Arid conditions limit the forest restoration potential of many regions of Australia.

Edited by **Jennifer Sills**

Forest restoration: Overlooked constraints

In their Report "The global tree restoration potential" (5 July, p. 76), J.-F. Bastin *et al.* use machine learning to derive the carbon storage potential of global tree restoration, which they identify as the most effective climate change mitigation option. However, the study likely overestimates the actual potential by identifying opportunities for increasing canopy cover in environments with obvious environmental or socioeconomic constraints.

In high-latitude regions of Russia, Scandinavia, and North America, permafrost and short growing seasons (*1*) impair tree growth. In large parts of Australia and other arid and hyperarid regions, salinity, sodicity, hardpans, and moisture limitations prevent tree establishment (*2*, *3*). In African grasslands, infertile soils, grazing animals, water constraints, and wildfires maintain patchy shrub–grass environments (*4*). In areas with severely degraded soils and biodiversity loss in the Americas and in Asia (*5*, *6*), prospects of restoring pre-degradation canopy cover are limited. In grazing lands and production forests, abandoning current uses implies staggering absolute opportunity costs. Finally, Bastin *et al.* excluded areas classified as urban, but the data set they used (*7*) fails to recognize some major urban centers and many towns and villages in rural areas (*7*); more than 2.5 billion people live in areas that Bastin *et al.* considered eligible for restoration (*8*), including entire cities, such as Kinshasa, the capital of the Democratic Republic of Congo.

PHOTO: TONYFEDER/ISTOCK.COM

Bastin *et al.* introduced further overestimation by multiplying tree cover expansion potential by total ecosystem carbon. This operation lowers the baseline by assuming that carbon stock is proportionally related to canopy cover—i.e., that land with no trees contains no carbon. The use of biome-level carbon stock averages, without considering spatial variation, also adds considerable error, especially in alleged high-potential areas, where these averages (154.7 to 282.5 Mg ha^{-1}) are approximately 5 times greater than what has been reported in site-specific assessments (*9*, *10*).

We appreciate the need for benchmark estimates of carbon storage and restoration potentials, but realistic predictions require tapping expert knowledge to ensure relevant constraints are considered, as well as more rigorous quality control, such as mapping how model validation errors are spatially distributed. Overly hopeful figures produced by models without necessary supervision may misguide the development of climate policy (*11*, *12*).

Eike Luedeling[1], Jan Börner[2], Wulf Amelung[3], Katja Schiffers[1], Keith Shepherd[4], Todd Rosenstock[5]

[1]Department of Horticultural Sciences, Institute of Crop Science and Resource Conservation, University of Bonn, 53121 Bonn, Germany. [2]Department of Economics of Sustainable Land Use and Bioeconomy and Center for Development Research, Institute for Food and Resource Economics, University of Bonn, 53115 Bonn, Germany. [3]Department of Soil Science and Soil Ecology, Institute of Crop Science and Resource Conservation, University of Bonn, 53115 Bonn, Germany. [4]World Agroforestry Centre, Gigiri, Nairobi, Kenya. [5]World Agroforestry Centre, Kinshasa, Democratic Republic of Congo.
*Corresponding author.
Email: luedeling@uni-bonn.de

REFERENCES AND NOTES

1. J. Obu *et al.*, *Earth-Sci. Rev.* **193**, 299 (2019).
2. FAO and ITPS, "Status of the World's Soil Resources (SWSR)—Main Report: Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils" (Rome, Italy, 2015).
3. S. R. Morton *et al.*, *J. Arid Environ.* **75**, 313 (2011).
4. M. Sankaran *et al.*, *Nature* **438**, 846 (2005).
5. M. A. Stocking, *Science* **302**, 1356 (2003).
6. IPBES, "The IPBES assessment report on land degradation and restoration," L. Montanarella, R. Scholes, A. Brainich, Eds. (Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 2018).
7. O. Arino, Global Land Cover Map for 2009, European Space Agency (ESA) & Université Catholique de Louvain (UCL), PANGAEA, 10.1594/PANGAEA.787668 (GlobCover 2009).
8. Center for International Earth Science Information Network, Columbia University, Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11. (2018); https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11/metadata.
9. D. D. Shirima *et al. African J. Ecol.* **49**, 332 (2011).
10. M. B. Siewert *et al. J. Geophys. Res. Biogeosci.* **120**, 1973 (2015).
11. M. D. Mastrandrea *et al.*, "Guidance note for lead authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties" (IPCC, 2010); https://wg1.ipcc.ch/AR6/documents/AR5_Uncertainty_Guidance_Note.pdf.
12. C. M. Anderson *et al.*, *Science* **363**, 933 (2019).

10.1126/science.aay7988

Forest restoration: Expanding agriculture

In their Report "The global tree restoration potential" (5 July, p. 76), J.-F. Bastin *et al.* determine the available potential forest restoration area by excluding areas with existing trees, urban settlement, and cropland. However, they overestimate the potential area because they do not account for projected agricultural land expansion or current use of pasture land.

There is evidence from satellite imagery that most of global agricultural land expansion in the previous three decades happened and is still happening on tropical forest land, especially in Brazil and Southeast Asia (*1*–*3*). Given that this trend is likely to continue, especially in the highly productive areas in Central and South America, agricultural land expansion must be taken into account when assessing future tree restoration potentials (*4*–*6*). Food and Agriculture Organization projections expect an increase of cropland by 7% until 2030 (*7*), and evidence suggests an increase in global cropland area between 11 and 26% until 2050 (*8*), the latter corresponding to 4 million km². Based on one approach (*4*), not using this area for crop production would reduce global crop production by 11% and increase crop prices by 23%.

Furthermore, Bastin *et al.* assume that grassland would be available for tree restoration. They choose to ignore the data showing that currently about 30 million km² of grassland areas are used for extensive livestock production (*9*). Not utilizing areas for cropland expansion and pasture land requires a higher intensification of agriculture, which in turn is associated with higher agricultural emissions (*10*) and loss of biodiversity (*4*).

Bastin *et al.* do not consider current and future trade-offs with food security and neglect socioeconomic aspects of increasing consumption that arise through population growth, income growth, and preference changes toward more livestock products in fast-growing economies (*11*). Excluding estimated expansion areas and grazing land reduces the calculated sequestration potential by 19 and 57%, respectively, when applying the carbon densities of the bookkeeping model BLUE (*12*).

Ruth Delzeit[1], Julia Pongratz[2,3], Julia M. Schneider[2], Franziska Schuenemann[1]*, Wolfram Mauser[2], Florian Zabel[2]*

[1]Kiel Institute for the World Economy, 24105 Kiel, Germany. [2]Ludwig-Maximilians-University, 80333 Munich, Germany. [3]Max Planck Institute for Meteorology, 20146 Hamburg, Germany.
*Corresponding author. Email: franziska.schuenemann@ifw-kiel.de (F.S.); f.zabel@lmu.de (F.Z.)

Expanding agricultural land and livestock production could conflict with forest restoration goals.

PHOTO: UMKEHRER/ISTOCK.COM

REFERENCES AND NOTES

1. J. A. Foley *et al.*, *Nature* **478**, 337 (2011).
2. H. K. Gibbs *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **107**, 16732 (2010).
3. Z. Zeng *et al.*, *Nat. Geosci.* **11**, 556 (2018).
4. F. Zabel *et al.*, *Nat. Commun.* **10**, 2844 (2019).
5. R. Delzeit, F. Zabel, C. Meyer, T. Václavík, *Region. Environ. Change* **17**, 1429 (2017).
6. A. Molotoks *et al.*, *Glob. Change Biol.* **24**, 5895 (2018).
7. N. Alexandratos, J. Bruinsma, "World agriculture towards 2030/2050: the 2012 revision," *ESA Working Paper No. 12-03* (FAO, Rome, 2012).
8. C. Schmitz *et al.*, *Agric. Econ.* **45**, 69 (2014).
9. N. Ramankutty, A. T. Evan, C. Monfreda, J. A. Foley, *Glob. Biogeochem. Cycles* **22**, GB1003 (2008).
10. C. L. van Beek, B. G. Meerburg, R. L. M. Schils, J. Verhagen, P. J. Kuikman, *Environ. Sci. Pol.* **13**, 89 (2010).
11. F. Schuenemann, R. Delzeit, *Schriften der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaues e.V.* **64**, 185 (2019).
12. E. Hansis, S. J. Davis, J. Pongratz, *Glob. Biogeochem. Cycles* **29**, 1230 (2015).

10.1126/science.aaz0705

Forest restoration: Transformative trees

We welcome the attention given to forest and trees by the Report "The global tree restoration potential" (5 July, p. 76), in which J.-F. Bastin *et al.* study the potential of tree cover to reduce climate change. However, we are concerned by their neglect of the water cycle. They consider how water influences tree cover but disregard how tree cover influences water. Bastin *et al.* recognize that their extrapolations are not "future projections of potential forest extent" but instead represent potential tree cover "under existing environmental conditions." However, given the influence of forests on their environment, the concept of potential tree cover under current conditions is problematic. Trees influence several of the variables Bastin *et al.* used to model tree cover, including precipitation quantity, variability, and seasonality, as well as soil moisture and atmospheric water transport (*1*–*4*).

While much remains uncertain (*2*), we know enough to foresee that afforestation and reforestation have potential for both negative and positive hydrological impacts. Negative impacts can result if plantings deplete groundwater and thus exacerbate local water scarcity. Changes can manifest quickly and are a recognized problem with fast-growing monoculture plantations (*5*). Positive impacts can result when tree cover improves soil and groundwater recharge and storage, such as through suitable species and tree densities (*6*). Forest cover can also promote rainfall recycling and thus bolster and stabilize regional and downwind rainfall (*1*, *7*, *8*). In suitable circumstances, increased forest cover may even return wetter climates to currently drier regions, expanding the land available for trees (*2*). These outcomes have profound implications given that reliable access to water is central to achieving the UN Sustainable Development Goals. Accounting for the potentially transformative power of trees for both water and carbon offers crucial constraints as well as vast benefits.

Douglas Sheil,[1,2] Aida Bargués-Tobella,[3,4] Ulrik Ilstedt,[4] Pierre L. Ibisch,[5] Anastassia Makarieva,[6] Clive McAlpine,[7] Cindy E. Morris,[8] Daniel

Murdiyarso,[2,9] Antonio D. Nobre,[10] Germán Poveda,[11] Dominick V. Spracklen,[12] Caroline A. Sullivan,[13] Obbe A. Tuinenburg,[14] Ruud J. van der Ent[15,16]
[1]Faculty of Environmental Sciences and Natural Resource Management (MINA), Norwegian University of Life Sciences (NMBU), 1432 Ås, Norway. [2]Center for International Forestry Research (CIFOR), Bogor, Jawa Barat 16115, Indonesia. [3]World Agroforestry Centre (ICRAF), 00100, Nairobi, Kenya. [4]Department of Forest Ecology and Management, Swedish University of Agricultural Sciences (SLU), 901 83 Umeå, Sweden. [5]Centre for Econics and Ecosystem Management, Faculty of Forest and Environment, Eberswalde University for Sustainable Development, D-16225, Eberswalde, Germany. [6]Theoretical Physics Division, Petersburg Nuclear Physics Institute, St. Petersburg, Russia. [7]School of Earth and Environmental Sciences, The University of Queensland, St. Lucia, QLD 4072, Australia. [8]INRA, Plant Pathology Research Unit 407, PACA Research Center, 84143 Montfavet, France. [9]Department of Geophysics and Meteorology, Bogor Agricultural University, Bogor, Indonesia. [10]Centro de Ciencia do Sistema Terrestre INPE, São José dos Campos, São Paulo, Brazil. [11]Department of Geosciences and Environment, Universidad Nacional de Colombia, Medellín, Colombia. [12]School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK. [13]National Centre for Flood Research, Southern Cross University, Lismore, NSW 2480, Australia. [14]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, Netherlands. [15]Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands. [16]Department of Physical Geography, Faculty of Geosciences, Utrecht University, Utrecht, Netherlands.
*Corresponding author.
Email: douglas.sheil@nmbu.no

REFERENCES AND NOTES

1. D. Ellison *et al.*, *Glob. Environ. Change* **43**, 51 (2017).
2. D. Sheil, *For. Ecosyst.* **5**, 1 (2018).
3. J. S. Wright *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **114**, 8481 (2017).
4. J. F. Salazar *et al.*, *Hydrol. Earth Syst. Sci.* **22**, 1735 (2018).
5. R. B. Jackson *et al.*, *Science* **310**, 1944 (2005).
6. U. Ilstedt *et al.*, *Sci. Rep.* **6**, 21930 (2016).
7. L. Wang-Erlandsson *et al.*, *Hydrol. Earth Syst. Sci.* **22**, 4311 (2018).
8. A. Staal *et al.*, *Nat. Clim. Change* **8**, 539 (2018).

10.1126/science.aay7309

Response

Luedeling and colleagues argue that we have overestimated the restoration capacity in several regions of the world. Our model predicts the expected optimal tree cover from a combination of 10 environmental variables that were selected through a variable selection procedure to avoid overfitting issues. As detailed in table S1 of our supplementary material, these 10 variables include mean annual temperature, temperature of the wettest quarter, annual precipitation, precipitation seasonality, precipitation of the driest quarter, elevation, hillshade, soil organic carbon, sand content, and depth to bedrock. These ecological variables cover average and seasonal variation in climate and variation in topographic and edaphic conditions. As such, we have done everything that is possible to represent all of the conditions raised by Luedeling and colleagues. Of course, cold and dry conditions are among the main limitations for tree growth, and that is why we have represented these environmental constraints in our model to ensure that we do not predict that trees can exist in regions that are too cold or dry.

As explained in the main text, our rigorous k-fold cross-validation (fig. S4A) revealed that our model could explain about 71% of the variation in tree cover without bias (fig. S3, B and C). This means that our model is unbiased at a global scale, but we do not explain 100% of the potential tree cover variation. It is consequently possible to find places where we overestimate or underestimate the potential tree cover—particularly in areas where uncertainties are high, as shown in fig S6.

Delzeit and colleagues claim that we overestimate the area available for tree restoration because the expansion of croplands in upcoming decades will reduce the land available for restoration, and because pasture lands are considered as potential land for restoration in our assessment. We agree that, if we continue to expand agricultural land area, there will be a reduction in the land available for restoration. As stated in our analysis, our model estimates the area that is currently available for restoration under present conditions. Of course, any changes in the area of land use will necessarily affect this global total. We exemplified this in our attempts to show how future changes in climate might reduce the area available for restoration. We hope that our analysis can also serve as a stepping stone for future research to evaluate how changes in agricultural land use will affect the potential restoration area.

It is true that we included rangelands in the area available for restoration. Of course, much of this land is used for the grazing of animals and so may not be available for complete forest restoration. However, as mentioned in the Report, several studies suggest that it is possible to increase the current tree cover in these areas without limiting food production (*1*, *2*), especially when forest cover is relatively low, as is the case for most of the pasture land in our model.

Because we removed all urban and agricultural land (i.e., we considered a potential increase of tree cover of 0% in cropland and urban areas), our numbers are likely to underestimate the total area that could currently be covered by trees. Indeed, both croplands and cities constitute great opportunities to increase the current tree cover and to play a major role in mitigating climate change (*3*–*5*). We maintain that our global estimate of the land available for restoration is a conservative one, and we encourage local land owners to use our forest restoration potential map in combination with more detailed local-scale estimates of land use when designing effective restoration strategies.

Sheil and colleagues point out that restoring ecosystems might have either positive or negative consequences regarding hydrology. We agree that these effects must be considered as a priority in upcoming research in restoration ecology.

Jean-Francois Bastin[1]*, Yelena Finegold[2], Claude Garcia[3,4], Danilo Mollicone[2], Marcelo Rezende[2], Devin Routh[1], Constantin M. Zohner[1], Thomas W. Crowther[1]
[1]Crowther Lab, Department of Environmental Systems Science, Institute of Integrative Biology, ETH Zürich, Zürich, Switzerland. [2]Food and Agriculture Organization of the United Nations, Rome, Italy. [3]Department of Environmental Systems Science, Institute of Integrative Biology, ETH Zürich, Zürich, Switzerland. [4]Centre de Coopération Internationale en la Recherche Agronomique pour le Développement (CIRAD), UR Forest and Societies, Montpellier, France.
*Corresponding author. Email: bastin.jf@gmail.com

REFERENCES AND NOTES

1. K.-H. Erb *et al.*, *Nature* **553**, 73 (2017).
2. K.-H. Erb *et al.*, *Nat. Commun.* **7**, 11382 (2016).
3. A. Albrecht, S. T. Kandji, *Agric. Ecosyst. Environ.* **99**, 15 (2003).
4. P. K. Ramachandran Nair, B. Mohan Kumar, V. D. Nair, *J. Plant Nutr. Soil Sci.* **172**, 10 (2009).
5. G. Manoli *et al.*, *Nature* **573**, 55 (2019).

10.1126/science.aaz2148

TECHNICAL COMMENT ABSTRACTS

Comment on "The global tree restoration potential"

Pierre Friedlingstein, Myles Allen, Josep G. Canadell, Glen P. Peters, Sonia I. Seneviratne

Bastin *et al*. (Reports, 5 July 2019, p. 76) claim that global tree restoration is the most effective climate change solution to date, with a reported carbon storage potential of 205 gigatonnes of carbon. However, this estimate and its implications for climate mitigation are inconsistent with the dynamics of the global carbon cycle and its response to anthropogenic carbon dioxide emissions.

Full text: dx.doi.org/10.1126/science.aay8060

Comment on "The global tree restoration potential"

Joseph W. Veldman, Julie C. Aleman, Swanni T. Alvarado, T. Michael Anderson, Sally Archibald, William J. Bond, Thomas W. Boutton, Nina Buchmann, Elise Buisson, Josep G. Canadell, Michele de Sá Dechoum, Milton H. Diaz-Toribio, Giselda Durigan, John J. Ewel, G. Wilson Fernandes, Alessandra Fidelis, Forrest Fleischman, Stephen P. Good, Daniel M. Griffith, Julia-Maria Hermann, William A. Hoffmann, Soizig Le Stradic, Caroline E. R. Lehmann, Gregory Mahy, Ashish N. Nerlekar, Jesse B. Nippert, Reed F. Noss, Colin P. Osborne, Gerhard E. Overbeck, Catherine L. Parr, Juli G. Pausas, R. Toby Pennington, Michael P. Perring, Francis E. Putz, Jayashree Ratnam, Mahesh Sankaran, Isabel B. Schmidt, Christine B. Schmitt, Fernando A. O. Silveira, A. Carla Staver, Nicola Stevens, Christopher Still, Caroline A. E. Strömberg, Vicky M. Temperton, J. Morgan Varner, Nicholas P. Zaloumis

Bastin *et al*.'s estimate (Reports, 5 July 2019, p. 76) that tree planting for climate change mitigation could sequester 205 gigatonnes of carbon is approximately five times too large. Their analysis inflated soil organic carbon gains, failed to safeguard against warming from trees at high latitudes and elevations, and considered afforestation of savannas, grasslands, and shrublands to be restoration.

Full text: dx.doi.org/10.1126/science.aay7976

Comment on "The global tree restoration potential"

Simon L. Lewis, Edward T. A. Mitchard, Colin Prentice, Mark Maslin, Ben Poulter

Bastin *et al*. (Reports, 5 July 2019, p. 76) state that the restoration potential of new forests globally is 205 gigatonnes of carbon, conclude that "global tree restoration [is] our most effective climate change solution to date," and state that climate change will drive the loss of 450 million hectares of existing tropical forest by 2050. Here we show that these three statements are incorrect.

Full text: dx.doi.org/10.1126/science.aaz0388

Response to Comments on "The global tree restoration potential"

Jean-Francois Bastin, Yelena Finegold, Claude Garcia, Nick Gellie, Andrew Lowe, Danilo Mollicone, Marcelo Rezende, Devin Routh, Moctar Sacande, Ben Sparrow, Constantin M. Zohner, Thomas W. Crowther

Our study quantified the global tree restoration potential and its associated carbon storage potential under existing climate conditions. We received multiple technical comments, both supporting and disputing our findings. We recognize that several issues raised in these comments are worthy of discussion. We therefore provide a detailed common answer where we show that our original estimations are accurate.

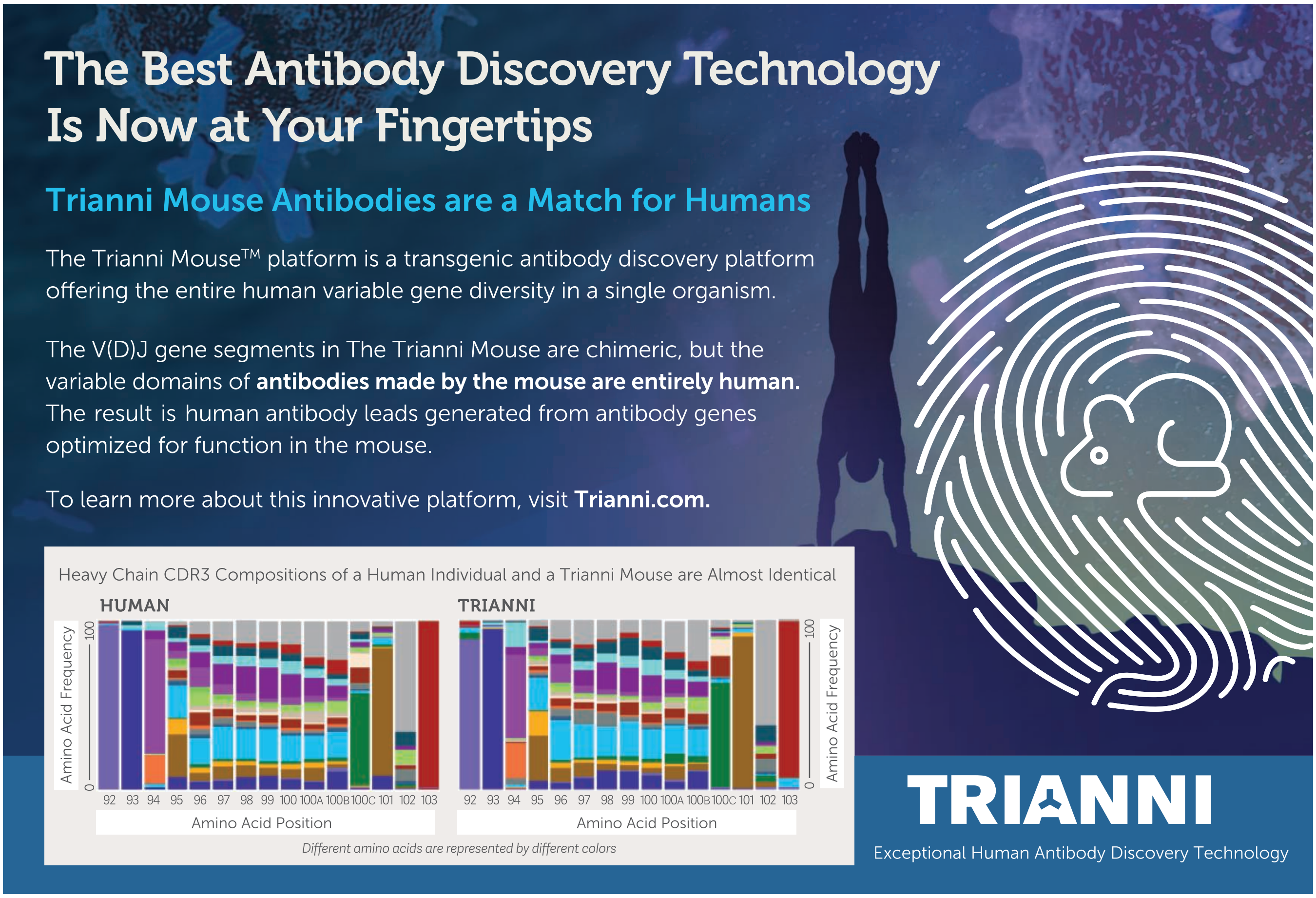
Full text: dx.doi.org/10.1126/science.aay8108

Comment on "The global tree restoration potential"

Alan Grainger, Louis R. Iverson, Gregg H. Marland, Anantha Prasad

Bastin *et al*. (Reports, 5 July 2019, p. 76) neglect considerable research into forest-based climate change mitigation during the 1980s and 1990s. This research supports some of their findings on the area of land technically suitable for expanding tree cover and can be used to extend their analysis to include the area of actually available land and operational feasibility.

Full text: dx.doi.org/10.1126/science.aay8334



Science

Forest restoration: Transformative trees

Douglas Sheil, Aida Bargués-Tobella, Ulrik Ilstedt, Pierre L. Ibisch, Anastassia Makarieva, Clive McAlpine, Cindy E. Morris,
Daniel Murdiyarso, Antonio D. Nobre, Germán Poveda, Dominick V. Spracklen, Caroline A. Sullivan, Obbe A. Tuinenburg and
Ruud J. van der Ent

Science **366** (6463), 316-317.
DOI: 10.1126/science.aay7309

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.