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• REPORT

Trading Water for Carbon with Biological Carbon Sequestration

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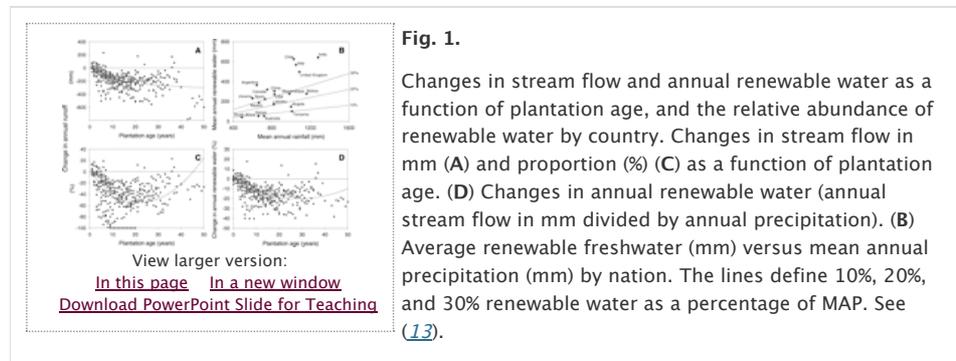
ABSTRACT

Carbon sequestration strategies highlight tree plantations without considering their full environmental consequences. We combined field research, synthesis of more than 600 observations, and climate and economic modeling to document substantial losses in stream flow, and increased soil salinization and acidification, with afforestation. Plantations decreased stream flow by 227 millimeters per year globally (52%), with 13% of streams drying completely for at least 1 year. Regional modeling of U.S. plantation scenarios suggests that climate feedbacks are unlikely to offset such water losses and could exacerbate them. Plantations can help control groundwater recharge and upwelling but reduce stream flow and salinize and acidify some soils.

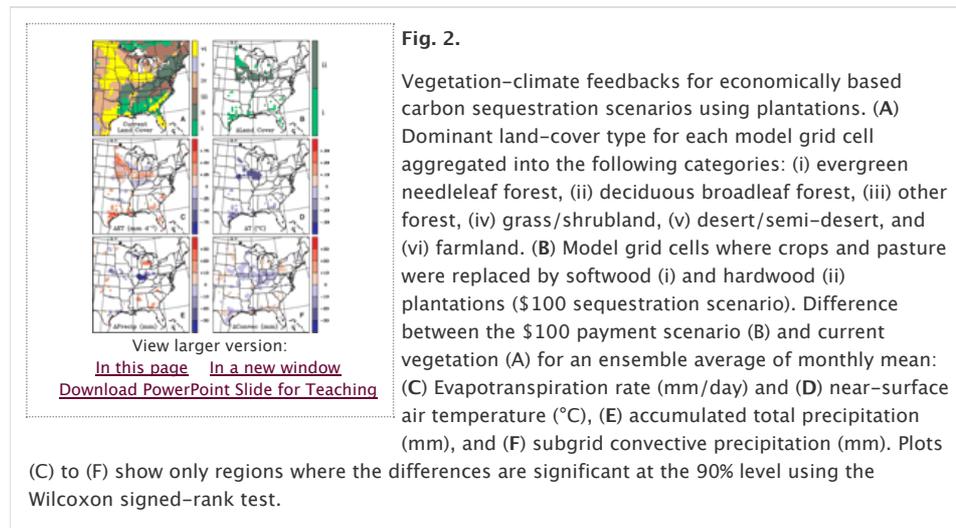
Tree plantations feature prominently among tools for carbon sequestration ([1–8](#)). Plantations typically combine higher productivity and biomass with greater annual transpiration and rainfall interception, particularly for evergreen species such as pines and eucalypts ([9–12](#)). In addition to influencing water budgets, plantations require additional base cations and other nutrients to balance the stoichiometry of their extra biomass. In consequence, trade-offs of sequestration with water yield and soil fertility, including nutrient depletion and increased acidity, are likely. The goal of our research was to account for the trade-offs and benefits of carbon sequestration, identifying potential problems and management needs for a sustainable sequestration policy. We examined changes in hydrology and biogeochemistry with afforestation, using global synthesis data, fieldwork, and regional modeling. We evaluated the extent to which plantations altered water yield, soil chemistry, and acidity at plot (ha), catchment (ha to km²), and regional (>10⁴ km²) scales, comparing environmental benefits of carbon sequestration with effects on other environmental services ([13](#)).

Our global analysis of 504 annual catchment observations shows that afforestation dramatically decreased stream flow within a few years of planting ([Fig. 1, A and C](#)) ($P < 0.0001$). Across all ages in the database, afforestation of grasslands, shrublands, or croplands decreased stream flow by 180 mm

year⁻¹ and 38% on average (Fig. 1) ($P < 0.001$). After slight initial increases in some cases (Fig. 1), substantial annual decreases of 155 mm and 42% were observed on average for years 6 to 10, and average losses for 10- to 20-year-old plantations were even greater, 227 mm year⁻¹ and 52% of stream flow (Fig. 1, A and C). Perhaps most important, 13% of streams dried up completely for at least 1 year (Fig. 1C), with eucalypts more likely to dry up streams than pines. Afforestation in drier regions [<1000 mm mean annual precipitation (MAP)] was more likely to eliminate stream flow completely than in wetter regions. Mean annual renewable water (percentage of annual precipitation lost as runoff) decreased ~20% with afforestation (Fig. 1D) ($P < 0.0001$). For many nations with total annual renewable freshwater $<30\%$ of precipitation (Fig. 1B), afforestation is likely to have large impacts on water resources.



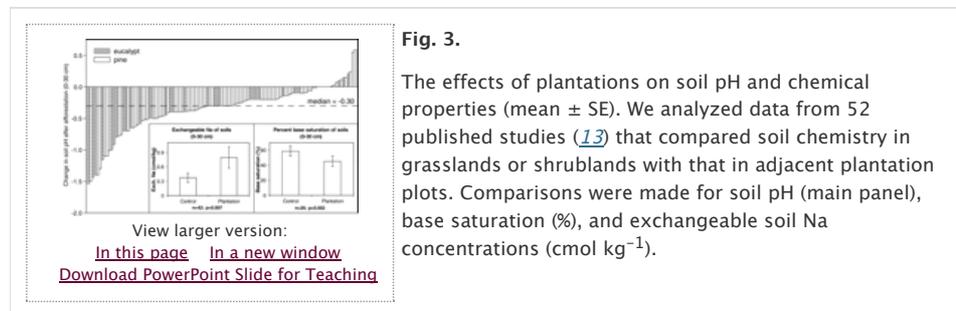
Climate feedbacks at regional scales could potentially offset some of these water losses through increased transpiration and convective rainfall (14-17), depending on site location, climate, and biophysical characteristics. To assess potential climate feedbacks, we first used the Forest and Agricultural Sector Optimization Model-Greenhouse Gases (FASOMGHG) (7, 18) to estimate the U.S. lands projected to convert to plantations for C sequestration payments of 50 and 100 \$US per Mg C (13); at a simulated price of \$100 per Mg C, FASOMGHG estimates that 72 million ha of land would initially convert to forestry from nonirrigated agriculture and pasture (Fig. 2, A and B). We then used the Regional Atmospheric Modeling System (RAMS) (19) to examine potential hydroclimate feedbacks using these economically based scenarios of land-use change (13).



On the basis of simulations for the United States, the higher water use of plantations and decreased stream flow is unlikely to be offset by atmospheric feedbacks operating at larger scales (Fig. 2). Climate simulations showed that plantations typically increased summer evapotranspiration (ET) by >0.3 mm day⁻¹ and decreased both summer surface air temperature by as much as 0.3°C and precipitation by as much as 30 mm per month in the most densely afforested areas, compared with the crop and pasture lands they replaced (Fig. 2) ($P < 0.10$ for each). No evidence for increased rainfall from local convection was observed with afforestation except in northern Florida and southern Georgia (Fig. 2). Increased ET did not generate more rain because, unlike in the tropics (17, 20), the temperate regions modeled here did not have sufficient energy to lift the additional atmospheric moisture high enough to condense and form clouds. Furthermore, the lack of sensible heating over plantations reduced the energy available for convection, reducing rainfall in general and the convective component in particular (Fig. 2F).

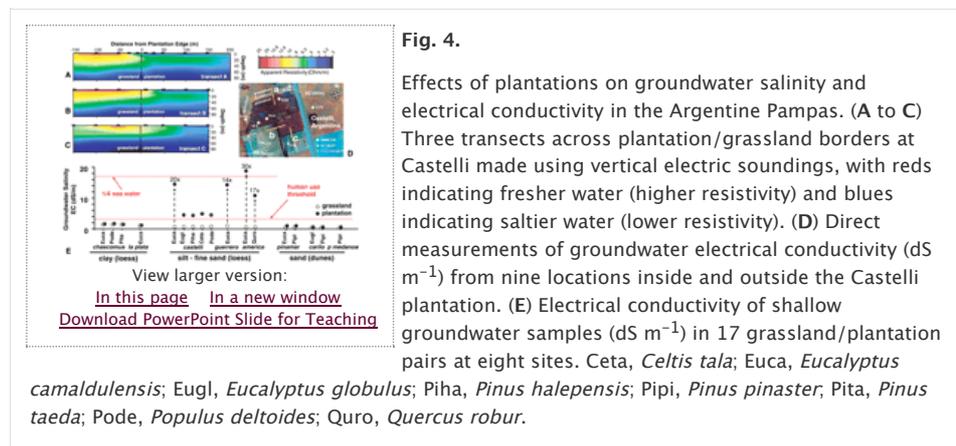
Plantations not only have greater water demands than grasslands, shrublands, or croplands, they typically have increased nutrient demands as well. These demands change soil chemistry in ways that affect fertility and sustainability. Global synthesis data show that the afforestation of grasslands or shrublands significantly increased Na concentrations, exchangeable sodium percentage (ESP), and soil

acidity and decreased base saturation, suggesting potential soil salinization and sodicity in some cases (Fig. 3). Saturation of the soil exchange complex with bases decreased by one-quarter on average for 26 paired observations globally (from 59% to 45%; $P = 0.002$) (Fig. 3). Declines in exchangeable Ca, Mg, and K caused this result, because exchangeable Na doubled across 42 paired observations ($P = 0.007$) (Fig. 3). In addition, exchangeable sodium percentage more than doubled for 36 pairs, increasing on average from 3.4% to 7.8% in plantations ($P = 0.001$). ESP increased in 29 of 36 pairs globally, in four cases crossing the severe sodic threshold of 15% associated with physical degradation of soils. Differences in nutrient cycling, root depth distributions, and water consumption between plantations and native vegetation (9-12, 21, 22) likely explained these patterns, with Ca, Mg, and K redistributed from soil to biomass pools and Na excluded by roots and concentrated in the soil (22).



In addition to redistributing and excluding soil nutrients, plantations produce acidic litter, canopy leachates, and decomposition products. Globally, plantation soils were more acidic in 98 of 114 cases, with afforestation resulting in a median decrease of 0.3 pH units ($P < 0.0001$) (Fig. 3). Declines of 0.5 to 1.6 pH units were observed in a quarter of observations (Fig. 3). Plantations that did not acidify soils tended to grow on highly buffered parent material such as limestone.

The dual characteristics of increased water use and higher nutrient demands quantified above should help scientists and land managers predict the environmental costs and benefits of plantations. In some regions, establishing extensive plantations can have strong negative effects on soil fertility and salinity (Fig. 4). For example, the Pampas of Argentina, one of the world's largest uncultivated grasslands, has brackish groundwater under shallow freshwater lenses that provide drinking water (22). Our vertical electric sounding (VES) measurements along three grassland-to-plantation transects show eucalypts eliminating this freshwater lens, with decreased resistivity at the plantation boundary and higher electrical conductivity (EC) and salinity in plantation groundwater (Fig. 4, A to D). The VES transect data were confirmed by direct sampling of groundwater chemistry from wells and boreholes showing EC under plantations to be larger by a factor of 15 compared with the surrounding grasslands and agricultural fields ($P < 0.001$) (Fig. 4D).



Additional analyses at eight sites across the Pampas using 17 paired native grassland and plantation stands revealed that the observed salinization was independent of tree species planted but depended strongly on soil texture (Fig. 4E). Intermediately textured loess soils showed 10-fold increases in salinity (Fig. 4E); finer soils likely had hydraulic conductivities too low for sufficient lateral movement of groundwater, and coarser soils underwent sufficient leaching of salts through the rooting zone to remove salt buildup. Increased salinity in intermediately textured soils occurred through at least two mechanisms. One was the buildup of salts, such as Na and Cl, excluded by tree roots. The other was upwelling of saline groundwater. These mechanisms have been linked to >5 -fold increases in groundwater salinization in southern Australia (23) and in the Caspian steppes of Russia (24). Grassland and agricultural regions around the world with shallow groundwater and similar intermediately textured soils include Hungary's Hortobágy grasslands, Russia's western Siberian steppes, and the eastern Chaco croplands of Paraguay and Argentina (22). We predict that plantations

could salinize soils in these locations as well if planted broadly.

A different situation is found in some other regions, where reforestation and afforestation can improve water quality. A notable example is the extensive eucalypt woodlands of southwestern Australia, where 4.4 Mha of lands are negatively affected by salinity. This salinization is attributed to increased groundwater recharge and rising water tables after the conversion of woodlands to agriculture. Afforestation and reforestation in southwestern Australia therefore have the dual environmental benefits of carbon sequestration and increased water use, reducing recharge, lowering water tables, and reversing dryland salinization associated with agriculture (25). Widespread conversion of croplands to forest in the central U.S. farm belt may also improve regional water quality as nutrient, pesticide, and erosion runoff from crop production is reduced (26).

General trends in water use and soil chemistry found in our global analyses and field work must be adjusted to include local factors, including site history, soil texture, and the availability and quality of groundwater. In regions such as southern Australia and the African Sahel, plantations are being used successfully to keep saline groundwater below crop rooting zones, although the recovered area is often a small proportion of the original area (27). Plantations are also being used successfully to help dry waterlogged soils and alleviate flooding (27, 28). The co-benefits of reforestation on water and soil resources may be the greatest where former forests have been replaced by crops, potentially restoring water quality and recharge to pre-agricultural levels (28). Reforestation of floodplains can also be beneficial for maintaining biodiversity, reducing erosion, improving water quality, mitigating peak flows, and controlling groundwater discharge (upwelling).

These cases contrast with monoculture plantations that maximize carbon sequestration but have considerable impact on runoff and groundwater recharge, as shown in our analysis. In these situations, plantations are likely to have adverse side effects, including reduced stream flow (10, 12, 29) and decreased soil pH and base saturation. In extreme cases, salinization and sodicity are possible. Although few data are available from second-rotation plantations, these effects would likely be exacerbated after harvesting, owing to the export of cations and other nutrients off site. In the framework described above, the potential positive and negative benefits of plantations for salinity are predictable based on the presence and type of groundwater available, biophysical evaporative demand, and soil texture.

Plantations provide a proven tool for managing Earth's carbon cycle. The Clean Development Mechanism of the Kyoto Protocol allows countries to offset part of their CO₂ emissions through carbon sequestration, when consistent with a country's sustainable development objectives. New carbon trading exchanges such as the European Union's Greenhouse Gas Emission Trading Scheme help make such offsets a reality. As demand increases for land to accommodate plantations, more comprehensive environmental planning will be needed to avoid problems and to manage land successfully and sustainably. One way to do this is to compare the value of other ecosystem services gained or lost with those of carbon sequestration. The field of ecosystem services valuation is becoming increasingly sophisticated, and markets are opening up for some other services. The co-benefits and trade-offs of plantations need to be taken into account when negotiating exchange agreements. We believe that decreased stream flow and changes in soil and water quality are likely as plantations are increasingly grown for biological carbon sequestration.

Supporting Online Material

www.sciencemag.org/cgi/content/full/310/5756/1944/DC1

Materials and Methods

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References

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References and Notes

1. P. M. Vitousek, *J. Environ. Qual.* **20**, 348 (1991). [Web of Science](#)
2. R. A. Houghton, J. L. Hackler, K. T. Lawrence, *Science* **285**, 574 (1999). [Abstract/FREE Full Text](#)
3. M. I. Hoffert *et al.*, *Science* **298**, 981 (2002). [Abstract/FREE Full Text](#)
4. R. B. Jackson, J. L. Banner, E. G. Jobbágy, W. T. Pockman, D. H. Wall, *Nature* **418**, 623 (2002). [CrossRef](#) [Medline](#)
5. S. Pacala, R. Socolow, *Science* **305**, 968 (2004). [Abstract/FREE Full Text](#)
6. R. B. Jackson, W. H. Schlesinger, *Proc. Natl. Acad. Sci. U.S.A.* **101**, 15827 (2004). [Abstract/FREE Full Text](#)
7. B. A. McCarl, U. A. Schneider, *Science* **294**, 2481 (2001). [FREE Full Text](#)
8. J. A. Wright, A. DiNicola, E. Gaitan, *J. Forestry* **98**, 20 (2000).

9. A. J. Pearce, L. K. Rowe, *J. Hydrol. N. Z.* **18**, 73 (1979).
10. L. Zhang, W. R. Dawes, G. R. Walker, *Water Resour. Res.* **37**, 701 (2001).
11. M. G. R. Cannell, *New For.* **17**, 239 (1999). [CrossRef](#) [Web of Science](#)
12. K. A. Farley, E. G. Jobbágy, R. B. Jackson, *Glob. Change Biol.* **11**, 1565 (2005).
13. Materials and methods and supporting material are available on *Science Online*.
14. Y. Xue, M. J. Fennessy, P. J. Sellers, *J. Geophys. Res.* **101**, 7419 (1996).
15. R. A. Pielke, R. Avissar, *Landscape Ecol.* **4**, 133 (1990). [CrossRef](#) [Web of Science](#)
16. S. Baidya Roy, R. Avissar, *J. Geophys. Res.* **107**, (D20), 8037 (2002).
17. W. A. Hoffmann, R. B. Jackson, *J. Clim.* **13**, 1593 (2000).
18. D. M. Adame, P. I. Alio, I. M. Callaway, R. A. McCarl, S. M. Winnett, "The forest and agriculture sector optimization model (FASOM): Model structure and policy applications" (Research Paper PNW-RP-495, USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon, 1996).
19. W. R. Cotton *et al.*, *Meteor. Atmos. Phys* **82**, 5 (2003). [CrossRef](#)
20. R. E. Dickinson, P. Kennedy, *Geophys. Res. Lett.* **19**, 1947 (1992). [CrossRef](#) [Web of Science](#)
21. D. C. Le Maitre, D. F. Scott, C. Colvin, *Water S.A.* **25**, 137 (1999). [Web of Science](#)
22. E. G. Jobbágy, R. B. Jackson, *Glob. Change Biol.* **10**, 1299 (2004).
23. A. Heuperman, *Agric. Water Manage.* **39**, 153 (1999).
24. M. K. Sapanov, *Eurasian Soil Sci.* **33**, 1157 (2000). [Web of Science](#)
25. G. R. Walker, L. Zhang, T. W. Ellis, T. J. Hatton, C. Petheram, *Hydrogeol. J.* **10**, 68 (2002).
26. S. K. Pattanayak *et al.*, *Clim. Change* **71**, 341 (2005).
27. R. J. George *et al.*, *Agric. Water Manage.* **39**, 91 (1999).
28. A. J. Plantinga, J. Wu, *Land Econ.* **79**, 74 (2003). [CrossRef](#) [Web of Science](#)
29. D. F. Scott, W. Lesch, *J. Hydrol.* **199**, 360 (1997). [CrossRef](#) [Web of Science](#)
30. We gratefully acknowledge the Duke University Center on Global Change and Provost's Office, the U.S. National Science Foundation, the National Institute for Global Environmental Change of the U.S. Department of Energy, the Inter-American Institute for Global Change Research, the Andrew W. Mellon Foundation, and the CSIR for financial support. A. Mendoza assisted with the database, and W. H. Schlesinger and two anonymous reviewers provided helpful suggestions on the manuscript.

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