Trends in
Ecology & Evolution

CellPress
OPEN ACCESS

Science & Society

A trillion trees: carbon capture or fuelling fires?

Nicola Stevens[1,2,@,*] and William J. Bond[3,4]

Afforesting grassy systems for carbon gain using flammable plantation trees could shift the fire regime from lower intensity grass-fuelled fires to high-intensity crown fires. Future changes in climate will worsen this. We highlight the fire risk of trees planted for carbon and costs of fire protection using African examples.

Tree planting as a nature-based solution

Tree planting has been widely advocated as a nature-based solution (NBS) to global warming [1]. Large areas of open (nonforested) ecosystems have been identified as suitable for tree planting as they have the greatest potential for increasing aboveground biomass [1] (see [2] for map for potential afforestation of grassy ecosystems in Africa). Africa's extensive grassy ecosystems are targeted because tree cover is below its climate-limited potential [1]. However, despite the well-documented benefits of restoring natural forests, afforestation of natural open ecosystems negatively impacts biodiversity, catchment cover, water resources, land use, and livelihoods [3]. Despite objections to the science behind the optimistic carbon estimates, ambitious targets and proposals continue to promote mass-scale tree planting in these regions, many of which aim to increase tree cover through agroforestry and plantations [4].

Carbon stored in grassy ecosystems is not as well studied as forest carbon. Current estimates are that grassy ecosystems store ~20–40% of the world's carbon with ~90% of it being stored belowground [5]. Soil storage contributes to a persistent carbon store as root carbon inputs can have a higher soil organic carbon stabilisation efficiency (five times greater than aboveground carbon inputs) [5]. Switching from a grassy ecosystem has consequences for long-term carbon storage. Trees shade out grasses, causing the loss of an effective source of belowground carbon as up to 70% of the soil organic carbon is derived from grass [6]. While models of carbon sequestration by afforestation assume that increasing tree cover increases both aboveground and belowground carbon [1], the changes of belowground carbon may be negligible [6]. Establishing plantations in grassy ecosystems increases the proportion of aboveground carbon exposed to disturbances such as drought and fire, increasing the proportion of carbon vulnerable to loss. Critically this shift can act to change the fire regime. Afforestation in grassy ecosystems represents a switch in fuel type from grass to trees. As the vast majority of the world's grassy ecosystems fall in a climate space that facilitates fire [7], planting fast growing trees such as eucalypts and conifers risks shifting the fire regime from low-intensity grass-fuelled surface fires to high-intensity crown fires [8].

Climate change is increasing the severity of fire weather and fire season length, and recent major wildfires have been linked to extreme fire weather conditions likely due to climate change [7]. With the increase of fire-prone weather, afforestation in already fire-prone grassy environments [9] is effectively adding 'fuel to the fire' and will contribute to more intense and severe fires than would occur in naturally grassy or shrubby ecosystems. Fireline intensity can increase several fold from grass to tree-fuelled fire greatly increasing the difficulty of fighting fires. For example, high-intensity fires in a Texan savanna ranged from 4000 to 4300 kW/m versus high-intensity crown fires under extreme weather in *Juniperus ashei*-invaded savannas with >23 879 kW/m [10]. Megafires in Chile and Portugal, for example, were concentrated in conifer and eucalypt plantations rather than native flammable shrubby ecosystems where fires would be less intense [7]. Unless considerable effort is spent on fire protection for the decades necessary to accumulate growth (carbon) before felling, tree-planting projects are at risk of burning down. It is astonishing that this major threat to sequestering carbon by tree planting is overlooked in global analyses [1,2].

The costs of suppressing fires have seldom been considered by tree planting advocates. The Bonn challenge aims to forest 3.5 million km^2 by 2030, with 1 million km^2 in Africa. The World Bank is contributing a billion US dollars to afforestation and an additional 0.5 billion dollars has been promised[i]. If all of this was to go to Africa, there would be $15 per hectare (ha) to plant the trees. For effective carbon sequestration, the trees would need to be maintained, and new plantations established, every decade or two to maintain high carbon uptake. Just how the maintenance of the plantations would be financed is not clear as funding essentially covers only planting.

As an indicator of the maintenance costs involved, South African plantation forestry provides a guide (for other African examples, see [11,12]). South Africa's plantations of conifers and eucalypts were established in flammable native grasslands. Trees are harvested at regular intervals thereby maintaining high productivity and carbon is sequestered and sold as forest products. In a report on the forest industry as of 2019[ii], ~1.2 million ha of mostly pines and eucalypts have been planted (~1% of the country's land area). Forestry employed ~150 000 people in 2019, contributing up to 2.5% of the country's gross domestic product (GDP) between 1980 and 2019 with exports valued at $2.1 billion in 2018.

Fire was the major cause of damage to plantations accounting for a total of 698 900 ha (58.7% of the total damaged area) from 1980 to 2019. This is over half the total plantation area. This is despite large expenditure on forest fire protection estimated (2019) as $35–$50 per ha per year in different regions. These costs cover insurance, labour, contractors, aerial standby teams, etc. and aimed to prevent fires from happening and from spreading from the adjacent areas. Firefighting, when fires do break out, costs ~$4.5–$9.00 per ha per year for 2019 (values assume exchange rate for 2019 of ZAR14.43 per US dollar). Thus, for the Bonn challenge, $15 per ha might look like a bonanza for planting trees, but is far too little to support subsequent fire protection, let alone all the other costs of managing, harvesting, and repeat plantings of plantations for the foreseeable future. From the South African forestry figures, African countries will be expected to come up with two to four times more funding, every year, than that provided by current international funders just for fire protection.

Even with significant expenditure on sophisticated fire protection, plantations do burn. Pines and eucalypts can generate high-intensity crown fires far more severe than grassland fires. Recent events have shown that even the best resourced countries, such as Australia, find forest fire suppression almost impossible in the age of climate change-induced megafires [7]. This suggests that with changing fire weather we are entering an era where fire management and prevention in flammable systems is almost impossible [7] – something that needs serious consideration when weighing up the benefits of afforestation programs.

What happens when these intense, often stand-replacing crown fires sweep through plantations in previously nonforested areas? A particular area of concern is that on watershed condition. Low-severity grass-fuelled fires rarely produce significant effects, but high-severity forest fires can alter the hydrology and soil erosion rates substantially (Box 1) [13]. High-severity stand-replacing forest fires cause an almost complete loss of tree cover and litter, leaving behind a bare soil surface, and increases the water repellency of the soil in some landscapes [13]. This causes a decrease in soil water infiltration, increased overland water flow, and increases in storm peak flows driving increased soil

Box 1. Low river sediment loads in an African montane grassland contrasting with high erosion from a burnt forestry plantation

Montane grasslands are often targeted for plantation forestry in Africa. Erosion rates following tree planting in grassy catchments have seldom been measured. A rare example, from the Drakensberg of South Africa, shows contrasting rates after a fire swept through a *Pinus patula* (Mexican weeping pine) plantation 26 years after establishment (Figure I). Grasslands, whether protected from fire or burnt, lost very little sediment [<2 megagram per hectare (Mgha)$^{-1}$ per annum] contrasting with 37 Mgha^{-1} per annum from the burnt plantations rising to a maximum of more than 1000 times greater (4162 Mgha^{-1}) during a spate after the burn (Figure II). High erosion rates are a common feature of burnt conifer and eucalypt forests more generally contrasting with very low erosion from perennial grasslands [13].

Trends in Ecology & Evolution

Figure I. Plantation fires can cause major erosion if burnt. Stilling pools for recording stream flow from gauged catchments in the Drakensberg, South Africa, show left: from a natural grassland burnt every second year, versus right: from a *Pinus patula* plantation after a 1981 wildfire. This stilling pool filled with silt, rubble, and boulders and was abandoned. Photo credits: adapted with permission from W.J. Bond (left) and E. Granger (right).

CellPress OPEN ACCESS

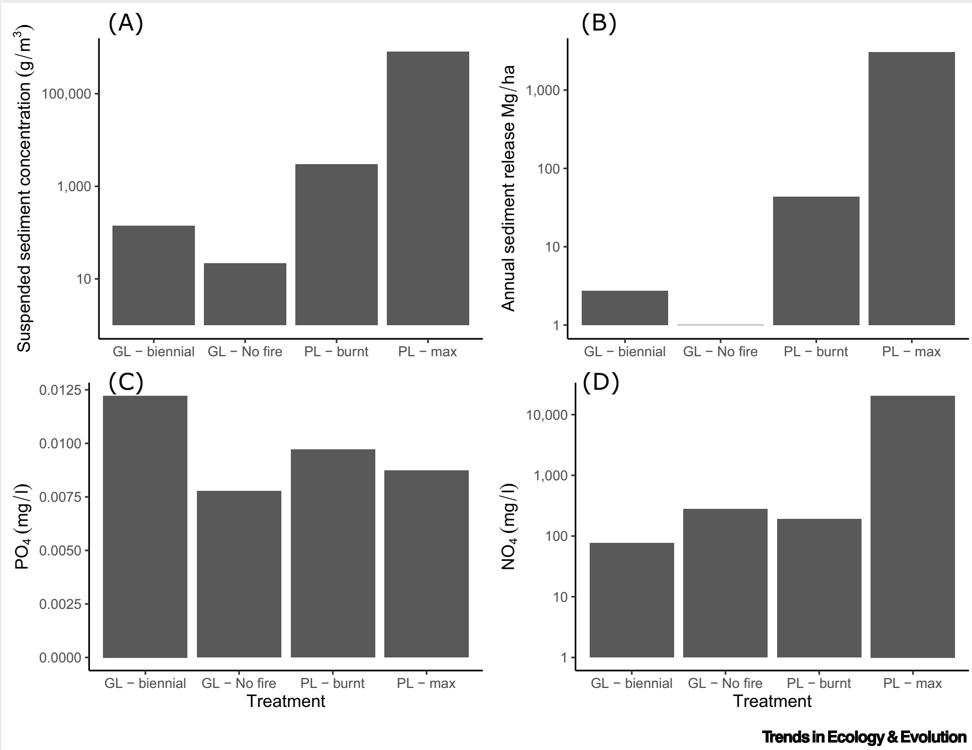

Figure II. Plantation fires trigger heavy erosion relative to frequently burnt native grasslands. (A) Suspended sediment concentration in runoff after the fire. (B) Sediment yield from each catchment. (C) Phosphate concentrations (mg/l) and (D) nitrate concentrations (mg/l) in water samples in streamflow from Cathedral Peak catchments. Landcover classes in figure are: GL – biennial = grassland burnt biennially, GL – No fire = grassland protected from fire, PL – burnt = *Pinus patula* plantation burnt during the sampling, PL – max = sediment during a spate. Note that the *y* axis for plot (A), (B), and (D) are on a logarithmic scale. Sampling was from 1980 to 1983. The fire burnt the pine plantation in September 1981. Data obtained from van Wyk [15].

erosion that is orders of magnitude greater than baseline rates (Box 1) causing declines in water quality [13].

The increased extent of plantation 'forest' in grassy ecosystems coupled with an increase in the probability of extreme fire weather means that more biomass will burn relative to the original grassy state and plantation fires will become more frequent. Climate change may also prolong the time needed for full carbon stock recovery [7]. These long-term carbon losses after unexpected 'forest' fires should be weighed against estimates of potential carbon gain by planting trees as widely promoted globally as an NBS to climate change.

Finally, what happens after the fires – will severely burnt areas be replanted, restored, or abandoned? The action of afforesting a grassy ecosystem results in significant land transformation, recovery to the natural grassy state and its biodiversity is difficult and slow. Following a fire, a burnt plantation seldom returns back to its natural state leaving the land in a newly degraded and transformed state with probable (but poorly quantified) carbon losses.

NBSs need to account for fire

Tree planting projects in previously open ecosystems using non-native flammable species such as pines and eucalypts should not be allowed to begin, or continue, unless the projections for future plantation management, and especially fire protection, have been planned and suitable funding models developed. Without adequate funding, and the skills and technology to protect plantations far into the future, investment in tree planting has a high probability of going up in smoke while adding more carbon to the atmosphere as the trees burn.

Well-planned and executed commercial and state forestry programmes can contribute significantly to national economies. But afforestation of grassy ecosystems with highly flammable non-native plantation trees has long-term costs far exceeding initial planting costs. These costs and consequences of tree planting as 'Natural Climate Solutions' to global change need careful scrutiny by those committing their land to major land transformation. Targeting deforested and denuded formerly forest areas offers considerable scope for carbon sequestration and restoration with native species in parts of Africa and South America [14]. However to reduce the risk of inappropriate NBS, it also demands revision of the historical misclassification of African grassy ecosystems which has resulted in large-scale inappropriate 'forest' restoration.

Acknowledgments

We thank Ed Grainger and Colin Everson for information on the Cathedral Peak fire and Tiaan Pool for South Africa forestry report. N.S. was funded by the Trapnell Fund and Linacre College, University of Oxford. We thank the reviewers for helpful comments.

Declaration of interests

No interests are declared.

Resources

[i]https://afr100.org/partners

[ii]https://forestrysouthafrica.co.za/wp-content/uploads/2020/11/FSA-Annual-report-2019-colour.pdf

[1]Environmental Change Institute, School of Geography and the Environment, University of Oxford, Oxford, UK
[2]Centre for African Ecology, School of Animal, Plant, and Environmental Sciences, University of the Witwatersrand, Wits, Johannesburg, 2050, South Africa
[3]Department of Biological Sciences, University of Cape Town, Cape Town, South Africa
[4]South African Environmental Observation Network, National Research Foundation, Claremont, South Africa

*Correspondence:
nicola.stevens@ouce.ox.ac.uk (N. Stevens).
[@]Twitter: @nicola_stvns

https://doi.org/10.1016/j.tree.2023.09.015

References

1. Bastin, J.-F. *et al.* (2019) The global tree restoration potential. *Science* 365, 76–79
2. Bond, W.J. *et al.* (2019) The trouble with trees: afforestation plans for Africa. *Trends Ecol. Evol.* 34, 963–965
3. Veldman, J.W. *et al.* (2015) Where tree planting and forest expansion are bad for biodiversity and ecosystem services. *BioScience* 65, 1011–1018
4. Martin, M.P. *et al.* (2021) People plant trees for utility more often than for biodiversity or carbon. *Biol. Conserv.* 261, 109224
5. Bai, Y. and Cotrufo, M.F. (2022) Grassland soil carbon sequestration: current understanding, challenges, and solutions. *Science* 377, 603–608
6. Zhou, Y. *et al.* (2023) Soil carbon in tropical savannas mostly derived from grasses. *Nat. Geosci.* 16, 1–7
7. Bowman, D.M. *et al.* (2020) Vegetation fires in the Anthropocene. *Nat. Rev. Earth Environ.* 1, 500–515
8. Archibald, S. *et al.* (2013) Defining pyromes and global syndromes of fire regimes. *Proc. Natl. Acad. Sci. U. S. A.* 110, 6442–6447
9. Jones, M.W. *et al.* (2022) Global and regional trends and drivers of fire under climate change. *Rev. Geophys.* 60, e2020RG000726
10. Scholtz, R. *et al.* (2022) High-intensity fire experiments to manage shrub encroachment: lessons learned in South Africa and the United States. *Afr. J. Range Forage Sci.* 39, 148–159
11. Jimu, L. and Nyakudya, I.W. (2018) Fires in exotic forest plantations of Zimbabwe: causes and management strategies. *World Dev. Perspect.* 9, 56–58
12. Andrew, S.M. (2022) Drivers, trends and management of forest plantation fires in Tanzania. *Trees For. People* 10, 100355
13. Shakesby, R.A. and Doerr, S.H. (2006) Wildfire as a hydrological and geomorphological agent. *Earth-Sci. Rev.* 74, 269–307
14. Holl, K.D. and Brancalion, P.H. (2020) Tree planting is not a simple solution. *Science* 368, 580–581
15. Van Wyk, D.B. (1985) The effects of catchment management on sediment and nutrient exports in the Natal Drakensberg. In *Proceedings of the Second South African National Hydrology Symposium, Pietermaritzburg*, pp. 16–18