Highlights

* natural climate solutions include managing forests to store carbon
* payments for carbon could lead to 61.2 million acres of additional afforested US rangeland
* payments for forestry carbon offsets could undermine other ecosystem services including reduced fire hazard
* offset generation from afforestation could lead to a net loss of carbon
* offset methodologies can mitigate the tradeoffs of afforestation

Limitations to carbon benefits from grassland afforestation in the

U.S. Great Plains

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A R T I C L E I N F O

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**Abstract**

In the United States, enhancing forest growth on native grasslands may initially appear as a cost-effective pathway for storing additional ecosystem carbon and generating carbon offsets needed by governments, companies, and other entities to reach their decarbonization targets. Yet, the social and ecological costs of grassland afforestation in the United States Great Plains includes increased vulnerability to wildfires, loss of critical habitat and other grassland ecosystem services, and even the potential for lower net ecosystem carbon over the long term (10+ year), especially if afforestation limits carbon storage equilibria in the soil. Failure to account for those costs during offset generation could lead to the afforestation of an additional 61.2 million acres of grasslands in the United States (U.S.) Great Plains under a scenario of carbon credits priced at $50 per metric ton carbon (C). Fortunately, methodologies from carbon registries can be applied to account for both the benefits and costs of grassland afforestation, thereby reducing its value as a natural climate solution. By including these considerations in the scoping phase of project development, carbon offset credit registries and project developers can avoid afforestation scenarios that undermine their commitment to generating durable carbon that incur no net harm on the social-ecological system.

# Background

Land management activities that enhance carbon storage in ecosystems represent an important pathway for mitigating global climate change. These so called "natural climate solutions" (NCS) ([Griscom et al.](#_bookmark15) [[2017](#_bookmark15)]) include managing forests, pastures, wetlands, and croplands to increase carbon fixation and retention in plants and soils. Avoided deforestation, reforestation of formerly forested lands, and afforestation of non-forest lands are all natural climate solutions that leverage the carbon storage benefits of forests ([Plantinga and](#_bookmark52) [Wu](#_bookmark52) [[2003](#_bookmark52)], [Forster et al.](#_bookmark11) [[2021](#_bookmark11)]). Yet afforestation of grasslands is distinct from the other two categories of forestation due to the well-documented net loss of ecosystem service provisioning that occurs when trees invade grasslands. Those diminished ecosystem services include fire hazard mitigation ([Donovan et al.](#_bookmark7) [[2017](#_bookmark7)]), long term (10+ year) carbon storage ([Jackson](#_bookmark24) [et al.](#_bookmark24) [[2002](#_bookmark24)]), habitat provisioning ([Wilcox et al.](#_bookmark47) [[2022](#_bookmark47)]), water availability and quality ([Kishawi et al.](#_bookmark26) [[2023](#_bookmark26)]), forage production ([Morford et al.](#_bookmark42) [[2022](#_bookmark42)]), and recreational value ([Birge et al.](#_bookmark1) [[2016a](#_bookmark1)]).

While carbon offset credit registries have methodologies in place to safeguard against any social and ecological costs of generating carbon offsets through NCS projects there is a lack of specificity in those methodologies regarding how net grassland afforestation cost and benefits are operationalized in a project monitoring, reporting, and verification scheme. As more countries, corporations, and private citizens look to NCS as a solution for offsetting their greenhouse gas (GHG) emissions, it is essential that carbon registries provide explicit instructions for the accounting of climate and non-climate related ecosystem service trade-offs associated with afforestation of grassland systems.

# The ecology of grassland afforestation

Grasslands are a critically endangered global ecosystem: in the U.S. alone, is estimated that as little as 1 percent of the original grassland extent remained by the start of the 21st century ([Samson and Knopf](#_bookmark28) [[1994](#_bookmark28)]). Those grassland fragments provide myriad ecosystem services, including habitat for rare and federally endangered grassland species, forage production, nutrient and waste cycling, and carbon storage. When an ecosystem experiences a persistent disturbance, like when a grassland fragment is afforested, the loss of its ecosystem services can be rapid and persistent (i.e., hysteretic) ([Twidwell et al.](#_bookmark38) [[2013](#_bookmark38)], [Birge et al.](#_bookmark1) [[2016a](#_bookmark1)]). The juniper (*Juniperus spp.*)invasion of U.S. Great Plains grasslands exemplifies this phenomenon. Junipers are woody plants native to the U.S. Great Plains but historically relegated to stream corridors and rocky outcroppings. Their expansion into grasslands is attributed to the suppression of grassland wildfires and the spread of propagules from planted tree stands (e.g., windbreaks) ([Elberg Nielsen et al.](#_bookmark8) [[2014](#_bookmark8)], [Twidwell et al.](#_bookmark40) [[2016](#_bookmark40)], [Donovan et al.](#_bookmark9) [[2018](#_bookmark9)]).

Reintroducing fire (e.g., controlled burns) and the use of mechanical removal can reverse afforestation during early juniper invasions ([Twidwell et al.](#_bookmark40) [[2016](#_bookmark40)], [Fogarty et al.](#_bookmark12) [[2022](#_bookmark12)]). At some threshold, however, invading junipers create a closed canopy forest vulnerable to uncontrolled wildfire and disproportionally more expensive to remove by mechanical means. Even when mechanical removal is successful, it can occur too late in the invasion process to restore grassland cover; i.e., the underlying self-reinforcing grassland ecosystem feedbacks are lost ([Angeler et al.](#_bookmark13) [[2015](#_bookmark13)]). When a mature juniper forest does burn, it often leaves behind standing remnant tree skeletons that interfere with light penetration, animal movement dynamics, and hydrology. Closed canopy juniper fires may also become hot enough to kill dormant grassland seeds in the soil. The threshold between reversibility and hysteresis in a grassland to juniper forest transition is dynamic and difficult to predict for any specific case ([Twidwell et al.](#_bookmark40) [[2016](#_bookmark40)]).

In addition to habitat loss, juniper afforestation of grasslands modifies nutrient cycling (e.g., nitrogen removal, [Reisinger](#_bookmark23) [et al.](#_bookmark23) [[2013](#_bookmark23)]) and ecosystem carbon storage. Global grassland soils store an estimated average 331,000 kg C *ha*−1 ([Schlesinger](#_bookmark30) [[1977](#_bookmark30)], [Conant](#_bookmark4) [[2011](#_bookmark4)]) while forested soils store an estimated average 96,000 kg C *ha*−1 ([Lal](#_bookmark32) [[2005](#_bookmark32)]). This could be attributed to grassland plants allocating a larger share of their annual production to the soil through root turnover and exudation (i.e., leaky roots; [Kuzyakov and Domanski](#_bookmark31) [[2000](#_bookmark31)]) and indirectly via the soil surface as dead plant tissue ([Chapin](#_bookmark5) [[1980](#_bookmark5)], [Vitousek](#_bookmark43) [[2004](#_bookmark43)], [McKinley et al.](#_bookmark34) [[2007](#_bookmark34)]). Junipers, by contrast, store much of their carbon in perennial aboveground biomass ([Norris et al.](#_bookmark50) [[2007](#_bookmark50)], [McKinley et al.](#_bookmark34) [[2007](#_bookmark34)], [Mckinley et al.](#_bookmark35) [[2011](#_bookmark35)], [Busch and Presley](#_bookmark6) [[2014](#_bookmark6)], [Mellor et al.](#_bookmark39) [[2013](#_bookmark39)]). In a fifty-year-old juniper stand in the U.S. Great Plains Flint Hills, aboveground carbon (C) was reported to contain roughly 64,090 kg C *ha*−1 ([Norris et al.](#_bookmark48) [[2001a](#_bookmark48),[b](#_bookmark49)], [McKinley et al.](#_bookmark34) [[2007](#_bookmark34)]). By contrast, an adjacent native grassland held an estimated 1660 kg aboveground C *ha*−1 at peak growing season ([Knapp](#_bookmark29) [et al.](#_bookmark29) [[1998](#_bookmark29)]).

The effect of afforestation on belowground, i.e., soil C stores is less understood, but essential from an offset generation perspective: if afforestation carbon shifts aboveground where it is vulnerable to fire loss, the effect would be, at minimum, no net gain of ecosystem C while incurring losses of other grassland ecosystem services. If afforestation intrinsically reduces soil C, subsequent fire loss would represent a net loss of ecosystem carbon, depending on the probability of tree loss to wildfire. C. Intrinsic changes in soil carbon Soil C storage equilibria can be understood as the result of physico-chemical adsorption of C to soil mineral surfaces ([Hassink and Whitmore](#_bookmark21) [[1997](#_bookmark21)]), physical protection of C in soil aggregates, the biochemical complexity of the C molecules themselves, and environmental limits on biological activity ([Baldock and](#_bookmark16) [Skjemstad](#_bookmark16) [[2000](#_bookmark16)], [Birge et al.](#_bookmark0) [[2015](#_bookmark0)]). In addition to consistently lower soil C stocks in native forest versus grassland ecosystems ([Schlesinger](#_bookmark30) [[1977](#_bookmark30)], [Lal](#_bookmark32) [[2005](#_bookmark32)], [Conant](#_bookmark4) [[2011](#_bookmark4)]), intrinsic soil C saturation equilibria (fig. 1) have been detected to shift in some systems following changes in ecosystem processes (e.g., nutrient fertilization ([Russell](#_bookmark27) [[1960](#_bookmark27)]), indicating that soil C storage limits can plausibly shift in response to change in plant cover. If saturation equilibria do shift in response to afforestation, the reversibility of that shift following tree removal is unknown (fig. 2). A meta-analysis ([Post and Kwon](#_bookmark20) [[2000](#_bookmark20)]) showed soil C response to afforestation ranging from -0.141 to 0.617 Mg C *ha*−1*yr*−1 in response to afforestation, with much of the response variability predicted by tree species, soil texture, and environmental conditions. A different meta-analysis ([Guo](#_bookmark19) [and Gifford](#_bookmark19) [[2002](#_bookmark19)]) reported 25 percent greater soil C gains in afforested cropland versus grassland, and a review from Paul ([Paul et al.](#_bookmark51) [[2001](#_bookmark51)]) reported higher soil C in afforested cropland but a decreasein soil C when grasslands were afforested. [Barger et al.](#_bookmark17) ([2011](#_bookmark17)) reported similar variability in soil C response to afforestation and [Jackson et al.](#_bookmark24) [[2002](#_bookmark24)] reported that moisture levels change whether grassland afforestation leads to a net gain or loss of whole ecosystem carbon.

While the effect of afforestation on soil carbon storage, and the impact of fire on soil is largely indirect (e.g., through charcoal inputs ([Skjemstad et al.](#_bookmark33) [[1996](#_bookmark33)]) and shifts in aboveground plant communities (e.g., [Rice et al.](#_bookmark25) [[2008](#_bookmark25)])), there is a large difference in ecosystem carbon loss when a grassland (with an estimated 1660 kg aboveground C *ha*−1, [Knapp et al.](#_bookmark29) [[1998](#_bookmark29)]) versus a juniper woodland (with an estimated 64,090 kg aboveground C *ha*−1, [Norris et al.](#_bookmark49) [[2001b](#_bookmark49)]) burns.

1. **Afforestation and wildfire cost**

The allocation of ecosystem C to the aboveground pool following grassland afforestation leaves that C vulnerable to fire-related loss over the longer term (i.e., 10+ years) ([Harmon](#_bookmark22) [[2001](#_bookmark22)], [Donovan et al.](#_bookmark7) [[2017](#_bookmark7)]). In the U.S. Great Plains, mature juniper forest fires are disproportionality more difficult to suppress relative to their grass fire counterparts and more likely to become uncontrolled wildfires that negatively impact infrastructure, private property, and public health ([Finney et al.](#_bookmark10) [[2011](#_bookmark10)], [Twidwell](#_bookmark37) [[2012](#_bookmark37)], [Twidwell et al.](#_bookmark40) [[2016](#_bookmark40)]). In the 2018 fire season, wildfire costs to the State of California alone were estimated at $148.5 (126.1–192.9) billion, or approximately 1.5 percent of the state’s annual $3 trillion GDP ([Wang et al.](#_bookmark44) [[2021](#_bookmark44)]). This figure includes direct costs, such as fire suppression costs and infrastructure destruction, and indirect costs such as human health impacts, lost livestock forage, and a depleted rural tax base. In the 2012 fire season, Nebraska wildfires burned more than 500,000 acres, destroying over 60 structures, and incurring fire suppression costs alone of nearly $12 million ([Nebraska](#_bookmark45) [Forest Service](#_bookmark45) [[2012](#_bookmark45)]). This single, direct cost (versus the myriad direct and indirect costs of California fires) equates to roughly 4 percent of the State of Nebraska’s entire 2012 budget ([Nebraska Legislature](#_bookmark46) [[2012](#_bookmark46)]). While California wildfires occur predominantly in chaparral and forest ecosystems, and there is no guarantee that afforested grasslands will burn the same way, these figures are provided to benchmark the diversity and magnitude of potential cost associated with wildfire suppression. The U.S. Department of Commerce estimates the annual national cost of wildfires to be $71.1 billion to $347.8 billion.

Afforestation of U.S. Great Plains grasslands increases wildfire risk in a region without the historical precedent or infrastructure to manage such events ([Andrews and Rothermel](#_bookmark14) [[1982](#_bookmark14)], [Bidwell et al.](#_bookmark18) [[2008](#_bookmark18)], [Twidwell et al.](#_bookmark38) [[2013](#_bookmark38)], [Donovan et al.](#_bookmark7) [[2017](#_bookmark7)]), and presents material economic, ecological, and social risk to rural communities.

# The Potential Magnitude of Afforestation

A reanalysis of data from a study by [Nielsen et al.](#_bookmark8) ([[2014](#_bookmark8)]) indicates that an additional 61.2 million acres of rangeland, 12.8 million acres of pasture land, and 15.3 million acres of cropland could be afforested in the United States under a scenario in which carbon credits are priced at 50 USD metric ton-1 C. In this scenario, nearly half of the carbon sequestered from afforested lands (93.7 of the 200 M tons) comes from rangeland, i.e., previously grassland acres (fig. 3), and much of this rangeland is concentrated in the U.S. Great Plains, where grasslands are already imperiled by conversion to cropland, fragmentation by urban and suburban sprawl, and suppression of reinforcing ecological processes of fire, flood, and native grazing regimes.

# Conclusion

U.S. Great Plains grassland afforestation may initially appear to be a cost effective NCS pathway to generate the carbon offsets needed by governments, companies, and other entities to reach their decarbonization targets. Yet the social and ecological costs of grassland afforestation in the U.S. Great Plains include increased vulnerability to wildfires, loss of critical habitat for increasingly rare grassland species, loss of forage production, and, potentially, the long-term (10+ year) carbon storage itself, especially if afforestation reduces soil carbon storage equilibria and wildfire occurs. Including non-carbon related ecosystem services considerations in the scoping phase of an NCS project is therefore critical for carbon offset registries and project developers to align with the Greenhouse Gas Protocol’s requirements of quality offset generation, which is to generate durable carbon offsets without incurring net harm for the people and ecology from whence those offsets are created.

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Diagram

Description automatically generated

**Figure 1:** Soil carbon I is a more stable, fire resistant form of ecosystem carbon storage relative to aboveground tree biomass, and its net storage capacity is determined by the type of plant carbon inputs (*Ix*) (left panel), and a soil’s intrinsic storage limits (i.e., when inputs and release in equilibrium) (right panel). As inputs increase, remaining storage capacity decreases. The greyed area in both panels shows gains in soil carbon when inputs increase. Intrinsic limits to carbon storage are understood to be the result of physico-chemical adsorption of C to clay surfaces ([Hassink](#_bookmark21) [and Whitmore](#_bookmark21) [[1997](#_bookmark21)]), physical protection of C in soil aggregates, the biochemical complexity or recalcitrance of the C inputs themselves, and other environmental limits on biological activity ([Baldock and Skjemstad](#_bookmark16) [[2000](#_bookmark16)], [Birge et al.](#_bookmark0) [[2015](#_bookmark0)]). Figures adapted from [Stewart et al.](#_bookmark36) ([[2007](#_bookmark36)]).

A picture containing diagram

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**Figure 2:** Alternate scenarios of afforestation on soil carbon stocks over time with supporting literature and the predicted change in soil carbon storage equilibria according to the carbon saturation hypothesis. The scenarios include increased soil carbon (top; highlighted in green), no change in soil carbon (middle; highlighted in yellow) and decrease in soil carbon (bottom; highlighted in red) following grassland afforestation. Overall quantity and source of soil carbon (grassland vs forest) shifts subtly in each scenario, also according to the carbon saturation hypothesis ([Stewart et al.](#_bookmark36) [[2007](#_bookmark36)]).

**Map

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**Figure 3:** Rangeland acres converted to afforestation when carbon is priced at $50 per metric ton C. Reanalyzed from  [Nielsen et al.](#_bookmark8) [[2014](#_bookmark8)].

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