long-term. Determining which additional costs to include in a price on carbon from afforestation can be improved an explicit accounting of the scale over which the carbon credits provide both benefit and risk to the primary (i.e., carbon storage) and ancillary (i.e., fire management, forage production) management objectives.

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