Comment on “The global tree restoration potential”

Joseph W. Veldman[1,2,*], Julie C. Aleman[1,3], Swanni T. Alvarado[4,5], T. Michael Anderson[6], Sally Archibald[7], William J. Bond[8], Thomas W. Boutton[1], Nina Buchmann[9], Elise Buisson[10], Josep G. Canadell[11], Michele de Sá Dechoum[12], Milton H. Diaz-Toribio[13], Giselda Durigan[14], John J. Ewel[13], G. Wilson Fernandes[15], Alessandra Fidelis[16], Forrest Fleischman[17], Stephen P. Good[18], Daniel M. Griffith[19], Julia-Maria Hermann[20], William A. Hoffmann[21], Soizig Le Stradic[22], Caroline E. R. Lehmann[23,24], Gregory Mahy[25], Ashish N. Nerlekar[1], Jesse B. Nippert[26], Reed F. Noss[27], Colin P. Osborne[28], Gerhard E. Overbeck[29], Catherine L. Parr[7,30,31], Juli G. Pausas[32], R. Toby Pennington[23,33], Michael P. Perring[34,35], Francis E. Putz[13], Jayashree Ratnam[36], Mahesh Sankaran[37,38], Isabel B. Schmidt[39], Christine B. Schmitt[40,41], Fernando A. O. Silveira[42], A. Carla Staver[43], Nicola Stevens[44], Christopher J. Still[45], Caroline A. E. Strömberg[46], Vicky M. Temperton[47], J. Morgan Varner[48], Nicholas P. Zaloumis[49] and Nicholas P. Zaloumis[49]

[1] *Department of Ecosystem Science and Management, Texas A&M University, College Station, TX 77843, USA.*
[2] *Instituto Boliviano de Investigación Forestal, Casilla 6204, Santa Cruz, Bolivia.*
[3] *Département de Géographie, Université de Montréal, Montreal, QC H3C 3J7, Canada.*
[4] *Programa de Pós-graduação em Agricultura e Ambiente, Universidade Estadual de Maranhão (UEMA), Balsas, Maranhão, Brazil.*
[5] *Programa de Pós-graduação em Geografia, Natureza e Dinâmica do Espaço, Universidade Estadual de Maranhão (UEMA), São Luis, Maranhão, Brazil.*
[6] *Department of Biology, Wake Forest University, Winston-Salem, NC 27109, USA.*
[7] *Centre for African Ecology, School of Animal, Plant and Environmental Sciences, University of the Witwatersrand, Johannesburg 2050, South Africa.*
[8] *Department of Biological Sciences, University of Cape Town, Rondebosch, South Africa.*
[9] *Department of Environmental Systems Science, ETH Zurich, 8092 Zurich, Switzerland.*
[10] *Avignon Université, IMBE, CNRS, IRD, Aix Marseille Université, Marseille, France.*
[11] *Global Carbon Project, CSIRO Oceans and Atmosphere, Canberra, ACT 2601, Australia.*
[12] *Departamento de Ecologia e Zoologia, Programa de Pós-graduação em Ecologia, Universidade Federal de Santa Catarina, Florianopolis, Santa Catarina 88040-900, Brazil.*
[13] *Department of Biology, University of Florida, Gainesville, FL 32611, USA.*
[14] *Floresta Estadual de Assis, Instituto Florestal do Estado de São Paulo, São Paulo 19807-300, Brazil.*
[15] *Departamento de Biologia Geral/ICB, Universidade Federal de Minas Gerais, Belo Horizonte, MG 30161, Brazil.*
[16] *Lab of Vegetation Ecology, Instituto de Biociências, Universidade Estadual Paulista (UNESP), Rio Claro 13506-900, Brazil.*
[17] *Department of Forest Resources, University of Minnesota, St. Paul, MN 55108, USA.*
[18] *Department of Biological and Ecological Engineering, Oregon State University, Corvallis, OR 97330, USA.*
[19] *Forest Ecosystems and Society, Oregon State University, Corvallis, OR 97331, USA.*
[20] *Environmental Management, Evangelical Lutheran Church District of Rendsburg-Eckernfoerde, Rendsburg, Germany.*
[21] *Department of Plant and Microbial Biology, North Carolina State University, Raleigh, NC 27695, USA.*
[22] *Chair of Restoration Ecology, Department Ecology and Ecosystem Management, Technische Universität München, 85354 Freising, Germany.*
[23] *Royal Botanic Garden Edinburgh, Edinburgh EH3 5LR, UK.*
[24] *School of GeoSciences, University of Edinburgh, Edinburgh EH9 3FF, UK.*
[25] *Terra Research Unit, Biodiversity and Landscape, Gembloux Agro-Bio Tech, University of Liège, Gembloux, Belgium.*
[26] *Division of Biology, Kansas State University, Manhattan, KS 66506, USA.*
[27] *Florida Institute for Conservation Science, Siesta Key, FL 34242, USA.*
[28] *Department of Animal and Plant Sciences, University of Sheffield, Sheffield S10 2TN, UK.*
[29] *Department of Botany, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS 91501-970, Brazil.*
[30] *School of Environmental Sciences, University of Liverpool, Liverpool L69 3GP, UK.*
[31] *Department of Zoology and Entomology, University of Pretoria, Pretoria, South Africa.*
[32] *Desertification Research Center (CIDE-CSIC), Valencia, Spain.*
[33] *Geography, University of Exeter, Exeter EX4 4QE, UK.*

[34]*Forest and Nature Lab, Department of Environment, Ghent University, Ghent, Belgium.*
[35]*Ecosystem Restoration and Intervention Ecology Research Group, School of Biological Sciences, University of Western Australia, Crawley, WA 6009, Australia.*
[36]*Wildlife Biology and Conservation Program, National Centre for Biological Sciences, GKVK Campus, Bengaluru 560065, India.*
[37]*National Centre for Biological Sciences, TIFR, Bengaluru 560065, India.*
[38]*School of Biology, University of Leeds, Leeds LS2 9JT, UK.*
[39]*Departamento de Ecologia, Universidade de Brasília, Campus Universitário Darcy Ribeiro, Brasília, DF 70910-900, Brazil.*
[40]*Center for Development Research (ZEF), University of Bonn, Bonn, Germany.*
[41]*Chair of Nature Conservation and Landscape Ecology, University of Freiburg, Freiburg, Germany.*
[42]*Departamento de Genética, Ecologia e Evolução, Universidade Federal de Minas Gerais, Belo Horizonte 31270-901, Brazil.*
[43]*Ecology and Evolutionary Biology, Yale University, New Haven, CT 06511, USA.*
[44]*Department of Botany and Zoology, University of Stellenbosch, Stellenbosch 7602, South Africa.*
[45]*College of Forestry, Oregon State University, Corvallis, OR 97331, USA.*
[46]*Department of Biology and Burke Museum of Natural History and Culture, University of Washington, Seattle, WA 98105, USA.*
[47]*Institute of Ecology, Faculty of Sustainability, Leuphana University Lüneburg, 21335 Lüneburg, Germany.*
[48]*Tall Timbers Research Station and Land Conservancy, Tallahassee, FL 32312, USA.*
[49]*Unaffiliated scholar, Cape Town 7708, South Africa.*

*Corresponding author. Email: veldman@tamu.edu

Abstract

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.

Bastin *et al*. (*1*) used remote sensing and machine learning to estimate that global "tree restoration" could sequester 205 gigatonnes of carbon (GtC). If accurate and achievable, this would constitute an astounding accomplishment, equal to 20 times the current annual fossil fuel emissions (10 GtC/year) (*2*) and about one-third of total historical anthropogenic emissions (660 GtC) (*2*). Unfortunately, key assumptions and data underlying Bastin *et al*.'s analyses are incorrect, resulting in a factor of 5 overestimate of the potential for new trees to capture carbon and mitigate climate change. We show that Bastin *et al*. (i) overestimated soil carbon gains from increased tree cover by a factor of 2; (ii) modeled new tree cover in regions where trees reduce albedo and increase climate warming (*3*, *4*); and (iii) relied heavily on afforestation of grasslands and savannas—biodiverse ecosystems where fires and large herbivores have maintained low tree cover for millions of years (*5*, *6*).

Bastin *et al*.'s inflation of soil carbon gains resulted in a ~98 GtC overestimate of potential carbon sequestration (Table 1). They mistakenly assumed that treeless areas have no soil organic carbon (SOC) and that SOC increases in direct (1:1) proportion to tree cover. The contribution of SOC to total carbon stocks is substantial in most terrestrial ecosystems. In humid tropical savannas, for example, 86% of all carbon is in soils (174 tonnes of SOC per hectare) (*7*). In boreal forests, 64% of carbon occurs in soils (*8*). North American grasslands can store as much carbon in soil (*9*) as tropical forests store as biomass (*8*). In Table 1, we display SOC-corrected carbon sequestration estimates that use more realistic (literature-derived) values for the changes in SOC that occur with afforestation and reforestation.

Table 1. Corrected estimates of the potential for increased tree cover to sequester carbon and mitigate climate change. We corrected Bastin *et al.*'s estimate (205 GtC) to represent realistic gains or losses of soil organic carbon (SOC) that occur with increased tree cover in each biome [based on (*9*, *16*–*21*)]. We then excluded biomes (assigned a value of 0 GtC) where tree planting for climate change mitigation should not occur because of unintended consequences (e.g., net warming from reduced albedo or loss of biodiversity). Although we disagree with several of the carbon density values used by Bastin *et al.* [e.g., they applied values for intact tropical forests (*8*) to estimate second-growth forest biomass, and applied values from humid tropical savannas (*7*) to deserts and tundra], we retained these values to demonstrate the magnitude of the SOC and biome corrections.

	Potential carbon stocks, Bastin *et al.* (*1*)						**Correction for soil carbon**			**Correction to avoid unintended**	
Biome*	**Canopy cov restoration a (Mha)***	**Carbon density (tC/ha)***	**Carbo density source***	**Carbo gain (GtC)***	**ΔC bioma (tC/ha)†**	**ΔSOC (tC/ha)**	**Realistic ΔSOC (tC/ha)**	**Realisti ΔSOC source**	**SOC-correc carbon gai (GtC)¶**	**Biome-correc carbon gain (GtC)**	**Detrimental effects of carbon-focused tree**
Boreal forests/taiga	178	239	(*8*)	42.6	85	154	0	(*16*)‡	15.2	0	↓albedo (net warming)
Deserts and xeric shrublands	78	202	(*7*)	15.7	28	174	5.1	(*9*)§	2.6	0	↓provisioning of water, ↑fire
Flooded grasslands	9	202	(*7*)	1.8	28	174	12.4	(*17*)	0.4	0	intensity ↓biodiversity
andsavannas Montane	19	202	(*7*)	3.9	28	174	–3.3	(*18*)	0.5	0	↓biodiversity, ↓albedo (net
grasslands and shrublands	73	155	(*8*)	11.2	81	74	–3.3	(*18*)	5.6	0	warming) ↓biodiversity,
Temperate grasslands											↓forage production, ↑fire
Tropical grasslands	190	283	(*8*)	53.5	199	84	12.4	(*17*)	40.0	0	↓biodiversity, ↓provisioning of water, ↓forage production, ↑fire severity
Tundra	51	202	(*7*)	10.2	28	174	0	(*19*)‡	1.4	0	↓albedo (net warming)
Mangroves	3	283	(*8*)	0.7	199	84	198	(*20*)	1.0	1.0	
Mediterranean forests	19	202	(*7*)	3.8	28	174	0	(*21*)‡	0.5	0.5	↑fire intensity#
Temperate broadleaf	109	155	(*8*)	16.9	81	74	–3.3	(*18*)	8.4	8.4	
Temperate conifer forests	36	155	(*8*)	5.6	81	74	–3.3	(*18*)	2.8	2.8	↑fire intensity and severity, ↓albedo#
Tropical coniferous	7	283	(*8*)	2.0	199	84	12.4	(*17*)	1.5	1.5	
forests Tropical dry	33	283	(*8*)	9.3	199	84	12.4	(*17*)	6.9	6.9	
broadleaf forests Tropical	97	283	(*8*)	27.4	199	84	12.4	(*17*)	20.5	20.5	
Total	900			205					107	42	

*From materials and methods and table S2 of Bastin *et al.* (*1*): Carbon gain = canopy cover restoration area × carbon density.

†Portion of carbon density attributable to biomass and soil, from the same sources used by Bastin *et al.* [i.e., (*7*, *8*)]. ‡Studies that report no statistically significant change in SOC.

§Mean of two sites with annual precipitation < 300 mm.

¶SOC-corrected carbon gain = canopy cover restoration area × (ΔC biomass + realistic ΔSOC).

#Strength of effects depends on ecological context, but effects are not universal enough to exclude the biome.

In addition to the SOC overestimate, Bastin *et al*. did not account for the warming effect of trees due to decreased albedo (*3*, *4*). Trees, particularly evergreen conifers, are less reflective than snow, bare ground, or grasses, and thus absorb more solar energy, which is ultimately emitted as heat. At high latitudes and elevations, the warming effect of trees is greater than their cooling effect via carbon sequestration (*3*, *4*). Similarly, trees planted in low-latitude, semi-arid regions can produce net warming for decades before carbon sequestration benefits are realized (*10*). Because, at a minimum, carbon from trees planted in boreal forests, tundra, or montane grasslands and shrublands should not be counted as climate change mitigation (Bastin *et al*. counted a SOC-corrected 17 GtC), in Table 1 we provide a corrected estimate that excludes these biomes.

The carbon sequestration estimate of Bastin *et al*. is also dependent on the false assumption that natural grasslands and savannas with fewer trees than predicted by their statistical model are "degraded" and in need of restoration (*11*). Ecological restoration of savannas and grasslands rarely involves planting trees, and more often requires tree-cutting and prescribed fire to promote biodiversity and ecosystem services (*12*). Yet after correcting for SOC, 46% of the carbon sequestration estimate of Bastin *et al*. comes from increased tree cover in grasslands, savannas, and shrublands (Table 1). Among all biomes, tropical grasslands are the largest contributor to Bastin *et al*.'s estimate of potential carbon sequestration (SOC-corrected 40 GtC or 37% of the global potential; Table 1).

Although Bastin *et al*.'s model, developed with climate and soil data in protected areas, may be reasonable in some of the driest and wettest places on Earth, any statistical approach to predict tree cover at intermediate precipitation (500 to 2500 mm annually) must include the effects of fire and, where they still exist, large grazing and browsing animals (*13*). Because Bastin *et al*. failed to account for fire, their model had low predictive power across many of the open-canopy biomes they analyzed, as shown by their own uncertainty analysis. Although we commend their intent to respect the "natural ecosystem type" by training their machine-learning algorithm on protected areas, they map many of these same areas—particularly those with grassland-forest mosaics (e.g., Yellowstone National Park, USA)—as opportunities for tree planting. Of additional concern, their method of interpolation between protected areas misrepresents some enormous savanna regions (e.g., western Los Llanos in Colombia is targeted for 75 to 100% tree cover), presumably because the protected areas are located in adjacent tropical forests, not savannas.

Bastin *et al*.'s model suggesting grasslands and savannas as potential sites for restoration using trees is inaccurate and misguided. Earth's savannas and grasslands predate humans by millions of years; their formation is a result of complex ecological and evolutionary interactions among herbaceous plants (grasses and forbs with extensive roots and underground storage organs), environmental change (climatic cooling, drying, changes in atmospheric CO_2), fires (first ignited by lightning, then by people), and large herbivores (*5*, *6*). These ecosystems and their iconic species are already gravely threatened by fire exclusion and afforestation, processes that replace species-diverse biotic communities with lower-diversity forests (*14*). Carbon-focused tree planting will exacerbate these threats, to the detriment of people who depend on grasslands to provide livestock forage, game habitat, and groundwater and surface-water recharge (*11*). Moreover, trees planted in grasslands will be prone to carbon loss from fires. Because these detrimental effects should preclude tree planting in grasslands, savannas, and shrublands, we excluded these biomes from Bastin *et al*.'s estimate in Table 1.

In combination, our corrections for SOC and corrections to avoid the unintended consequences of misguided tree planting (i.e., warming and biodiversity loss with afforestation) would reduce Bastin *et al.*'s estimate of potential carbon sequestration by a factor of 5, to the still-substantial amount of ~42 GtC (Table 1). Although ecological restoration, if carefully implemented, can have a role in mitigating climate change, it is no substitute for the fact that most fossil fuel emissions will need to stop to meet the targets of the Paris Agreement (*15*). Such action should be accompanied by policies that prioritize the conservation of intact, biodiverse ecosystems, irrespective of whether they contain a lot of trees.

Acknowledgments: J.W.V. thanks B. J. Danielson for many conversations on related topics. **Funding:** Supported by the Texas A&M Sid Kyle Global Savanna Research Initiative (T.W.B.); Swiss National Science Foundation (20FI20_173691) (N.B.); Centre National pour la Recherche Scientifique CNRS PICS 2018-2020 (RESIGRASS) (E.B.); CNPq (Brazil, 303179/2016-3) (G.D.); CNPq (Brazil) (G.W.F.); CNPq (Brazil, 303988/2018-5) (A.F.); NASA award NNX17AK14G (F.F.); NSF award 1354943 (W.A.H.); Fundação de Amparo à Pesquisa do Estado de Minas Gerais (Brazil, 2016/13232-5) (S.L.S.); the Office of the Royal Society (IC170015) (C.E.R.L.); CNPq (Brazil, 310345/2018-9) (G.E.O.); the Spanish Government (FIROTIC, PGC2018-096569-B-I00) (J.G.P.); the National Research Foundation (ACCESS, 114695) (N.S.); CNPq (Brazil, 303568/2017-8) (F.A.O.S.); NSF awards 1342703 and 1926431 (C.J.S. and D.M.G.); NSF award EAR-1253713 (C.A.E.S.); Deutsche Forschungsgemeinschaft grant 5579 POEM (V.M.T.); and USDA-NIFA Sustainable Agricultural Systems Grant 12726253 (J.W.V.). **Author contributions:** J.W.V. wrote the paper with conceptual input from C.L.P., S.A., C.J.S., G.M., W.J.B., J.J.E., and V.M.T.; J.W.V. performed the carbon sequestration corrections in Table 1; J.G.P. and A.N.N. contributed to the literature search for ΔSOC values. All authors read and provided feedback on the draft manuscript. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data, explanations of calculations, and references to literature-derived values are presented in Table 1.

References

1. J. F. Bastin, Y. Finegold, C. Garcia, D. Mollicone, M. Rezende, D. Routh, C. M Zohner, T. W. Crowther, The global tree restoration potential. *Scienc*e 365, 76–79 (2019). doi:10.1126/science.aax0848 Medline
2. C. Le Quéré, R. M. Andrew, P. Friedlingstein, S. Sitch, J. Hauck, J. Pongratz, P. A. Pickers, J. I. Korsbakken, G. P. Peters, J. G. Canadell, A. Arneth, V. K. Arora, L. Barbero, A. Bastos, L. Bopp, F. Chevallier, L. P. Chini, P. Ciais, S. C. Doney, T. Gkritzalis, D. S. Goll, I. Harris, V. Haverd, F. M. Hoffman, M. Hoppema, R. A. Houghton, G. Hurtt, T. Ilyina, A. K. Jain, T. Johannessen, C. D. Jones, E. Kato, R. F. Keeling, K. K. Goldewijk, P. Landschützer, N. Lefèvre, S. Lienert, Z. Liu, D. Lombardozzi, N. Metzl, D. R. Munro, J. E. M. S. Nabel, S. Nakaoka, C. Neill, A. Olsen, T. Ono, P. Patra, A. Peregon, W. Peters, P. Peylin, B. Pfeil, D. Pierrot, B. Poulter, G. Rehder, L. Resplandy, E. Robertson, M. Rocher, C. Rödenbeck, U. Schuster, J. Schwinger, R. Séférian, I. Skjelvan, T. Steinhoff, A. Sutton, P. P. Tans, H. Tian, B. Tilbrook, F. N. Tubiello, I. T. van der Laan-Luijkx, G. R. van der Werf, N. Viovy, A. P. Walker, A. J. Wiltshire, R. Wright, S. Zaehle, B. Zheng, Global carbon budget 2018. *Earth Syst. Sci. Data* 10, 2141–2194 (2018). doi:10.5194/essd-10-2141-2018

3. Y. Li, M. Zhao, S. Motesharrei, Q. Mu, E. Kalnay, S. Li, Local cooling and warming effects of forests based on satellite observations. *Nat. Commun*. 6, 6603 (2015). doi:10.1038/ncomms7603 Medline
4. P. M. Mykleby, P. K. Snyder, T. E. Twine, Quantifying the trade-off between carbon sequestration and albedo in midlatitude and high-latitude North American forests. *Geophys. Res. Lett*. 44, 2493–2501 (2017). doi:10.1002/2016GL071459
5. C. A. E. Strömberg, Evolution of grasses and grassland ecosystems. *Annu. Rev. Earth Planet. Sci*. 39, 517–544 (2011). doi:10.1146/annurev-earth-040809- 152402
6. J. W. Veldman, E. Buisson, G. Durigan, G. W. Fernandes, S. Le Stradic, G. Mahy, D. Negreiros, G. E. Overbeck, R. G. Veldman, N. P. Zaloumis, F. E. Putz, W. J. Bond, Toward an old-growth concept for grasslands, savannas, and woodlands. *Front. Ecol. Environ*. 13, 154–162 (2015). doi:10.1890/140270
7. J. Grace, J. S. José, P. Meir, H. S. Miranda, R. A. Montes, Productivity and carbon fluxes of tropical savannas. J. Biogeogr. 33, 387–400 (2006). doi:10.1111/j.1365-2699.2005.01448.x
8. Y. Pan, R. A. Birdsey, J. Fang, R. Houghton, P. E. Kauppi, W. A. Kurz, O. L. Phillips, A. Shvidenko, S. L. Lewis, J. G. Canadell, P. Ciais, R. B. Jackson, S. W. Pacala, A. D. McGuire, S. Piao, A. Rautiainen, S. Sitch, D. Hayes, A large and persistent carbon sink in the world’s forests. *Science* 333, 988–993 (2011). doi:10.1126/science.1201609 Medline
9. R. B. Jackson, J. L. Banner, E. G. Jobbágy, W. T. Pockman, D. H. Wall, Ecosystem carbon loss with woody plant invasion of grasslands. *Natur*e 418, 623–626 (2002). doi:10.1038/nature00910 Medline
10. E. Rotenberg, D. Yakir, Contribution of semi-arid forests to the climate system. *Science* 327, 451–454 (2010). doi:10.1126/science.1179998 Medline
11. J. W. Veldman, G. E. Overbeck, D. Negreiros, G. Mahy, S. Le Stradic, G. W. Fernandes, G. Durigan, E. Buisson, F. E. Putz, W. J. Bond, Where tree planting and forest expansion are bad for biodiversity and ecosystem services. *Bioscience* 65, 1011–1018 (2015). doi:10.1093/biosci/biv118
12. E. Buisson, S. Le Stradic, F. A. O. Silveira, G. Durigan, G. E. Overbeck, A. Fidelis, G. W. Fernandes, W. J. Bond, J.-M. Hermann, G. Mahy, S. T. Alvarado, N. P. Zaloumis, J. W. Veldman, Resilience and restoration of tropical and subtropical grasslands, savannas, and grassy woodlands. *Biol. Rev. Camb. Philos. Soc.* 94, 590–609 (2019). doi:10.1111/brv.12470 Medline
13. A. C. Staver, S. Archibald, S. A. Levin, The global extent and determinants of savanna and forest as alternative biome states. *Science* 334, 230–232 (2011). doi:10.1126/science.1210465 Medline
14. R. C. R. Abreu, W. A. Hoffmann, H. L. Vasconcelos, N. A. Pilon, D. R. Rossatto, G. Durigan, The biodiversity cost of carbon sequestration in tropical savanna. *Sci. Adv*. 3, e1701284 (2017). doi:10.1126/sciadv.1701284 Medline
15. IPCC, *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, V. Masson-Delmotte et al., Eds. (World Meteorological Organization, Geneva, 2018).
16. O. V. Menyailo, B. A. Hungate, W. Zech, Tree species mediated soil chemical changes in a Siberian artificial afforestation experiment. *Plant Soi*l 242, 171–182 (2002). doi:10.1023/A:1016290802518

17. A. Don, J. Schumacher, A. Freibauer, Impact of tropical land-use change on soil organic carbon stocks–a meta-analysis. *Glob. Change Biol*. 17, 1658–1670 (2011). doi:10.1111/j.1365-2486.2010.02336.x
18. C. Poeplau, A. Don, L. Vesterdal, J. Leifeld, B. Van Wesemael, J. Schumacher, A. Gensior, Temporal dynamics of soil organic carbon after land-use change in the temperate zone–carbon response functions as a model approach. *Glob. Change Biol*. 17, 2415–2427 (2011). doi:10.1111/j.1365-2486.2011.02408.x
19. K. Makoto, S. V. Bryanin, V. V. Lisovsky, K. Kushida, N. Wada, Dwarf pine invasion in an alpine tundra of discontinuous permafrost area: Effects on fine root and soil carbon dynamics. *Trees* 30, 431–439 (2016). doi:10.1007/s00468-015-1192-5
20. J. P. Zhang, C. D. Shen, H. Ren, J. Wang, W. D. Han, Estimating change in sedimentary organic carbon content during mangrove restoration in southern China using carbon isotopic measurements. *Pedosphere* 22, 58–66 (2012). doi:10.1016/S1002-0160(11)60191-4
21. M. Hoogmoed, S. C. Cunningham, J. R. Thomson, P. J. Baker, J. Beringer, T. R. Cavagnaro, Does afforestation of pastures increase sequestration of soil carbon in Mediterranean climates? Agric. Ecosyst. Environ. 159, 176–183 (2012). doi:10.1016/j.agee.2012.07.011