Trading Water for Carbon with Biological Carbon Sequestration

Robert B. Jackson,[1]* Esteban G. Jobbágy,[1,2] Roni Avissar,[3] Somnath Baidya Roy,[3] Damian J. Barrett,[4] Charles W. Cook,[1] Kathleen A. Farley,[1] David C. le Maitre,[5] Bruce A. McCarl,[6] Brian C. Murray[7]

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 km^2), and regional (>10^4 km^2) 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*).

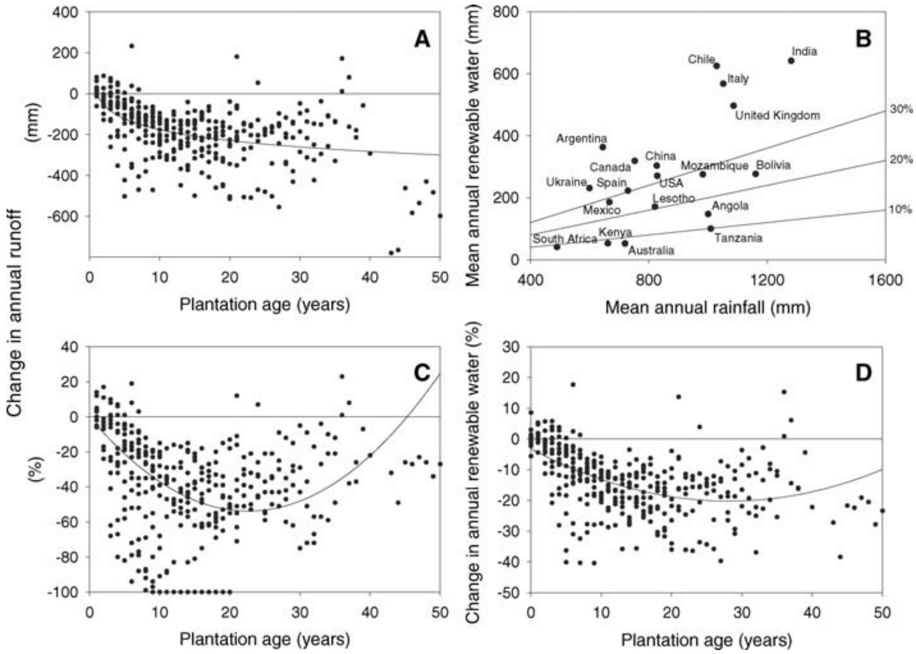

Fig. 1. Changes in stream flow and annual renewable water as a function of plantation age, and the relative abundance of renewable water by country. Changes in stream flow in mm (**A**) and proportion (%) (**C**) as a function of plantation age. (**D**) Changes in annual renewable water (annual stream flow in mm divided by annual precipitation). (**B**) Average renewable freshwater (mm) versus mean annual precipitation (mm) by nation. The lines define 10%, 20%, and 30% renewable water as a percentage of MAP. See (*13*).

[1]Department of Biology, Nicholas School of the Environment and Earth Sciences, and Center on Global Change, Duke University, Durham, NC 27708–1000, USA. [2]Grupo de Estudios Ambientales–Instituto de Matematica Aplicada de San Luis (IMASL), Universidad Nacional de San Luis and Consejo Nacional de Investigaciones Cientificas y Tecnicas (CONICET), San Luis 5700, Argentina. [3]Department of Civil and Environmental Engineering, Duke University, Durham, NC 27708, USA. [4]Commonwealth Scientific and Industrial Research Organisation (CSIRO) Land and Water, Canberra, ACT, Australia 2601. [5]Natural Resources and Environment CSIR, Stellenbosch 7599, South Africa. [6]Department of Agricultural Economics, Texas A&M University, College Station, TX 77843, USA. [7]Center for Regulatory Economics and Policy Research, Research Triangle Institute, Research Triangle Park, NC 27709, USA.

*To whom correspondence should be addressed. E-mail: jackson@duke.edu

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

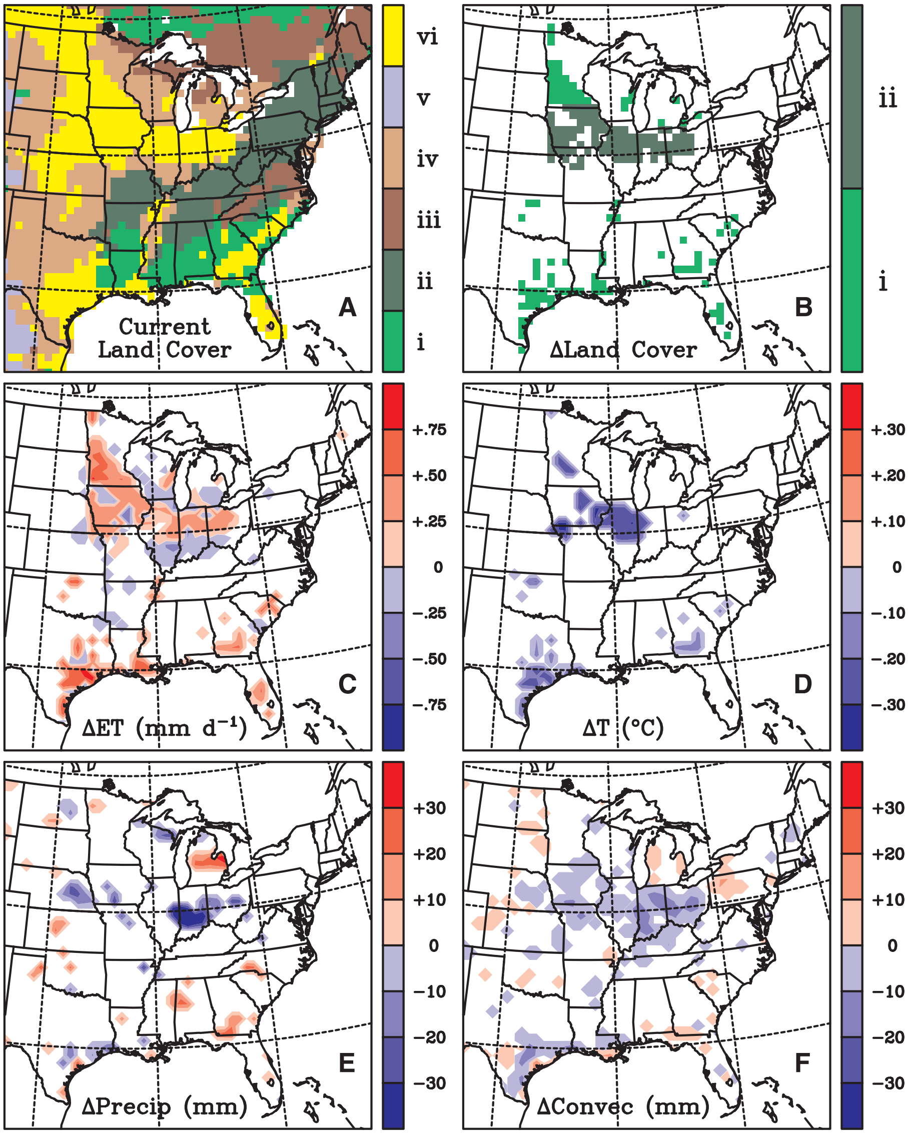

Fig. 2. Vegetation-climate feedbacks for economically based carbon sequestration scenarios using plantations. (**A**) Dominant land-cover type for each model grid cell aggregated into the following categories: (i) evergreen needleleaf forest, (ii) deciduous broadleaf forest, (iii) other forest, (iv) grass/shrubland, (v) desert/semi-desert, and (vi) farmland. (**B**) Model grid cells where crops and pasture were replaced by softwood (i) and hardwood (ii) plantations ($100 sequestration scenario). Difference between the $100 payment scenario (B) and current vegetation (A) for an ensemble average of monthly mean: (**C**) Evapotranspiration rate (mm/day) and (**D**) near-surface air temperature (°C), (**E**) accumulated total precipitation (mm), and (**F**) subgrid convective precipitation (mm). Plots (C) to (F) show only regions where the differences are significant at the 90% level using the Wilcoxon signed-rank test.

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.

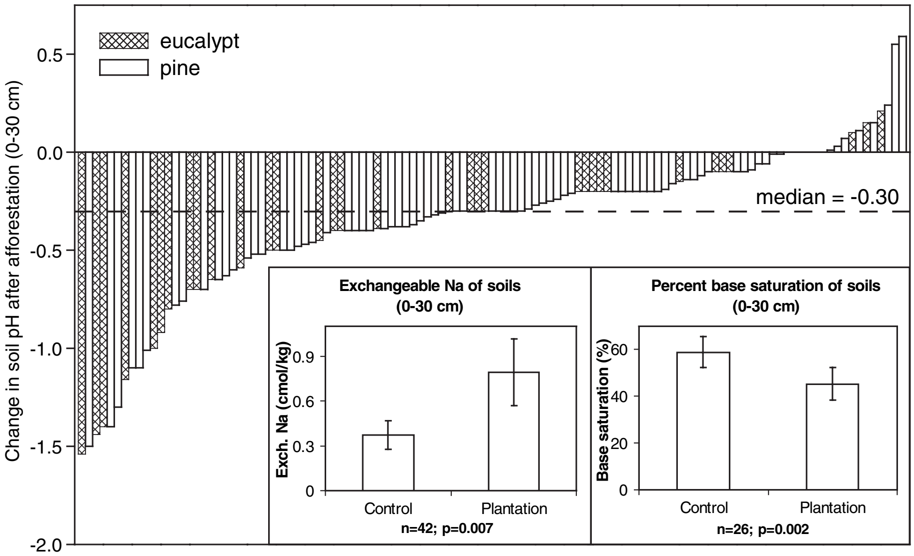

Fig. 3. The effects of plantations on soil pH and chemical properties (mean ± SE). We analyzed data from 52 published studies (*13*) that compared soil chemistry in grasslands or shrublands with that in adjacent plantation plots. Comparisons were made for soil pH (main panel), base saturation (%), and exchangeable soil Na concentrations (cmol kg^{-1}).

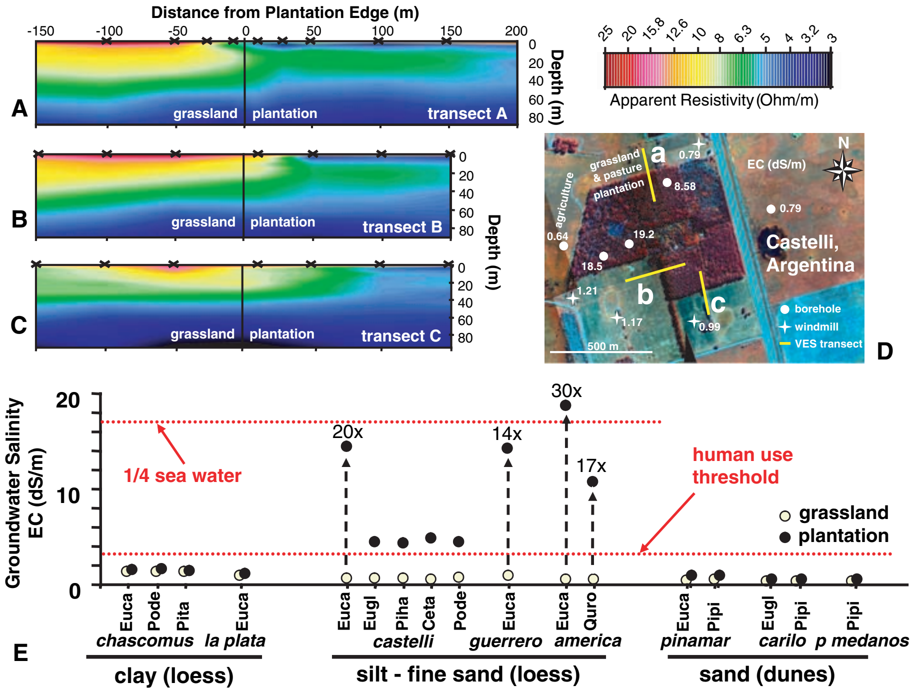

Fig. 4. Effects of plantations on groundwater salinity and electrical conductivity in the Argentine Pampas. (**A** to **C**) Three transects across plantation/grassland borders at Castelli made using vertical electric soundings, with reds indicating fresher water (higher resistivity) and blues indicating saltier water (lower resistivity). (**D**) Direct measurements of groundwater electrical conductivity (dS m^{-1}) from nine locations inside and outside the Castelli plantation. (**E**) Electrical conductivity of shallow groundwater samples (dS m^{-1}) in 17 grassland/plantation pairs at eight sites. Ceta, *Celtis tala*; Euca, *Eucalyptus camaldulensis*; Eugl, *Eucalyptus globulus*; Piha, *Pinus halepensis*; Pipi, *Pinus pinaster*; Pita, *Pinus taeda*; Pode, *Populus deltoides*; Quro, *Quercus robur*.

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 CO_2 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.

References and Notes

1. P. M. Vitousek, *J. Environ. Qual.* **20**, 348 (1991).
2. R. A. Houghton, J. L. Hackler, K. T. Lawrence, *Science* **285**, 574 (1999).
3. M. I. Hoffert *et al.*, *Science* **298**, 981 (2002).
4. R. B. Jackson, J. L. Banner, E. G. Jobbágy, W. T. Pockman, D. H. Wall, *Nature* **418**, 623 (2002).
5. S. Pacala, R. Socolow, *Science* **305**, 968 (2004).
6. R. B. Jackson, W. H. Schlesinger, *Proc. Natl. Acad. Sci. U.S.A.* **101**, 15827 (2004).
7. B. A. McCarl, U. A. Schneider, *Science* **294**, 2481 (2001).
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).
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).
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. Adams, R. J. Alig, J. M. Callaway, B. 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).
20. R. E. Dickinson, P. Kennedy, *Geophys. Res. Lett.* **19**, 1947 (1992).
21. D. C. Le Maitre, D. F. Scott, C. Colvin, *Water S.A.* **25**, 137 (1999).
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).
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).
29. D. F. Scott, W. Lesch, *J. Hydrol.* **199**, 360 (1997).

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.

Supporting Online Material
www.sciencemag.org/cgi/content/full/310/5756/1944/DC1
Materials and Methods
Tables S1 to S3
References

24 August 2005; accepted 21 November 2005
10.1126/science.1119282

Heterogeneous Hadean Hafnium: Evidence of Continental Crust at 4.4 to 4.5 Ga

T. M. Harrison,[1,2]* J. Blichert-Toft,[3] W. Müller,[1,4] F. Albarede,[3] P. Holden,[1] S. J. Mojzsis[5]

The long-favored paradigm for the development of continental crust is one of progressive growth beginning at ~4 billion years ago (Ga). To test this hypothesis, we measured initial $^{176}Hf/^{177}Hf$ values of 4.01- to 4.37-Ga detrital zircons from Jack Hills, Western Australia. ε_{Hf} (deviations of $^{176}Hf/^{177}Hf$ from bulk Earth in parts per 10^4) values show large positive and negative deviations from those of the bulk Earth. Negative values indicate the development of a Lu/Hf reservoir that is consistent with the formation of continental crust (Lu/Hf ≈ 0.01), perhaps as early as 4.5 Ga. Positive ε_{Hf} deviations require early and likely widespread depletion of the upper mantle. These results support the view that continental crust had formed by 4.4 to 4.5 Ga and was rapidly recycled into the mantle.

A fundamental question of Earth's evolution is: When did the growth of continental crust begin? One model is that the first crust formed after 4 Ga and grew slowly until the present day (*1*, *2*). This view reflects the absence of a >4-Ga rock record (*3*) and the broadly coherent post–4 Ga evolution of depleted mantle $^{143}Nd/^{144}Nd$ (*4*) and $^{176}Hf/^{177}Hf$ (*5*). Long-standing observations of early Nd (*6*) and Hf (*7*, *8*) depletions, however, leave open the possibility of even earlier global fractionations. Another view (*9*, *10*) is that continental crust was widespread during the Hadean Eon [the first 500 million years (My) of Earth history]. In such a scenario, the lack of direct evidence of earlier depletion events reflects subsequent remixing. Detrital zircons from Jack Hills, Western Australia, with 4.0- to 4.4-Ga U-Pb ages (*11–13*) represent pieces of crust that have been sequestered for up to ~4.4 Ga. Hf isotopic compositions vary because of radioactive decay of ^{176}Lu, and such variations in zircons constitute an excellent tracer of Earth's crust/mantle differentiation. This is because zircons have very low Lu/Hf ratios and thus record near-initial $^{176}Hf/^{177}Hf$ at the time given by their U-Pb age. Amelin and co-workers (*14*) investigated Hf isotopes in Jack Hills zircons as old as 4.14 Ga and inferred the existence of reworked Hadean crust. We have now extended this application by undertaking Lu-Hf analyses of grains ranging in age up to 4.37 Ga, thereby narrowing the gap to less than 200 My from the end of Earth's accretion to the first mineral record. We document significant Hf isotopic heterogeneity during the early Hadean and conclude that major differentiation of the silicate Earth, possibly the formation of continental crust with a volume similar in magnitude to the present day, may have occurred by 4.4 to 4.5 Ga.

Using the multicollector Sensitive High Resolution Ion Microprobe II, we have surveyed the radiogenic $^{207}Pb/^{206}Pb$ ($^{207}Pb/^{206}Pb^*$) ratio

[1]Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia. [2]Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California at Los Angeles, Los Angeles, CA 90095, USA. [3]Ecole Normale Supérieure, CNRS Unité Mixte de Recherche 5570, 69364 Lyon Cedex 7, France. [4]Department of Geology, Royal Holloway University of London, Egham, TW20 0EX, UK. [5]Department of Geological Sciences, University of Colorado, Boulder, CO 80309, USA.

*To whom correspondence should be addressed. E-mail: mark.harrison@anu.edu.au

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

Supporting Online Material for

Trading Water for Carbon with Biological Carbon Sequestration

Robert B. Jackson,* Esteban G. Jobbágy, Roni Avissar, Somnath Baidya Roy,
Damian J. Barrett, Charles W. Cook, Kathleen A. Farley, David C. le Maitre,
Bruce A. McCarl, Brian C. Murray

*To whom correspondence should be addressed. E-mail: jackson@duke.edu

Published 23 December 2005, *Science* **310**, 1944 (2005)
DOI: 10.1126/science.1119282

This PDF file includes:

Materials and Methods
Tables S1 to S3
References

Supporting Online Material

Materials and Methods

Soil and catchment database analyses. We analyzed data from 52 published studies (see soil database analyses table below) and 114 paired observations that compared the chemistry of soils in grasslands or shrublands with those in adjacent afforested plots in Argentina, Australia, Belgium, Brazil, China, Costa Rica, Denmark, Germany, India, New Zealand, Philippines, Puerto Rico, Scotland, Siberia, South Africa, and the United States (Table S1). Data for soil pH, exchangeable Na, ESP, and base saturation were compared for the top 30 cm of mineral soil using paired t-tests.

For the analysis of stream flow, we analyzed data from 26 long-term catchment studies (Table S2) including 504 annual observations comparing grassland, shrubland, or agricultural catchments with afforested catchments at the same sites (*S1*). For the analyses with plantation age, the best fit among linear, logarithmic, and quadratic models was selected based on adjusted least squares regression. In more than three-fourths of the datasets >50% of the catchment was planted, but in almost no cases was afforestation 100% of catchment area. Because we did not scale projected changes to 100% of catchment areas, our estimates of reduced runoff with afforestation are conservative. See (*S1*) for additional details of the database. Regression equations for Figure 1: 1a: $Y = 15.648 - 80.579\ln(x)$, 1b: $Y = -4.7134X + 0.1041X^2$, 1c: $Y = -3.2109 - 1.2095X + 0.0215X^2$. Estimates of changes in annual renewable water (Fig. 1c) for the catchments were made by taking the changes in annual stream flow (in mm) and dividing each value by actual annual precipitation or mean annual precipitation estimates (where annual measurements were unavailable). For the country analysis (Fig. 1d), estimates of annual precipitation by nation (*S2*) and mean annual renewable water (renewable freshwater supply by nation (*S3*) divided by national land area) were calculated. For some countries, such national averages mask important regional differences in precipitation.

Groundwater sampling. The Pampas region of Argentina covers ~50 million Ha and has soils that are typically Mollisols developed on loess-like sediments. At the eight study sites with seventeen grassland and plantation pairs (*S4*), groundwater was collected a few cm below the water table from boreholes. Groundwater salinity/electrical conductivity (EC) was measured using an open-cell conductimeter (Orion 115; automatic temperature calibration). The Castelli stand is a 40-ha *Eucalyptus camaldulensis* plantation (36° 02.0′ S, 57° 50.3′ W; mean annual precipitation for 1950-2002 of 987 mm) established in 1951 at 6-m^2 spacing without fertilization or irrigation. The current tree density is 500 - 700 stems/ha with a mean tree height ~45 m. Groundwater salinity along the grassland-plantation transects was characterized in summer 2003 using VES technology (Schlumberger electrode configuration) that used an inverse 1-D model routine to estimate the resistivity of the terrain using a three-layer structure (SchlumBG software, MicroFEM Development and Support, Amsterdam). Vertical salinity patterns derived from VES estimates were confirmed directly by groundwater EC measurements.

Economic modeling and plantation scenarios. We estimated the extent of land area in the U.S. projected to convert to plantations in response to payments for C sequestration. The land use simulations were generated using the Forest and Agricultural Sector Model – Greenhouse Gases (FASOMGHG) (*S5*, *S6*), which is a dynamic spatial equilibrium model simulating economic activities in, and land transfers between, the agriculture and forest sectors (Table S3). The model reallocates land based on economic conditions. Changes in economic conditions may be related to changes in markets for commodities, but in this case the conditions are changed by hypothetical payments of 50 and 100 U.S. dollars per Mg (tonne) C sequestered. When a C payment is offered, this increases the returns to high C sequestering land uses such as forestry or lands growing biofuels that can be used to offset fossil fuel use in energy production, relative to land uses sequestering less C or emitting C (or other greenhouse gases), such as conventional agriculture or pastures. At the two prices simulated ($50 and $100 per Mg C), FASOMGHG estimates initial land movements from agriculture to forestry of ~33 and 72 million ha, respectively, across the US. Most of this land conversion to plantations comes from nonirrigated cropland and pastures in the North-Central, South-Central, and Southeastern U.S. (Fig. 2).

FASOMGHG is an augmented version of the Forest and Agricultural Sector Optimization Model (FASOM; Ref. *S6*) as developed by Lee (*S7*). The model has all of the forest- and agricultural-sector economic coverage of the original FASOM model unified with a detailed representation of the possible mitigation strategies in the agricultural sector adapted from Schneider (*S8*) and McCarl and Schneider (*S5*).

FASOMGHG is a 100-year intertemporal, price-endogenous, mathematical programming model depicting land transfers and other resource allocations between and within the agricultural and forest sectors in the United States. The model solution portrays a multiperiod equilibrium on a decadal basis. The results from FASOMGHG yield a dynamic simulation of prices, production, management, consumption, and GHG effects within these two sectors under the scenario depicted in the model data.

FASOMGHG can simulate responses in the U.S. forest and agricultural sectors to economic incentives such as GHG prices or mitigation quantity targets. Economic responses include changes in land use between and within the sectors and intrasectoral changes in forest and agricultural management (*S9*-*S11*).

FASOMGHG's key endogenous variables include land use, management strategy adoption, resource use, commodity and factor prices, production and export and import quantities, and environmental impact indicators: GHG emission/absorption (CO_2, CH_4, N_2O) and surface, subsurface, and groundwater pollution for nitrogen, phosphorous, and soil erosion.

Regional scale modeling of climate-vegetation feedbacks.

The Regional Atmospheric Modeling System (RAMS; Refs. *S12*, *S13*) solves the full three-dimensional, compressible, nonhydrostatic dynamic equations, a thermodynamic equation and a set of microphysics equations. The system is closed with the Mellor-Yamada level 2.5 scheme (*S14*) that explicitly solves for turbulent kinetic energy while other second-order moments are parameterized. The coordinate system is rectangular Cartesian in the horizontal and terrain-following sigma-type (*S15*) in the vertical. It uses a two-stream radiative transfer scheme (*S16*) that treats the interaction of three solar and five infrared bands with the atmospheric gases and hydrometeors. The detailed bulk microphysical model prognoses mixing ratio and number concentration of rain, ice crystals, aggregates, graupel and hail for all resolved processes (*S17*, *S18*). The cumulus convection parameterization is based on Kuo (*S19*), which is appropriate for regional climate models (*S20*).

Interactions between the land and atmosphere are modeled by the Land Ecosystem-Atmosphere Feedback-2 (LEAF-2, Ref. *S21*) submodel. LEAF-2 characterizes the land surface by prognosing energy, mass and moisture in multiple soil and snow layers, vegetation matter and canopy air. To account for fine-scale heterogeneity, multiple land cover types are allowed in each grid cell but their effects are aggregated weighted by their relative areal coverage. The fluxes of mass, energy and momentum from the surface to the atmosphere are calculated using surface similarity theory (*S22*).

We used RAMS to model atmospheric and land processes over a 6780 km x 5820 km region centered over the U. S. using a three-dimensional grid with uniform

60 km spacing in the horizontal. The domain went up to 25 km in the vertical and was discretized with a stretched grid with a stretch ratio of 1.2 between successive levels, starting from 50 m near the surface to a maximum of 1500 m. We used eleven soil layers that went down to a depth of 2 m.

We used the NCEP-DOE AMIP-II reanalysis data (*S23*) as atmospheric initial and boundary conditions and the Olson Global Ecosystem database (*S24*) as land cover. Up to 5 different land cover types were used in each grid cell. We also used the NCEP-DOE AMIP-II reanalyses to initialize soil moisture and temperature.

The FASOMGHG model was used to estimate the extent of croplands that would be converted to hardwood or softwood plantations in different regions of the U.S. under the $50 and $100 carbon payment scenarios. Based on these projections, we replaced appropriate amounts of croplands by evergreen needleleaf or deciduous broadleaf forests. Arguing that maintaining plantations on small dispersed farms would be expensive, we randomly picked sites from the largest cropland patches for this conversion.

We ran RAMS eleven times for each case with eleven different sets of initial and boundary conditions corresponding to the Julys of 1994-2004. The ensemble-averaged outputs of the experimental scenarios were compared with the control to estimate the possible impact of the plantations on regional summer climate.

Converting croplands to plantations significantly lowered the albedo and bowen ratio of the land surface. Plantations trapped more solar energy than crops but released more of the absorbed energy as latent rather than sensible heat (SH). Consequently, near-surface air temperature over the plantations was lower and ET was higher. The increase in ET enhanced local moisture supply but did not necessarily produce more convective rainfall. This is because the intensity of convective rain depends not only on moisture supply but on the surface SH flux as well. Strong SH is required to produce convection that can lift moisture high enough to condense and form rain-bearing clouds. Unlike in the tropics, the background surface SH flux in the northern U.S. was not strong enough to support sustained vertical transport of this additional moisture. Furthermore, convective precipitation actually decreased because lower SH reduced convection. These effects were statistically significant at the 99% level of confidence.

The impact of plantations on total precipitation, which is a sum of subgrid and resolved precipitation, was significant at the 90% confidence level. At 60-km spatial resolution, resolved precipitation is primarily stratiform in nature and dominated by processes such as large-scale advective transport of heat and moisture. The land-atmosphere interaction is one of many sources of variability in this parameter and, hence, the impact of plantations was harder to isolate.

Table S1: List of the 52 references used in the soil database analyses (see Materials and Methods).

1. Adams, M. L., Davis, M. R., & Powell, K. J. Effects of grassland afforestation on exchangeable soil and soil solution aluminium. *Aust. J. Soil Res.* **39**, 1003 (2001).

2. Alfredsson, H., Dondron, L. M., Clarholm, M., & Davis, M. R. Changes in soil acidity and organic matter following the establishment of conifers on former grassland in New Zealand. *Forest Ecology and Management* **112**, 245 (1998).

3. Alriksson, A. & Olsson, M. T. Soil changes in different age classes of Norway spruce (Picea abies (L) Karst.) on afforested farmland. *Plant Soil* **169**, 103 (1995).

4. Barton, D., Gammack, S. M., Billett, M. F., & Cresser, M. S. Sulphate adsorption and acidification of Calluna heathland and Scots pine forest podzol soils in north-east Scotland. *Forest Ecology and Management* **114**, 151 (1999).

5. Binkley, D. & Resh, S. C. Rapid Changes in Soils Following Eucalyptus Afforestation in Hawaii. *Soil Science Society of America Journal* **63**, 222 (1999).

6. Binkley, D., Valentine, D., Wells, C., & Valentine, U. An empirical analysis of the factors contributing to 20-year decrease in soil pH in an old-field plantation of loblolly pine. *Biogeochemistry* **8**, 39 (1989).

7. Chen, C. R., Condron, L. M., Davis, M. R., & Sherlock, R. R. Effects of afforestation on phosphorus dynamics and biological properties in a New Zealand grassland soil. *Plant and Soil* **220**, 151 (2000).

8. Condron, L. M. & Newman, R. H. Chemical nature of soil organic matter under grassland and recently established forest. *European Journal of Soil Science* **49**, 597 (1998).

9. Davis, M. Soil properties under pine forest and pasture at two hill country sites in Canterbury. *New Zealand Journal of Forestry Science* **31**, 3 (2001).

10. Davis, M. R. Influence of radiata pine seedlings on chemical properties of some New Zealand montane grassland soils. *Plant and Soil* **176**, 255 (1995).

11. Davis, M. R. Topsoil properties under tussock grassland and adjoining pine forest in Otago, New Zealand. *New Zealand Journal of Agricultural Research* **37**, 465 (1994).

12. Davis, M. R. & Lang, M. H. Increased nutrient availability in topsoils under conifers in the South Island high country. *New Zealand Journal of Forestry Science* **2**, 165 (1991).

13. Mao, D. M., Min, Y. W., Yu, L. L., Martens, R., & Insam, H. Effect of afforestation on microbial biomass and activity in soils of tropical China. *Soil Biology & Biochemistry* **24**, 865 (1992).

14. Garg, V. K. & Jain, R. K. Influence of fuelwood trees on sodic soils. *Canadian Journal of Forest Research* **22**, 729 (1992).

15. Giddens, K. M., Parfitt, R. L., & Percival, H. J. Comparison of some soil properties under Pinus radiata and improved pasture. *New Zealand Journal of Agricultural Research* **40**, 409 (1997).

16. Gilmore, A. R. & Boggess, W. R. Effects of past agricultural practices on the survival and growth of planted trees. *Soil Science Society Proceedings* **27**, 98 (1963).

17. Groenendijk, F. M., Condron, L. M., & Rijkse, W. C. Effects of afforestation on organic carbon, nitrogen and sulfur concentrations in New Zealand hill country soils. *Geoderma* **108**, 91 (2002).

18. Guevara-Escobar, A., Kemp, P. D., Mackay, A. D., & Hodgson, J. Soil properties of a widely spaced, planted poplar (Populus deltoides)-pasture system in a hill environment. *Australian Journal of Soil Research* **40**, 873 (2002).

19. Hawke, M. F. & O'Connor, M. B. Soil pH and nutrient levels at Tikitere Agroforestry Research Area. *New Zealand Journal of Forestry Science* **23**, 40 (1993).

20. Hofstede, R. G. M., Groenendijk, J. P., Coppus, R., Fehse, J. C., & Sevink, J. Impact of pine plantations on soils and vegetation in the Ecuadorian High Andes. *Mountain Research and Development* **22**, 159 (2002).

21. Jain, R. K. & Singh, B. Biomass production and soil amelioration in a high density Terminalia arjuna plantation on sodic soils. *Biomass and Bioenergy* **15**, 187 (1997).

22. Jobbagy, E. G. & Jackson, R. B. Patterns and mechanisms of soil acidification in the conversion of grasslands to forests. *Biogeochemistry* **64**, 205 (2003).

23. Jug, A., Makeschin, F., Rehfuess, K. E., & Hofmann-Schielle, C. Short-rotation plantations of balsam poplars, aspen, and willows on former arable land in the Federal Republic of Germany. III. Soil Ecological effects. *Forest Ecology and Management* **121**, 85 (1999).

24. Lilienfein, J., Wilcke, W., Ayarza, M. A., Vilela, L., Lima, S. d. C., & Zech, W. Soil acidification in Pinus caribaea forests on Brazilian savanna Oxisols. *Forest Ecology and Management* **128**, 145 (2000).

25. Markewitz, D., Richter, D. D., Allen, H. L., & Urrego, J. B. Three decades of observed soil acidification in the Calhoun experimental forest: Has acid rain made a difference?. *Soil Science Society of America Journal* **62**, 1428 (1998).

26. Menyailo, O. V., Hungate, B. A., & Zech, W. Tree species mediated soil chemical changes in a Siberian artificial afforestation experiment. *Plant and Soil* **242**, 171 (2002).

27. Montagnini, F. Accumulation in aboveground biomass and soil storage of mineral nutrients in pure and mixed plantations in a humid tropical lowland. *Forest Ecology and Management* **134**, 257 (2000).

28. Musto, J. W. Impacts of plantation forestry on various soil types. *Institute for Commercial Forestry Research Annual Research Report 1991*, 37 (1991).

29. Muys, B. & Lust, N. Ecological changes following afforestation with different tree species on a sandy loam soil in Flanders, Belgium. *Ecological Effects of Afforestation*, ed. by C Watkins, Wallingford, UK: CAB International, 179 (1993).

30. Nielsen, K. E., Ladekarl, U. L, & Nornberg, P. Dynamic soil processes on heathland due to changes in vegetation to oak and Sitka spruce. *Forest Ecology and Management* **114**, 107-116 (1999).

31. Noble, A. D., Little, I. P., & Randall, P. J. The influence of Pinus radiata, Quercus suber, and improved pasture on soil chemical properties. *Aust. J. Soil Res.* **37**, 509 (1999).

32. Ohta, S. Initial soil changes associated with afforestation with Acacia auriculiformis and Pinus kesiya on denuded grasslands of the Pantabangan Area, Central Luzon, the Philippines. *Soil Science and Plant Nutrition* **36**, 633 (1990).

33. Parfitt, R. L., Percival, H. J., Dahlgren, R. A., & Hill, L. F. Soil and solution chemistry under pasture and radiata pine in New Zealand. *Plant and Soil* **191**, 279 (1997).

34. Payet, C., Scholes, M. C., & Balkwill, K. Some effects of the cultivation of pine on the chemistry of ultramafic soils. *South African Journal of Science* **97**, 603 (2001).

35. Prosser, I. P. et al. A comparison of soil acidification and aluminium under Eucalyptus forest and unimproved pasture. *Australian Journal of Soil Research* **31**, 245 (1993).

36. Quideau, S. A. & Bockheim, J. G. Biogeochemical cycling following planting to red pine on a sandy prairie soil. *Journal of Environmental Quality* **26**, 1167 (1997).

37. Resh, S. C., Binkley, D., & Parrotta, J. A. Greater soil carbon sequestration under nitrogen-fixing trees compared with Eucalyptus species. *Ecosystems* **5**, 217 (2002).

38. Reynolds, B., Neal, C., Hornung, M., Hughes, S., & Stevens, P. A. Impact of afforestation on the soil solution chemistry of stagnopodzols in mid-Wales. *Water, Air, and Soil Pollution* **38**, 55 (1988).

39. Rhoades, C. & Binkley, D. Factors influencing decline in soil pH in Hawaiian Eucalyptus and Albizia plantations. *Forest Ecology and Management* **80**, 47 (1996).

40. Richter, D. D. et al. Soil chemical change during three decades in an old-field loblolly pine ecosystem. *Ecology* **75**, 1463 (1994).

41. Ross, D. J., Tate, K. R., Scott, N. A., Wilde, R. H., Rodda, N. J., & Townsend, J. A. Afforestation of pastures with Pinus radiata influences soil carbon and nitrogen pools and mineralisation and microbial properties. *Australian Journal of Soil Research* **40**, 1303 (2002).

42. Ross, D. J., Tate, K. R., Scott, N. A., & Feltham, C. W. Land-use change: effects on soil carbon, nitrogen and phosphorus pools and fluxes in three adjacent ecosystems. *Soil Biology and Biochemistry* **31**, 803 (1999).

43. Saggar, S., Hedley, C. B., & Salt, G. J. Soil microbial biomass, metabolic quotient, and carbon and nitrogen mineralisation in 25-year-old Pinus radiata agroforestry regimes. *Aust. J. Soil Res.* **39**, 491 (2001).

44. Schipper, L. A. & Sparling, G. P. Performance of soil condition indicators across taxonomic groups and land uses. *Soil Science Society of America Journal* **64**, 300 (2000).

45. Singh, G., Singh, H., & Bhojvaid, P. P. Amelioration of sodic soils by trees for wheat and oat

production. *Land Degradation & Development* **9**, 453 (1998).
46. Sparling, G. P., Shepherd, T. G., & Schipper, L. A. Topsoil characteristics of three contrasting New Zealand soils under four long-term land uses. *New Zealand Journal of Agricultural Research* **43**, 569 (2000).
47. Vesterdal, L., Ritter, E., & Gundersen, P. Change in soil organic carbon following afforestation of former arable land. *Forest Ecology and Management* **169**, 137 (2002).
48. Williams, B. L., Cooper, J. M., & Pyatt, D. G. Effects of afforestation with Pinus contorta on nutrient content, acidity and exchangeable cations in peat. *Forestry* **51**, 29 (1978).
49. Yeates, G. W. & Saggar, S. Comparison of soil microbial properties and fauna under tussock-grassland and pine plantation. *Journal of the Royal Society of New Zealand* **28**, 523 (1998).
50. Yeates, G. W., Hawke, M. F., & Rijke, W. C. Changes in soil fauna and soil conditions under Pinus radiata agroforestry regimes during a 25-year tree rotation. *Biology and Fertility of Soils* **31**, 391 (2000).
51. Zinn, Y. L., Resck, D. V. S., & da Silva, J. E. Soil organic carbon as affected by afforestation with Eucalyptus and Pinus in the Cerrado region of Brazil. *Forest Ecology and Management* **166**, 285 (2002).
52. Zou, X. & Bashkin, M. Soil carbon accretion and earthworm recovery following revegetation in abandoned sugarcane fields. *Soil Biology & Biochemistry* **30**, 825 (1998).

Table S2. References and attributes of the catchments used in the water yield database analyses.

Source	Name of site(s)	**Location**	**Latitude/ Longitude**	**MAP (mm)**	**Original vegetation**	**Plant species**	**Plant age (yrs)**	**Percent planted**	**Data type**	**Notes**
Borg et al 1988	Padbury Reservoir	southwest Australia	N/A	880	crops and pastures	P. radiata, E. globulus	3-8	70	P-O	
Bosch 1979	Cathedral Peak II	Winterton, Natal Drakensberg, South Africa	29º00´S/ 29º15´E	1400	grassland	P. patula	1-26	52	Supp	
Calder and Newson 1979	Wye and Severn rivers, Plynlimon	Wales, UK	N/A	2350	pasture	Picea sitchensis (80%)	43-50	100	C-P	Planting from 1937-1964; 1937 used to calculate plantation age
Dons 1986	Tarawera	North Island, New Zealand		1500	scrub and native bush	pine	ave. for 1-18	28	C-P	MAP estimated from graph
Dons 1987	Purukohukohu	North Island, New Zealand	38º26´S/ 176º13´E	1550	pasture	P. radiata	ave. for 8-11	N/A	C-P	
Duncan 1995	C14	Moutere Gravel hill country, Nelson, New Zealand	N/A	1020	pasture	P. radiata	1-21	N/A	C-P	
Fahey and Jackson 1997	Glendhu	Waipori River, Otago, New Zealand	45º50´S	1350	tussock grassland	P. radiata	9-12	67	C-P	
Fahey and Watson 1991	Glendhu	Waipori River, Otago, New Zealand	45º50´S	1355	tussock grassland	P. radiata	1-8	67	C-P	Catchment was contour-ripped to 60 cm depth

										prior to planting
Mwendera 1994	Luchelemu River	Malawi	11º45´S/ 33º50´E	1300	montane grass and scrub	pine and eucalyptus	mean	93	C-P	Low flow only
Nanni 1970	Cathedral Peak II Cathedral Peak III	Winterton, Natal Drakensberg, South Africa	28º00´S/ 29º15´E	1660 1545	grassland grassland	P. patula P. patula	1-16 1-8	75 81	Supp	Planting of CP II began in 1951, but not finished until 1961.
Robinson 1998	Coalburn	Northwest England	N/A	1350	grassland and bog	Sitka spruce	24	N/A	C-P	
Robinson et al 1991	FM/N FM/S	Chiemseemoors, Germany	47º48´N/ 12º26´E	1440	bog formerly used for agriculture	Norway spruce	4-25	N/A	P-O	
Samraj et al 1988	Glenmorgan, Ootacamund	Nilgiri Plateau, South India	11º28´N/ 76º37´E	1535	grassland and woodland	E. globulus	1-10	59	P-O	
Scott and Lesch 1997	Mokobulaan A Mokobulaan B	Lydenburg, Mpumalanga, South Africa	27º17´S/ 30º34´E	1135 1170	grassland grassland	E. grandis P. patula	1-17 1-21	100 100	Supp	
Scott et al 2000	Westfalia D	Tzaneen, Mpumalanga, South Africa	23º43´S/ 30º04´E	1250	scrub	E. grandis	1-15	83	P-O	Scrub forest cleared before planting
	Mokobulaan A Mokobulaan B	Lydenburg, Mpumalanga, South Africa	27º17´S/ 30º34´E	1170 1180	grassland grassland	E. grandis P. patula	1-22 1-20	97 95		
	Cathedral Peak II Cathedral Peak III	Winterton, Natal Drakensberg, South Africa	28º00´S/ 29º15´E	1400 1515	grassland grassland	P. patula P. patula	1-29 1-22	75 86		Controlled burn before planting
	Bosboukloof	Jonkershoek,	33º57´S/	1125	fynbos	P. radiata	5-38	57		

	Biesievlei Tierkloof Lambrechtsbos B Lambrechtsbos A	Western Cape, South Africa	18º15´E	1300 1320 1145 1125	shrubland		1-35 1-40 1-32 1-18	98 36 82 89		
Sharda et al 1998	Glenmorgan, Ootacamund	Nilgiri Plateau, South India	11º28´N/ 76º37´E	1535	grassland and woodland	E. globulus	1-10	59	P-O	Second rotation
Smith 1987	Taieri River (Jura Creek)	East Otago, South Island, New Zealand	N/A	1000	pasture	P. radiata, P. nigra	N/A	N/A	C-P	Catchments cleared of native grasses and shrubs, planted with pasture or pine
Smith 1992	Moutere Hills	Nelson, New Zealand	41º22´S/ 173º04´E	1050	pasture (ryegrass)	P. radiata	5-9	20	P-O	
Smith and Scott 1992	Westfalia D Mokobulaan A Mokobulaan B	Tzaneen, Mpumalanga, South Africa Lydenburg, Mpumalanga, South Africa	22º43´S/ 30º04´E 24º17´S/ 30º34´E	1600 1150 1150	scrub grassland grassland	E. grandis E. grandis P. patula	1-8 1-12 1-11	83 100 95	P-O	Low flow data
Van Wyk 1987	Bosboukloof Biesievlei Tierkloof Lambrechtsbos B Lambrechtsbos A	Jonkershoek, Western Cape, South Africa	33º57´S/ 18º15´E	1300 1425 1800 1475 1415	fynbos	P. radiata		57 98 36 82 89	Supp	

Table S3. FASOMGHG Model: Key Dimensions

Model Dimension	Forest Sector	Agriculture Sector
General scope and coverage		
Geographic coverage	Land coverage for conterminous United States with other regions linked by international trade	Same
Regional detail	11 U.S. regions, 9 of which produce forest goods	11 U.S. regions, 10 of which produce agricultural goods
Land ownership coverage	All private timberland in conterminous United States	All agricultural land in major commodity production in the conterminous United States
Economic dimensions		
Economic modeling approach	Optimizing producer and consumer behavior over finite time horizon	Same
Time horizon	Model base year = 2000 Resolution = 10-year time steps Typically run for 100 years	Same
Discount rate	4%	Same
Commodities	10 commodities 5 products: sawlogs, pulpwood, fuelwood and milling residues 2 species: softwood and hardwood	48 primary products 45 secondary products
Price and cost data	Resource Planning Act (RPA) assessment (*S9*)	USDA NRCS data with updates based on *Agricultural Statistics*
Supply/land inventory	USDA Forest Service Forest Inventory and Analysis Data	USDA NRI, Agricultural Census, and NASS data
Supply/biophysical yield	USDA Forest Service ATLAS model (*S10*)	Crop budgets and EPIC (*S11*) model simulations
Demand	Adapted from demand models used in latest RPA Assessment[5]	Variety of demand studies
International trade	10 excess-demand regions facing each timber-producing region plus Canada	28 international regions for main traded commodities plus excess supply and demand for others
Environmental variables		
GHG coverage	CO_2 as carbon sequestration in forest ecosystem pools and in harvested wood products	CO_2 sequestration and emissions CH_4 emissions N_2O emissions
Non-GHG environmental indicators	Timberland area by region, species, owner, age class	Agricultural land allocation Tillage practices Irrigation water use
	Forest management intensity	Cropland loadings of nitrogen, phosphorous, potassium, erosion, and pesticides

Supporting References

1. K. A. Farley, E. G. Jobbágy, R. B. Jackson, *Global Change Biol*. **11**, 1565 (2005).

2. R. Leemans, W. Cramer, “The IIASA database for mean monthly values of temperature, precipitation and cloudiness on a global terrestrial grid” (IIASA Research Report RR/91/18, 1991).

3. P. H. Gleick, *The World’s Water: 2000-2001*. (Island Press, Washington, D.C., 2000).

4. E. G. Jobbágy, R. B. Jackson, *Global Change Biol.* **10**, 1299 (2004).

5. B. A. McCarl, U. A. Schneider, *Science* **294**, 2481 (2001).

6. D. M. Adams, R. J. Alig, J. M. Callaway, B. 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).

7. H. Lee, thesis, Texas A&M University (2002).

8. U. A. Schneider, dissertation, Texas A&M University (2000).

9. “An Analysis of the Timber Situation in the United States: 1952 to 2050” (Gen. Tech. Rep. PNW-GTR-560, USDA Forest Service, Pacific Northwest Research Station, Portland, OR, 2003).

10. J. Mills, J. Kincaid, “The Aggregate Timberland Assessment Model-ATLAS: A Comprehensive Timber Projection Model” (General Technical Report PNW-GTR-281, USDA Forest Service, Pacific Northwest Research Station. Portland, OR, 1992).

11. J. R. Williams, C. A. Jones, J. R. Kiniry, D. K. Spanel, *Trans. ASAE* **32**, 497 (1989).

12. W. R. Cotton *et al*., *Meteor. Atmos. Phys*. **82**, 5 (2003).

13. R. A. Pielke, *Meteorol. Atmos. Phys*. **49**, 69 (1992).

14. G. L. Mellor, T. Yamada, *Rev. Geophys*. **20**, 851 (1982).

15. T. L. Clark, *J. Comput. Phys*. **24**, 186 (1977).

16. J. Y. Harrington, dissertation, Colorado State Univ. (1997).

17. R. L. Walko, W. R. Cotton, M. P. Meyers, and J. Y. Harrington, *Atmos. Res*. **38**, 29 (1995).

18. M. P. Meyers, R. L. Walko, J. Y. Harrington, W. R. Cotton, *Atmos. Res*. **45**, 3 (1997).

19. J. Molinari, *Monthly Weather Rev*. **113**, 1411 (1985).

20. R. A. Pielke, *Mesoscale Meteorological Modeling* (Academic, San Diego, CA, 2002).

21. R. L. Walko *et al*., *J. Appl. Meteor*. **39**, 931 (2000).

22. J. F. Louis, *Boundary Layer Meteorol*. **17**, 187 (1979).

23. M. Kanamitsu, *Bull. Amer. Meteorol. Soc*. **83**, 1631 (2002).

24. J.S. Olson, World Ecosystems (WE1.4). Digital Raster Data on a 10-minute Cartesian Orthonormal Geodetic 1080x2160 grid. In: Global Ecosystems Database, Version 2.0. (National Geophysical Data Center, Boulder, CO, 1992).