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Trading Water for Carbon with Biological Carbon Sequestration

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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 dramati-

cally 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).

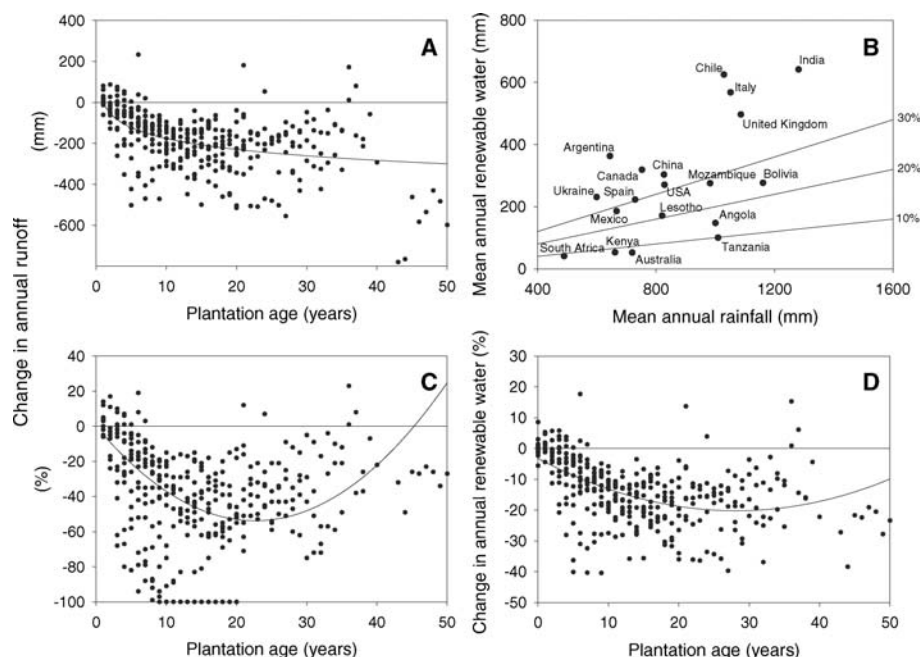


Fig. 1. Changes in stream flow and annual renewable water as a function of plantation age, and the relative abundance of renewable water by country. Changes in stream flow in mm (A) and proportion (%) (C) as a function of plantation age. (D) Changes in annual renewable water (annual stream flow in mm 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).

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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 $>0.3 \text{ mm day}^{-1}$ 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

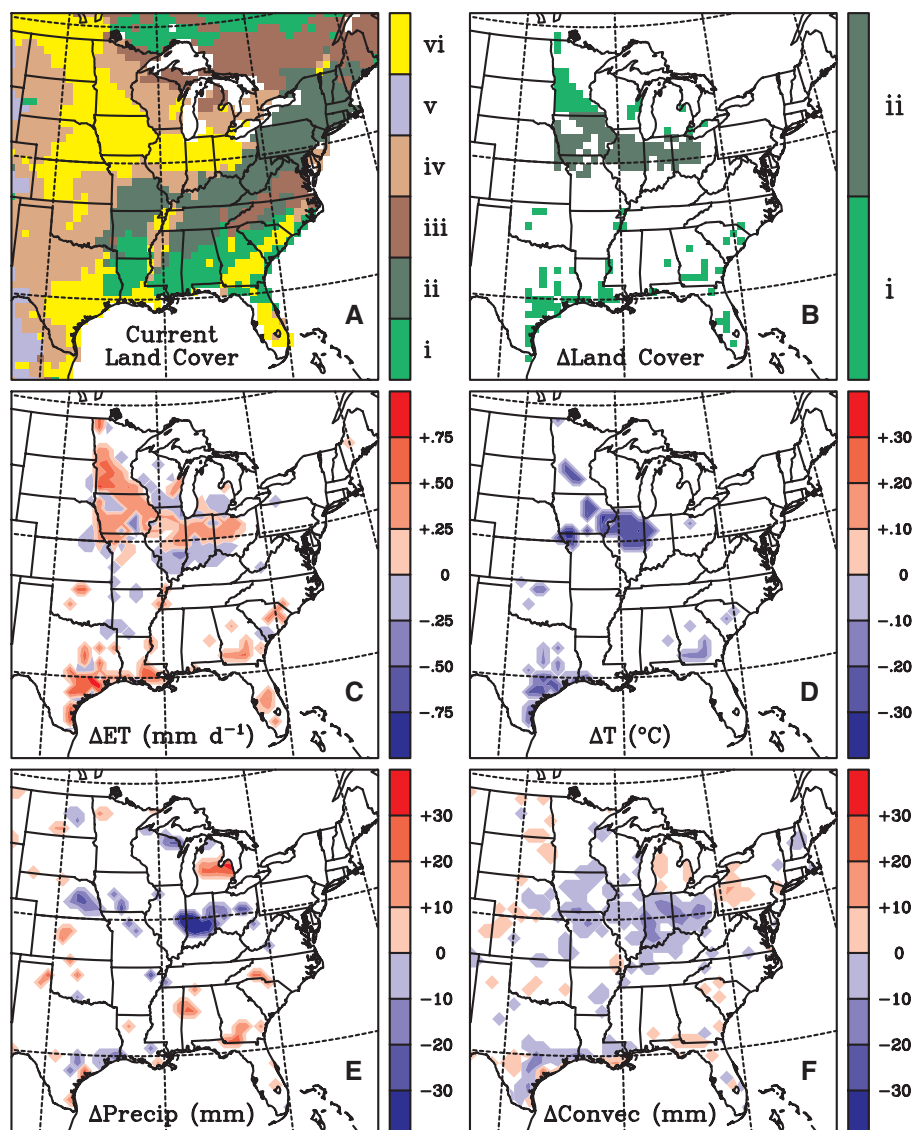


Fig. 2. Vegetation-climate feedbacks for economically based carbon sequestration scenarios using plantations. (A) Dominant land-cover type for each model grid cell aggregated into the following categories: (i) evergreen needleleaf forest, (ii) deciduous broadleaf forest, (iii) other forest, (iv) grass/shrubland, (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 ($^\circ\text{C}$), (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.

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 water-logged 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

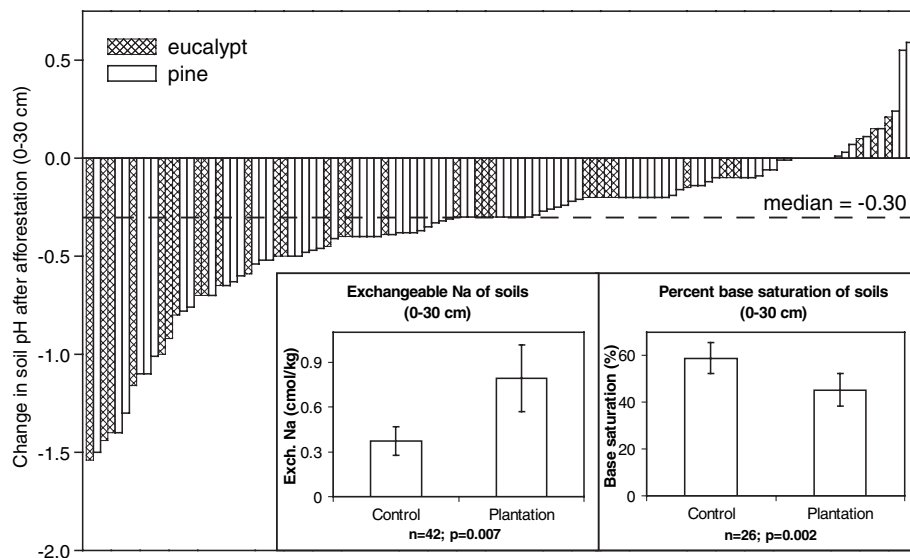


Fig. 3. The effects of plantations on soil pH and chemical properties (mean \pm SE). We analyzed data from 52 published studies (13) that compared soil chemistry in grasslands or shrublands with that in adjacent plantation plots. Comparisons were made for soil pH (main panel), base saturation (%), and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

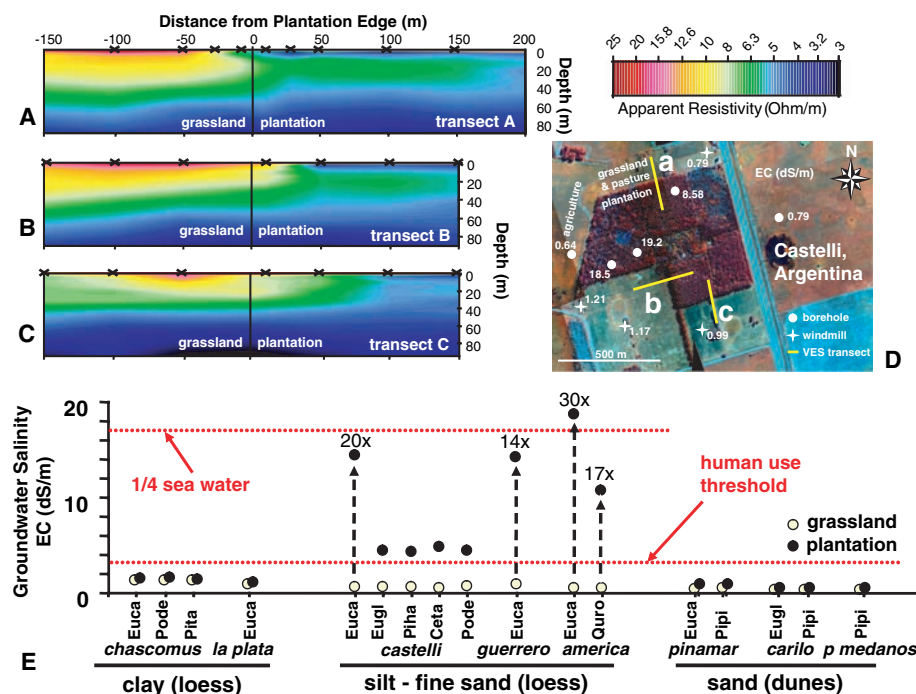


Fig. 4. Effects of plantations on groundwater salinity and electrical conductivity in the Argentine Pampas. (A to C) Three transects across plantation/grassland borders at Castelli made using vertical electric soundings, with reds indicating fresher water (higher resistivity) and blues indicating saltier 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*; Poda, *Populus deltoides*; Quro, *Quercus robur*.

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 negotiat-

ing 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.

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Supporting Online Material

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Materials and Methods

Tables S1 to S3

References

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

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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 ¹⁷⁶Hf/¹⁷⁷Hf values of 4.01- to 4.37-Ga detrital zircons from Jack Hills, Western Australia. ϵ_{Hf} (deviations of ¹⁷⁶Hf/¹⁷⁷Hf from bulk Earth in parts per 10⁴) 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 ¹⁴³Nd/¹⁴⁴Nd (4) and ¹⁷⁶Hf/¹⁷⁷Hf (5). Long-standing observations of early Nd (6) and Hf (7, 8) depletions, however, leave open the possibility of even earlier global frac-

tionations. 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 ¹⁷⁶Lu, 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 ¹⁷⁶Hf/¹⁷⁷Hf 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 ²⁰⁷Pb/²⁰⁶Pb (²⁰⁷Pb/²⁰⁶Pb*) ratio

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