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Marshall Wise, *et al.*

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Implications of Limiting CO_2 Concentrations for Land Use and Energy

Marshall Wise, Katherine Calvin, Allison Thomson, Leon Clarke, Benjamin Bond-Lamberty, Ronald Sands,* Steven J. Smith, Anthony Janetos, James Edmonds†

Limiting atmospheric carbon dioxide (CO_2) concentrations to low levels requires strategies to manage anthropogenic carbon emissions from terrestrial systems as well as fossil fuel and industrial sources. We explore the implications of fully integrating terrestrial systems and the energy system into a comprehensive mitigation regime that limits atmospheric CO_2 concentrations. We find that this comprehensive approach lowers the cost of meeting environmental goals but also carries with it profound implications for agriculture: Unmanaged ecosystems and forests expand, and food crop and livestock prices rise. Finally, we find that future improvement in food crop productivity directly affects land-use change emissions, making the technology for growing crops potentially important for limiting atmospheric CO_2 concentrations.

There is increasing concern over the connection between fossil and industrial emissions and terrestrial ecosystem emissions, and the implications of this interaction for climate change mitigation strategies. Several research studies (*1*–*8*) have shown that the outcome of imposing a mitigation regime that only values carbon from energy and industrial sources creates incentives to increase bioenergy. As the use of bioenergy increases, land uses shift from food and fiber crops, forests, and unmanaged ecosystems to dedicated biomass crops. This in turn increases terrestrial carbon emissions globally—a perverse result of curbing energy and industrial emissions.

Terrestrial systems hold ~2000 Pg C in soils and aboveground biomass (*9*), and a long history of research has highlighted the benefits of slowing or reversing carbon emissions that occur with land-use change. Because the total carbon emissions budget for 2005 to 2100 would have to be kept below ~500 Pg C to keep the atmospheric CO_2 concentration from exceeding 450 parts per million (ppm) (*8*, *10*), terrestrial emissions must be limited, in addition to energy and industrial emissions.

Numerous integrated analyses have examined the implication of limiting the concentration of atmospheric CO_2 with prescribed land use and land-use change assumptions. This literature is summarized by the Intergovernmental Panel on Climate Change (IPCC) (*11*). Here, we examine

Pacific Northwest National Laboratory, Joint Global Change Research Institute at the University of Maryland–College Park, 5825 University Research Court, Suite 3500, College Park, MD 20740, USA.

*Present address: Economic Research Service, U.S. Department of Agriculture, 1800 M Street NW, Washington, DC 20036, USA.

†To whom correspondence should be addressed. E-mail: jae@pnl.gov

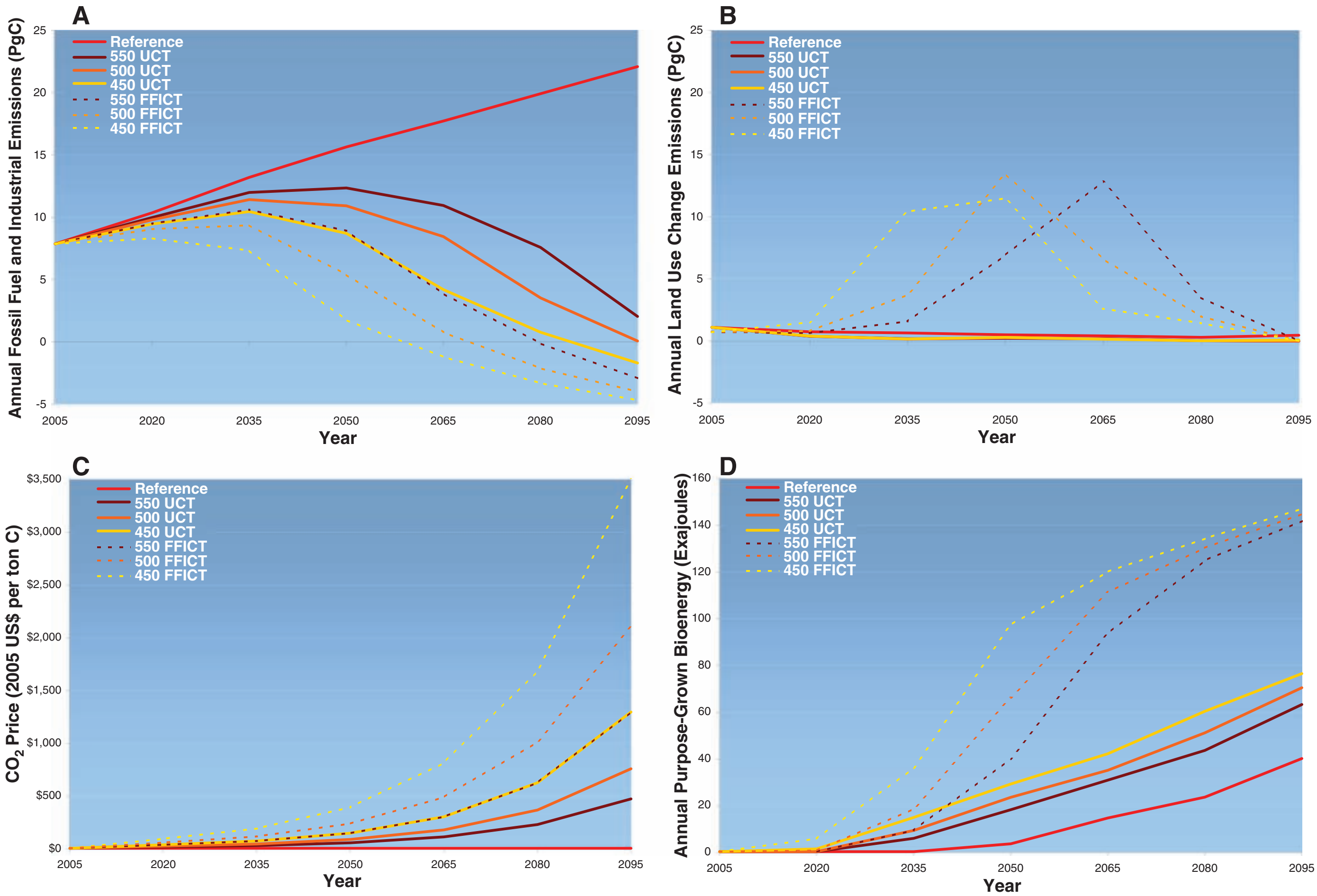


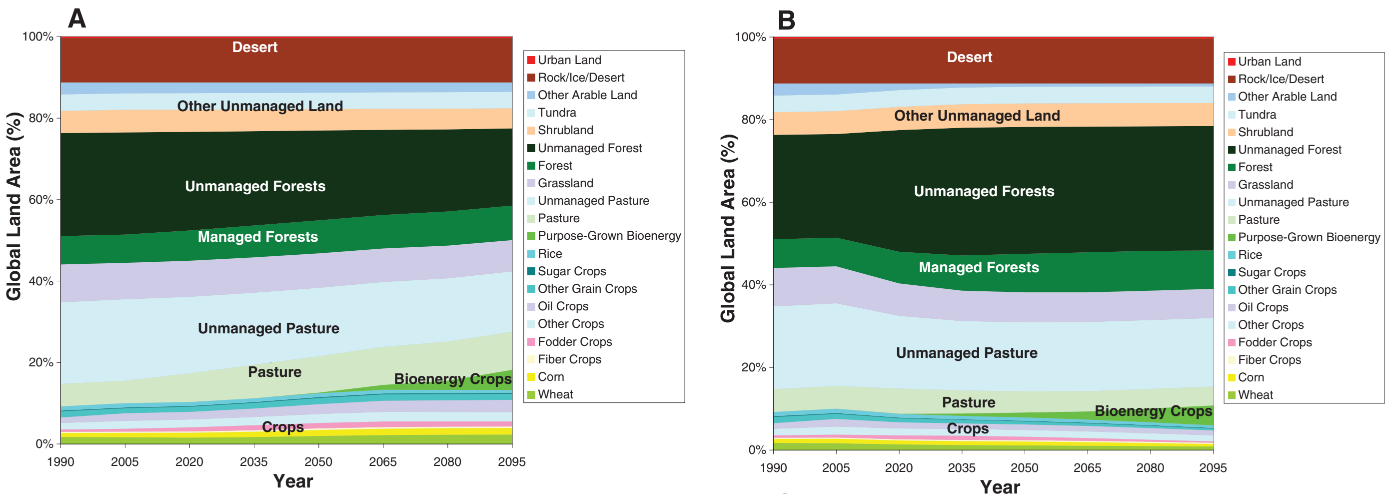
Fig. 1. A comparison of three alternative CO_2 concentration targets under UCT pathways that limit fossil fuel, industrial, and terrestrial carbon emissions with a common carbon tax on emissions to the corresponding FFICT scenarios in which only fossil fuel and industrial emissions are controlled to achieve the same CO_2 concentration. (**A**) Fossil fuel and industrial carbon emissions under these pathways. (**B**) Corresponding carbon emissions from land-use changes. (**C**) Carbon taxes associated with these CO_2 concentration targets and pathways. (**D**) Global quantity of purpose-grown biomass energy in each of these scenarios.

the implications for land use and land-use change from limiting atmospheric CO_2 concentrations in an analysis that endogenously integrates land use with demands in both the agriculture and energy systems.

The results from this integrated assessment study show that if terrestrial carbon emissions are valued equally with carbon emissions from energy and industrial systems in a regime designed to limit atmospheric CO_2 concentrations, there are wide-ranging differences from the case where only carbon emissions from energy and industrial systems are valued. Deforestation is replaced by afforestation, crop prices rise, purpose-grown bioenergy becomes an important agricultural product, and people shift away from consumption of beef and other carbon-intensive protein sources. Further, the total cost of limiting atmospheric CO_2 concentrations is reduced, relative to an alternative regime that prices only fossil fuel and industrial carbon emissions, which implies that lower atmospheric CO_2 concentrations are achievable for any commitment of society's resources, a result consistent with other studies (*12*–*14*) that have examined the potential role of afforestation in limiting CO_2 concentrations. We also find that for any given atmospheric CO_2 limitation goal, the reduction in the cost relative to an alternative regime that prices only fossil fuel and industrial carbon emissions becomes more pronounced as the concentration limit is lowered. We further find that the assumed rate of improvement in crop productivity has a strong influence on land-use change emissions and, correspondingly, on the cost of mitigating climate change.

We employ the Joint Global Change Research Institute's MiniCAM integrated assessment model (*15*–*20*) to explore the implication of limiting atmospheric CO_2 concentrations at levels ranging from 450 ppm to 550 ppm. MiniCAM is a dynamic recursive model of energy, economy, agriculture, land use, and land cover that fully integrates the energy and agriculture systems with economic equilibrium in energy and agriculture markets. Our analysis employs the MiniCAM scenario documented in (*8*) but with an updated, fully integrated terrestrial ecosystem component as described in (*15*, *16*). This MiniCAM scenario assumes a growing population, an increasing standard of living, and the improvement of technology over time. Available energy technology options include CO_2 capture and storage (CCS); hydrogen production and use; nuclear energy; wind, solar, and geothermal power; improved end-use energy technologies in the building, industry, and transportation sectors; and bioenergy. We consider bioenergy production from biological waste streams and next-generation bioenergy from cellulosic (purpose-grown) bioenergy crops. In our reference scenario, we assume that the productivity of land-based products is subject to change over time based on future estimates of crop productivity change up to 2030 (*21*) and then converges to 0.25% per year thereafter (*15*). Land use is determined endogenously in MiniCAM by market forces (*15*, *22*). We also consider fossil fuel, industrial, and land-use change emissions in response to policy intervention modeled as a carbon tax. The distribution of terrestrial carbon reservoirs and their rates of change are computed endogenously in MiniCAM. Emissions limitation scenarios treat bioenergy as carbon neutral in the energy system. We assume that bioenergy can be used in a wide range of applications, including liquefaction to create fuels for transport. We also consider options to gasify bioenergy and use it in conjunction with CCS to make electricity. Market forces are assumed to determine the highest value applications.

We limit the concentration of atmospheric CO_2 by imposing a global carbon tax on anthropogenic carbon emissions (*23*). We consider two canonical tax regimes: (i) a Universal Carbon Tax regime (UCT) in which all carbon emissions in all sectors—including emissions from land-use change—and all regions of the world have



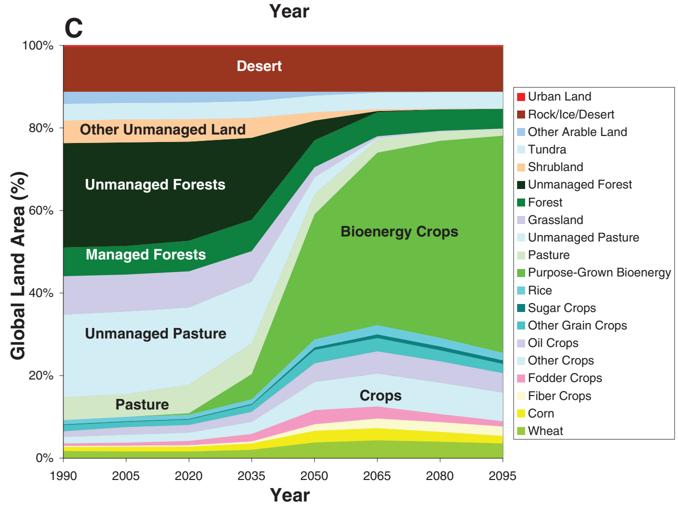


Fig. 2. A comparison of global land use under different scenarios. (**A**) Land use along the reference pathway. (**B**) Land use under a UCT pathway defined to achieve a CO_2 concentration target of 450 ppm, which limits fossil fuel, industrial, and terrestrial carbon emissions with a common carbon tax on emissions. (**C**) Land use along the corresponding FFICT scenario in which only fossil fuel and industrial emissions are controlled to achieve the same 450-ppm CO_2 concentration. In the FFICT scenario, the substantial increase in demand for purpose-grown biomass (four times as much as the reference scenario in Year 2095) intensifies its competition with food and fiber crops for the best cropland, pushing crops and biomass growth beyond traditional croplands and into lands that are inherently less productive. As a result, the relative increase in land required for biomass and other crops exceeds the relative increase in demand.

the same value at any point in time, and (ii) a Fossil Fuel and Industrial Emissions Carbon Tax regime (FFICT) in which the carbon tax is applied to fossil fuel and industrial emissions but not to terrestrial carbon emissions. In both cases, the carbon tax rises over time so as to limit atmospheric CO_2 concentrations to a prescribed level.

Whether the carbon tax is applied as a UCT or a FFICT has important implications for the source of emissions and for land-use patterns. Placing an increasingly stringent tax on only the fossil fuel and industrial carbon emissions without placing any corresponding tax on terrestrial carbon (i.e., the FFICT regime) causes land-use change emissions to increase to a peak greater than 10 Pg C per year, as lands are converted to meet the growing demands for purpose-grown bioenergy crops in a growing but decarbonizing energy system (Fig. 1). This is the same effect observed by earlier studies, including (*1*, *3*). The increased demand for bioenergy crops pushes land requirements beyond traditional croplands and into lands that are increasingly less productive, requiring increasing quantities of land to grow each successive unit of agricultural product. The result is that in the FFICT regimes virtually all land that is not required for growing food and forest products is used for growing bioenergy (Fig. 2).

Such grand-scale deforestation is hard to imagine in reality, because it is hard to imagine that society would find this result acceptable. Nevertheless, this admittedly extreme case stands in sharp contrast to the UCT regime in which land-use change emissions face the same carbon tax as fossil fuel and industrial emissions. The application of a carbon tax to terrestrial carbon emissions sends an increasingly strong price signal that expands forested land while land dedicated to bioenergy crop production is limited (Fig. 2) (*24*), although bioenergy remains an important technology in the overall mitigation portfolio. The difference in cumulative land-use change emissions between the FFICT and UCT regimes, from 2005 through 2100, ranges from >300 Pg C (550-ppm limit) to >400 Pg C (450-ppm limit).

For any given concentration limit, the proportion of emissions from fossil fuel and industrial sources and land-use change is affected by the tax regime. The UCT regime results in a higher proportion of emissions from fossil fuel and industrial sources, with a correspondingly lower proportion of emissions from land-use change (*25*). Equivalently, at any given carbon price, carbon emissions are lower when terrestrial carbon is valued.

Applying a carbon tax to all carbon emissions (the UCT regime) reduces economic impacts relative to the FFICT approach. At all atmospheric CO_2 concentration limits, we find that the resulting carbon tax under the UCT regime was less than half that of the carbon tax resulting from the FFICT regime. This reduction in economic impacts flows naturally from economic principles. The UCT regime covers all emissions sources rather than a subset of emissions sources and thus is economically more efficient.

We also note that crop (including food and fiber) prices rise in the UCT regime as a consequence of the economic impact from valuing terrestrial carbon, even in the absence of purpose-grown bioenergy crops. This follows directly from limitations on land availability and the expanded use of land in the form of managed forests and unmanaged ecosystems in the UCT scenarios. The crop price increase is highest for the most carbon-intensive agricultural activities, and the crop price effect becomes more pronounced for stricter concentration limits. Changing agricultural prices flowing from the UCT also drive changes in dietary composition, reducing emphasis on beef and other carbon-intensive protein sources, which in turn frees up land for bioenergy and other crop production.

By comparing results to scenarios in which no purpose-grown bioenergy crops are allowed, Fig. 3 decomposes the effects of valuing carbon on crop prices, using corn prices as representative. The figure shows that there is virtually no discernible effect on corn prices in the reference scenario when purpose-grown bioenergy crops are removed from the analysis. However, when CO_2 concentration is limited (to 500 ppm here, for example), both valuing terrestrial carbon and allowing purpose-grown bioenergy exert upward pressure on crop prices.

Finally, terrestrial carbon emissions are sensitive to crop productivity growth assumptions. As a sensitivity experiment, we held crop productivity constant at 2005 levels. Land-use change carbon emissions in a scenario where no climate policy was imposed were more than 70 Pg C higher over the 21st century because greater amounts of land were necessary to produce the same amount of food. In the "frozen productivity" scenario, crop land expansion dramatically encroaches on forested lands, releasing the carbon stored in forest vegetation and soils. The difference in land-use change emissions in 2050 is larger than one "wedge" (*26*), defined as approximately 1 Pg C per year in 2050. Improved crop productivity thus has the potential to reduce anthropogenic carbon emissions at a magnitude similar to the energy technologies identified by other studies (*26*, *27*).

Limiting atmospheric CO_2 concentrations through a comprehensive approach that fully incorporates both terrestrial emissions and fossil and industrial emissions carries with it profound implications for forests, crop and livestock prices, diet, the global energy system, and the cost of meeting environmental goals. However, in this study we have not examined the implications for non-CO_2 emissions, which are a major component of terrestrial system emissions. These interactions are important, as was shown by (*6*, *28*). Another limitation of this study is water, which we have not explicitly modeled.

Most of the world's fossil fuel and industrial carbon emissions today carry no value, explicit or implicit. Considerable research has investigated alternative mechanisms for pricing fossil fuel and industrial carbon, both explicitly through taxes or cap-and-trade regimes and implicitly through regulatory frameworks. Less attention has been placed on developing methods of associating carbon values with terrestrial systems, at least in part because they are less straightforward than those dealing with fossil fuel carbon emissions and because the cost of implementing emissions mitigation policies in terrestrial systems would probably be higher than in the energy system. The development of methods for conveying carbon values to land-use decision-makers could substantially improve the environmental effectiveness of global carbon emissions limitation systems. Improved land-use management and improved agricultural practices could reduce upward pressure on crop prices and the cost of emissions mitigation. However, the allocation of scarce land resources to competing ends will remain a major challenge for the 21st century.

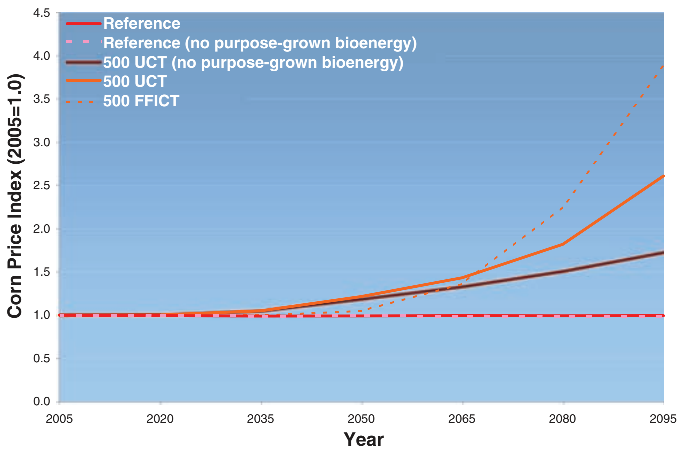


Fig. 3. The price of corn associated with a reference pathway; a pathway defined to achieve a UCT CO_2 concentration target of 500 ppm in 2095, which limits fossil fuel, industrial, and terrestrial carbon emissions with a common carbon tax on emissions; and a comparison to the corresponding FFICT scenario in which only fossil fuel and industrial emissions are controlled to achieve the same CO_2 concentration. To isolate the impact of bioenergy on the price, a second reference pathway and a second UCT-derived 500-ppm 2095 CO_2 concentration target pathway are constructed under the assumption that no purpose-grown bioenergy is available.

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24. Our analysis finds that bioenergy derived from biological waste streams (e.g., agriculture and forestry residues) is potentially of comparable magnitude to purpose-grown bioenergy production in the UCT policy regimes.
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Supporting Online Material

www.sciencemag.org/cgi/content/full/324/5931/1183/DC1
Materials and Methods
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Figs. S1 and S2
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References

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Penultimate Deglacial Sea-Level Timing from Uranium/Thorium Dating of Tahitian Corals

Alex L. Thomas,[1]* Gideon M. Henderson,[1] Pierre Deschamps,[2] Yusuke Yokoyama,[3,4,5] Andrew J. Mason,[1] Edouard Bard,[2] Bruno Hamelin,[2] Nicolas Durand,[2] Gilbert Camoin[2]

The timing of sea-level change provides important constraints on the mechanisms driving Earth's climate between glacial and interglacial states. Fossil corals constrain the timing of past sea level by their suitability for dating and their growth position close to sea level. The coral-derived age for the last deglaciation is consistent with climate change forced by Northern Hemisphere summer insolation (NHI), but the timing of the penultimate deglaciation is more controversial. We found, by means of uranium/thorium dating of fossil corals, that sea level during the penultimate deglaciation had risen to ~85 meters below the present sea level by 137,000 years ago, and that it fluctuated on a millennial time scale during deglaciation. This indicates that the penultimate deglaciation occurred earlier with respect to NHI than the last deglacial, beginning when NHI was at a minimum.

Fossil corals are a valuable archive of past sea level, but the density of coral data is biased toward sea-level highstands because of the inaccessibility of fossil corals that grew during lower sea level and are now further submerged. Reconstruction of lower sea levels has relied on dredging and submersible sampling, occasional fortuitous finds in uplifted terraces (*1*, *2*), and the challenging approach of coral-reef drilling. Such drilling, while technically demanding and expensive, has yielded valuable records of sea-level change for the last deglacial (*3*, *4*) and more limited constraints on the onset of the last interglacial (*5*).

To target deeper and earlier portions of the sea-level curve, Integrated Ocean Drilling Program (IODP) Expedition 310 (known as the "Tahiti Sea Level" expedition) drilled submerged reefs in seawaters ranging from 41.7 to 117.5 m (*6*). The island of Tahiti Nui (French Polynesia) is located in the southern tropical Pacific and is distant from locations of glacial ice sheets. Sea-level change at Tahiti during deglaciation is therefore dominated by the addition of meltwater to the oceans rather than by the effects of ice mass redistribution and isostacy. Steady subsidence of 0.25 m per 1000 years (*4*), resulting from the load of the island on the underlying oceanic plate coupled with a location distant from ice loading, makes Tahiti an ideal site to reconstruct past sea levels. Material from before the Last Glacial Maximum was recovered at each of the three locations where Tahiti drilling was performed (Faaa, Maraa, and Tiarei) (*6*) (fig. S1) and seven separate cores have yielded pre-LGM corals suitable for U/Th dating from 113 to 147 m below sea level (mbsl).

Corals were screened for secondary calcite and aragonite by x-ray diffraction (XRD) and thin-section petrography. Of the 25 pre-LGM corals analyzed for U-Th isotopes (*7*), 12 had values of $(^{234}U/^{238}U)_i$ ($^{234}U/^{238}U$ ratios corrected for decay since deposition) between 137 and 151 per mil (‰), which we take as a reasonable range on the basis of known variability of past seawater $^{234}U/^{238}U$ ratios during the glacial-interglacial cycle (*5*, *8*). These 12 are considered pristine and are discussed further here; replicate measurements that differ significantly have been excluded from discussion (but are illustrated in Fig. 1B as small circles).

Corals of marine isotope stage 3 (MIS 3) age, after a correction for subsidence [0.25 m per 1000 years (*4*)], occur at 105 to 130 mbsl with ages

[1]Department of Earth Sciences, Oxford University, Parks Road, Oxford OX1 3PR, UK. [2]CEREGE (UMR 6635), Aix-Marseille Université, CNRS, IRD, Collège de France, Europole de l'Arbois, BP80, 13545 Aix-en-Provence, France. [3]Ocean Research Institute, University of Tokyo, Tokyo 164-8639, Japan. [4]Department of Earth and Planetary Sciences, Graduate School of Science, University of Tokyo, Tokyo 113-0033, Japan. [5]Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology, Yokosuka 237-0061, Japan.

*To whom correspondence should be addressed. E-mail: alext@earth.ox.ac.uk