

# Monitoring plant functional diversity from space

The world's ecosystems are losing biodiversity fast. A satellite mission designed to track changes in plant functional diversity around the globe could deepen our understanding of the pace and consequences of this change, and how to manage it.

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The ability to view Earth's vegetation from space is a hallmark of the Space Age. Yet decades of satellite measurements have provided relatively little insight into the immense diversity of form and function in the plant kingdom over space and time. Humans are rapidly impacting biodiversity around the globe<sup>1,2</sup>, leading to the loss of ecosystem function<sup>3</sup> as well as the goods and services they provide<sup>4,5</sup>. Recognizing the gravity of this threat, the international community has committed to urgent action to halt biodiversity loss<sup>6-9</sup>.

Ecosystem processes<sup>10-12</sup> are often directly linked to the functional biodiversity of plants, that is, to a wide range of plant chemical, physiological and structural properties that are related to the uptake, use and allocation of resources. The functional biodiversity of plants varies in space and time and across scales of biological organization. Capturing and understanding this variation is vitally important for tracking the status and resilience of Earth's ecosystems, and for predicting how our ecological life support systems will function in the future.

We currently lack consistent, repeated, high-resolution global-scale data on the functional biodiversity of the Earth's vegetation<sup>2,10-12</sup>. However, the technological tools, informatics infrastructure, theoretical basis and analytical capability now exist to produce this essential data. Here we suggest that this capability should be used in a satellite mission supporting a 'global biodiversity observatory' that tracks temporal changes in plant functional traits around the globe to fill critical knowledge gaps, aid in the assessment of global environmental change, and improve predictions of future change. The continuous, global coverage in space and

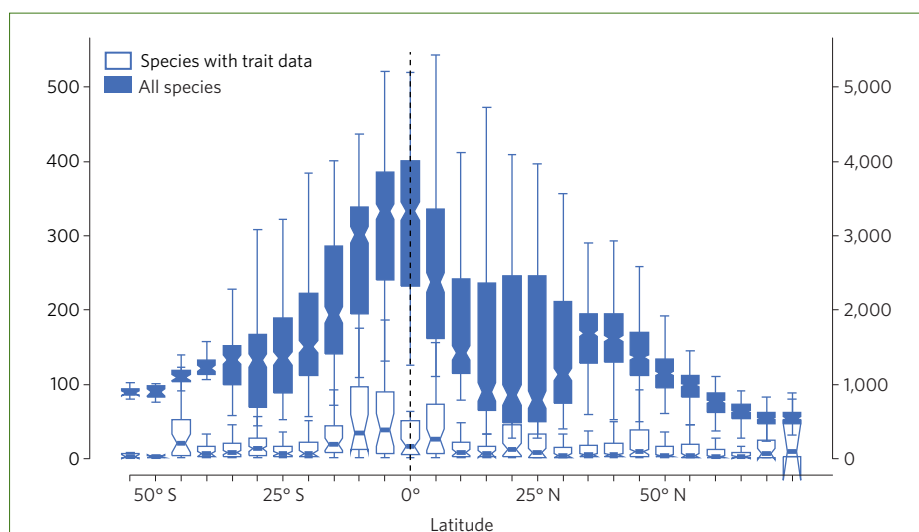
time that such a mission would provide has the potential to transform basic and applied science on diversity and function, and to pave the way to a more mechanistically detailed representation of the terrestrial biosphere in Earth system models.

## The data and knowledge gap

Plant functional biodiversity encompasses the vast variation in the chemical, physiological and morphological properties of plants, such as the concentration of metabolites and non-structural carbohydrates in leaves and the ratio of leaf

mass to leaf area. These attributes are related functionally to the uptake, allocation and use of resources such as carbon and nutrients within the plant, and to the defence against pests and environmental stresses.

Functional properties vary within and among individuals (for instance, as determined by the position of a leaf on a plant, or a tree in a forest), populations, species and communities, and may be measured at any of these levels of biological organization. With increasing spatial scale (and thus decreasing spatial resolution of measurements), the capture of functional



**Figure 1** | The data gap in regional species trait measurements. The graph shows the latitudinal variation in the number of vascular plant species for which at least one trait has been measured regionally (open boxes; left axis) in relation to all species expected for that region (filled boxes; right axis). Regions are here defined as 110 × 110 km grid cells ( $n = 11,626$ ); data on their expected richness is from ref. 25, and region trait data comes from the TRY database (version June 2015)<sup>18</sup>. Regions are analysed at the grid cell level and their variation is summarized in latitudinal bands of 5° width. On average, only about 2% of species have any such regional measurements, and the data gap is largest in the tropics. This limits understanding of both biodiversity and ecosystem function and services.

**Table 1 | Key functional plant traits that are remotely observable from space.**

Trait	Trait definition	Trait functions	Trait role (refs)	Remote observation (refs)
Leaf mass per area (LMA) (g m <sup>-2</sup> )	The dry mass of a leaf divided by its one-sided area measured when fresh. The reciprocal is specific leaf area (SLA).	A primary axis of the global leaf economics spectrum <sup>11</sup> .	49,66,67	34,35,68–70
Nitrogen (N) (%)	Concentration of elemental nitrogen in a leaf or canopy.	Important for photosynthesis and other metabolic processes as a constituent of plant enzymes.	67,71,72	34,35,73–75
Non-structural carbohydrates (NSC) (%)	Direct products of photosynthesis (sugars and starches), not yet incorporated into plant structural components and thus readily assimilable.	Indicator of tolerance to environment stress.	76	77
Chlorophyll (mg g <sup>-1</sup> )	Green pigments.	Responsible for capturing light in the process of photosynthesis.	78,79	35,80,81
Carotenoids (mg g <sup>-1</sup> )	Orange and yellow pigments.	Involved in the xanthophyll cycle for dissipating excess energy and avoiding oxygen radical damage under stress conditions (drought, chilling, low nutrients).	82,83	31,35
Lignin (%)	A complex organic polymer.	Provides mechanical support and a barrier against pests and pathogens; negatively correlated with tree growth rate and microbial decomposition.	84,85	32,35,73,86

See Supplementary Table 1 for more traits.

properties may increasingly represent the aggregate properties of many individuals and species, reflecting the functional biodiversity of whole communities. Aggregate ‘functional diversity’ metrics that characterize the breadth of functional properties of a group of organisms are known to be strongly associated with taxonomic<sup>13</sup> and phylogenetic<sup>14</sup> measures of biodiversity and their potential decrease under habitat loss<sup>15</sup>. Plant functional biodiversity is also closely linked to ecosystem processes such as carbon, water and energy exchange, which enables a direct integration with Earth system models<sup>16,17</sup>. Global information on the functional composition and diversity of plant communities thus provides a necessary foundation for monitoring, understanding and predicting the productivity of ecosystems, and for relating productivity and carbon uptake to other critical ecosystem services.

Available global data on plant functional biodiversity are grossly incomplete and non-representative taxonomically, geographically, environmentally, temporally and functionally. Although datasets of traits and their connection to function continue to grow<sup>18,19</sup>, local observations of plant functional traits are limited along multiple dimensions. On average, only around 2% of currently known vascular plant species have any trait measurements available at the regional scale (here defined

as a 110 × 110 km grid cell,  $n = 11,626$ ); in the species-rich tropical regions, this figure is even smaller (Fig. 1). Data on other biodiversity attributes such as species occurrence, abundance and biomass hold similar biases<sup>20,21</sup>. These spatial and environmental data gaps and biases are exacerbated by even scarcer information on temporal variation in plant functional biodiversity. Even in areas for which current data are relatively complete, widespread biodiversity change driven by anthropogenic pressures is rapidly outpacing incremental gains in our knowledge of the Earth’s biodiversity afforded by *in situ* biodiversity sampling<sup>22</sup>. Furthermore, existing ‘global’ datasets have not been collected consistently or systematically, but instead compiled post hoc from thousands of disparate research activities, often not designed to address long-term trends or large-scale patterns<sup>23</sup>. These severe sampling inhomogeneities and resulting biases cannot be readily overcome statistically, and continue to impose severe limits on inference and application in global biodiversity science<sup>21,24,25</sup>. An integrated system for rapidly and consistently monitoring plant functional diversity globally is thus urgently needed.

### Filling the gap

Remote sensing has already proved to be a pivotal technology for addressing the

global biodiversity data gap. Data on plant productivity, phenology, land cover and other environmental parameters from MODIS (moderate resolution imaging spectroradiometer) and Landsat satellites currently serve as reasonably effective covariates for spatiotemporal biodiversity models based on *in situ* data<sup>12,20,26</sup>. However, the coarse spectral resolution of current satellite-borne sensors has prevented a more direct capture of biodiversity, and correlative models are limited by the above-mentioned data gaps.

In contrast, imaging spectroscopy is a well-established, continuously advancing technology capable of monitoring terrestrial plant functional biodiversity in a way that is vastly richer and more sensitive than other remote sensing techniques<sup>22,27,28</sup>. It captures environmental information at extremely fine spectral resolution by simultaneously mapping the reflectance and emission of light from the Earth’s surface in hundreds of narrow spectral bands, producing essentially continuous spectra from the visible to infrared wavelengths<sup>29</sup>. Distinctive features are imprinted in these spectra as light interacts with the chemical bonds and structural composition of plants. Spectra are thus an aggregate signal of the chemical and structural composition of vegetation, and can be directly related to a number of leaf biochemical and morphological functional traits (Table 1)<sup>30–32</sup>. Air- or

satellite-borne spectrometers are able to measure the aggregate functional traits of plant communities represented in the top layers of vegetation, and even the attributes of single species directly, depending on community spatial and spectral characteristics<sup>33</sup>. This capability has been successfully demonstrated using airborne spectrometers for many traits at regional scales across multiple biomes<sup>34,35</sup>. There are similar techniques (that are at various stages of development) for characterizing freshwater<sup>36</sup> and tidal ecosystems<sup>37</sup>, marine phytoplankton<sup>38,39</sup> and coral reefs<sup>40</sup>. Satellite technology is now poised to provide global coverage at spatial resolutions sufficiently fine (30 to 60 m pixel size) to support biodiversity inference and applications.

### Linking data across scales

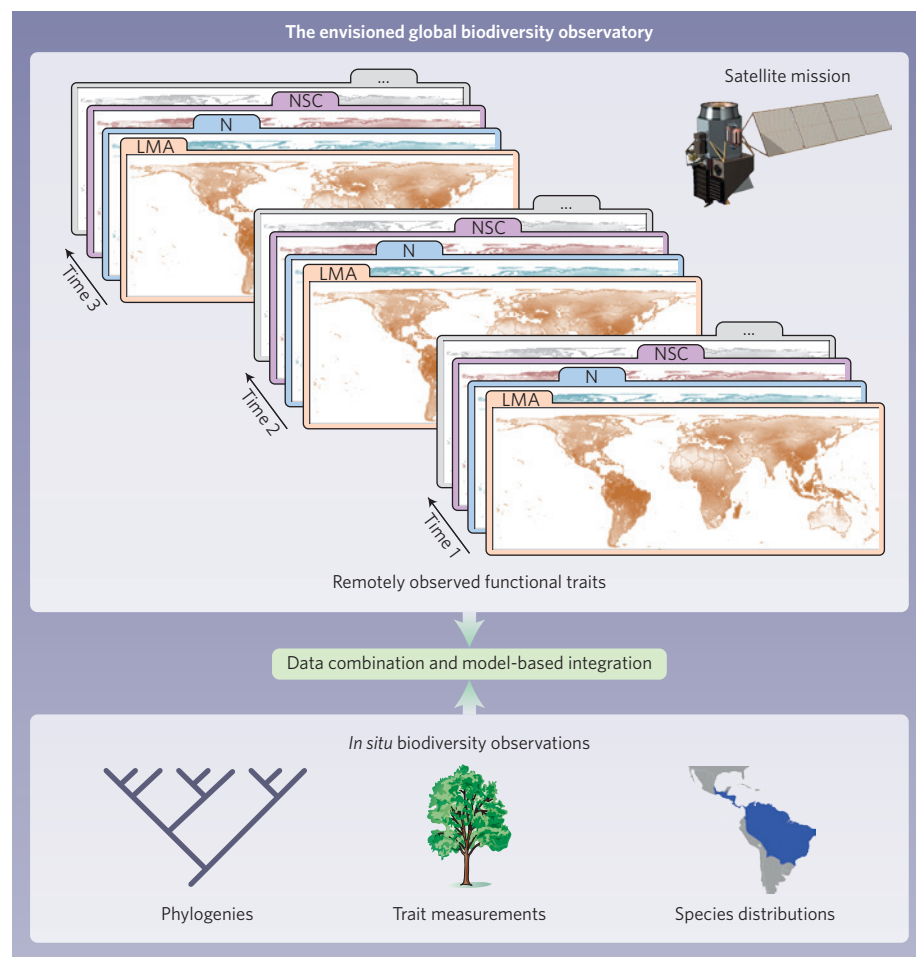
A global biodiversity observatory would integrate remotely sensed information on functional traits together with other remotely sensed information and *in situ* observations of phylogenetic relationships, functional traits and species distributions (Fig. 2). Developing such an observatory would not be without challenges, however. Cloud cover, especially in the tropics, poses constraints for any optical remote-sensing method aiming to be spatially and temporally representative (but see ref. 41 for some encouraging evidence regarding space-based spectrometry). Further, direct measurements of plant traits by imaging spectroscopy are currently limited to only those traits with a clear spectral signature expressed in the canopy layer (Table 1), rendering root and stem traits hard to capture. Finally, the vast quantity of data generated will constrain the spatial resolution that a global mission can support, at least initially: envisioned spatial grains of around 30 m will limit the direct capture of individuals or stands of single species to only a few select cases.

The convergence of imaging spectroscopy with other remote-sensing advances, together with prominent developments in plant biology and biogeography, can pave the way to a more integrated global assessment of plant functional biodiversity. Specifically, spectroscopic trait measurements combined with LiDAR (light detection and ranging) data on ecosystem vertical structure at similar spatial resolutions may dramatically enhance the ecological interpretation of the spectral imagery and help overcome its current limitation to surface signals only<sup>42,43</sup>. Although significant gaps remain (Fig. 1), select trait data has now been collected *in situ* for more than 100,000 vascular plant species, providing a means to both directly and indirectly connect, through models, spectral observations from the

top layer of vegetation to a variety of plant traits<sup>18</sup>. And the global phylogeny ('tree of life') for plants is becoming ever more complete<sup>44</sup>, enabling researchers to trace the evolutionary history of plant traits within lineages<sup>45</sup>. Although for some traits and functions convergent evolution has pulled disparate (and often geographically distant) lineages into functional similarity<sup>46–49</sup>, traits and associated functions are in many cases conserved to relatively deep phylogenetic levels<sup>50–52</sup>. In combination, this provides several relevant opportunities. For example, advances in macroevolutionary models and data-gap-filling techniques<sup>53–55</sup>, when coupled with increasingly complete phylogenies, can allow for the prediction of traits for species lacking observations. Further, the strong phylogenetic signal in the individual traits that make up overall

functional biodiversity means that spectral observations of aggregate species may in some cases still be meaningfully connected to specific functional properties or clades, and interpreted or monitored as a unit<sup>56</sup>.

The increasing volume of online species occurrence data is a fourth synergistic development that supports the predictive modelling and mapping of species' and plant community distributions<sup>57</sup>. Combined with trait and phylogenetic data, and potentially other ecological information (such as typical stand density), hierarchical statistical models and downscaling techniques<sup>58,59</sup> may, with some uncertainty, allow the pinpointing of particular species and the make-up of communities. We hypothesize that such predictions will generally be much more effective at coarser levels of biological organization, such as higher-level clades



**Figure 2** | The envisioned global biodiversity observatory. Top: space-based imaging spectrometer sensors capture global spatial data on key functional attributes in time, including leaf mass per area (LMA), nitrogen concentration (N) and non-structural carbohydrates (NSC), among others (see Table 1). Other sensors (such as LiDAR) may also contribute measurements. An informatics infrastructure and appropriate modelling techniques connect this information with trait, evolutionary and spatial biodiversity information<sup>20</sup> collected worldwide *in situ* at different spatial scales and levels of biological organization (bottom).



or other well-characterized species groups that can be associated with the aggregate functions of the spectral signal of a pixel.

The envisioned imaging spectroscopy mission will naturally provide only some of the data required for global biodiversity monitoring and modelling. Nevertheless, the model-based integration of detailed and global spectral information with other remote sensing data and rapidly growing *in situ* biological information points to an array of transformative new opportunities for monitoring plant functional biodiversity through space and time.

### A global biodiversity observatory

Scaling up processes from fine-grained local studies to larger regions (and ultimately the entire globe) is an urgent challenge for all of the Earth sciences. Environmental understanding at larger scales requires observations that capture dimensions of the entire system to place the microscale measurements in context. Plant functional biodiversity observations from space have the potential to provide a global context for biodiversity science, and to link the evolutionary and functional diversity of plants at local scales to ecosystem function around the globe. Such information would link key dimensions of diversity to ecosystem processes including the carbon cycle, the water cycle and the provisioning of ecosystem services. And it would revolutionize large-scale research on the stability and resilience of ecosystems to shocks such as drought, fire and pathogen outbreaks. Several space missions planned for launch within this decade<sup>60</sup> — such as EnMAP (German Spaceborne Imaging Spectrometer Mission)<sup>61</sup> and HISUI (Japan Aerospace Exploration Agency, JAXA)<sup>62</sup> — will have some capability for mapping plant functional diversity over limited geographic areas. However, none of these will provide the spatial coverage, repeat frequency or mission duration needed to monitor ecosystem-relevant changes in global plant functional biodiversity through time. Satellites technology such as that proposed for HypSIRI<sup>63</sup>, a mission that was called for in the 2007 National Research Council (NRC) Decadal Survey<sup>64</sup>, would be able to serve the initial remote sensing capabilities of the envisioned global biodiversity observatory, but no satellite development process or launch date has yet been determined.

Predicting how ecosystems and the services they provide will respond to accelerating environmental change requires more comprehensive, globally consistent and repeated data on the patterns and dynamics of functional biodiversity.

Advanced observing technology (which is available but not yet deployed at scale) integrated with *in situ* measurements<sup>65</sup> could transform this situation. The envisioned global biodiversity observatory offers vastly more biologically relevant and spatially and temporally highly resolved information about vegetation than any existing or otherwise planned global sampling or observation scheme. Rates of change today are so high that the longer a global spectroscopic mission is delayed, the more biological information is irretrievably lost<sup>22</sup>. The earliest possible launch of a mission able to spectroscopically monitor key plant functional traits globally is an urgent priority for understanding and managing our changing biosphere. □

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### References

- Pereira, H. M., Navarro, L. M. & Martins, I. S. *Annu. Rev. Environ. Resour.* **37**, 25–50 (2012).
- Tittensor, D. P. *et al. Science* **346**, 241–244 (2014).
- Cardinale, B. J. *et al. Nature* **486**, 59–67 (2012).
- Dobson, A. *et al. Ecology* **87**, 1915–1924 (2006).
- Quijas, S., Schmid, B. & Balvanera, P. *Basic Appl. Ecol.* **11**, 582–593 (2010).
- Convention on Biological Diversity Decision X/2: *The Strategic Plan for Biodiversity 2011–2020 and the Aichi Biodiversity Targets* (UNEP, 29 October 2010); <https://www.cbd.int/doc/decisions/cop-10/cop-10-dec-02-en.pdf>

- Inouye, D. W. *Front. Ecol. Environ.* **12**, 371 (2014).
- Cadotte, M. W., Carscadden, K. & Mirotchnick, N. J. *Appl. Ecol.* **48**, 1079–1087 (2011).
- Diaz, S. *et al. Curr. Opin. Environ. Sustain.* **14**, 1–16 (2015).
- Pereira, H. M. *et al. Science* **339**, 277–278 (2013).
- Geijzendorffer, I. R. *et al. J. Appl. Ecol.* <http://dx.doi.org/10.1111/1365-2664.12417> (2015).
- Skidmore, A. K. *et al. Nature* **523**, 403–405 (2015).
- Petchev, O. L. & Gaston, K. J. *Ecol. Lett.* **5**, 402–411 (2002).
- Flynn, D. F. B., Mirotchnick, N., Jain, M., Palmer, M. I. & Naeem, S. *Ecology* **92**, 1573–1581 (2011).
- Keil, P., Storch, D. & Jetz, W. *Nature Commun.* **6**, 8837 (2015).
- Scheiter, S., Langan, L. & Higgins, S. I. *New Phytol.* **198**, 957–969 (2013).
- Yang, Y., Zhu, Q., Peng, C., Wang, H. & Chen, H. *Prog. Phys. Geogr.* **39**, 514–535 (2015).
- Kattge, J. *et al. Glob. Change Biol.* **17**, 2905–2935 (2011).
- Violle, C., Reich, P. B., Pacala, S. W., Enquist, B. J. & Kattge, J. *Proc. Natl Acad. Sci. USA* **111**, 13690–13696 (2014).
- Jetz, W., McPherson, J. M. & Guralnick, R. P. *Trends Ecol. Evol.* **27**, 151–159 (2012).
- Schimel, D. *et al. Glob. Change Biol.* **21**, 1762–1776 (2015).
- Schimel, D. S., Asner, G. P. & Moorcroft, P. *Front. Ecol. Environ.* **11**, 129–137 (2013).
- Scholes, R. J. *et al. Science* **321**, 1044–1045 (2008).
- Sandel, B. *et al. J. Veg. Sci.* **26**, 828–838 (2015).
- Krefl, H. & Jetz, W. *Proc. Natl Acad. Sci. USA* **104**, 5925–5930 (2007).
- De Jong, S., Schaepman, M. E., Furrer, R., Bruin, S. & Verburg, P. H. *Glob. Change Biol.* **19**, 1953–1964 (2013).
- Homolová, L., Malenovsky, Z., Clevers, J. G. P. W., Garcia-Santos, G. & Schaepman, M. E. *Ecol. Complex.* **15**, 1–16 (2013).
- Schaepman, M. E. *et al. Remote Sens. Environ.* **158**, 207–219 (2015).
- Schaepman, M. E. *et al. Remote Sens. Environ.* **113**, S123–S137 (2009).
- Asner, G. P. & Martin, R. E. *Front. Ecol. Environ.* **7**, 269–276 (2009).
- Ustin, S. L. *et al. Remote Sens. Environ.* **113**, S67–S77 (2009).
- Serbin, S. P., Singh, A., McNeil, B. E., Kingdon, C. C. & Townsend, P. A. *Ecol. Appl.* **24**, 1651–1669 (2014).
- Roth, K. L. *et al. Remote Sens. Environ.* **167**, 135–151 (2015).
- Singh, A., Serbin, S. P., McNeil, B. E., Kingdon, C. C. & Townsend, P. A. *Ecol. Appl.* **25**, 2180–2197 (2015).
- Asner, G. P., Martin, R. E., Anderson, C. B. & Knapp, D. E. *Remote Sens. Environ.* **158**, 15–27 (2015).
- Hestir, E. L. *et al. Remote Sens. Environ.* **167**, 181–195 (2015).
- Turpie, K. R., Klemas, V. V., Byrd, K., Kelly, M. & Jo, Y.-H. *Remote Sens. Environ.* **167**, 206–217 (2015).
- Palacios, S. L. *et al. Remote Sens. Environ.* **167**, 269–280 (2015).
- Moisan, T. A. H., Moisan, J. R., Linkswiler, M. A. & Steinhardt, R. A. *Cont. Shelf Res.* **55**, 17–28 (2013).
- Hochberg, E. J. in *Coral Reefs: An Ecosystem in Transition* (eds Dubinsky, Z. & Stambler, N.) 25–35 (Springer, 2011).
- Mercury, M. *et al. Remote Sens. Environ.* **126**, 62–71 (2012).
- Torabzadeh, H., Hossein, T., Felix, M. & Schaepman, M. E. *ISPRS J. Photogramm. Remote Sens.* **97**, 25–35 (2014).
- Asner, G. P. *et al. Remote Sens. Environ.* **124**, 454–465 (2012).
- Zanne, A. E. *et al. Nature* **506**, 89–92 (2014).
- Cornwell, W. K. *et al. J. Ecol.* **102**, 345–356 (2014).
- Reich, P. B., Walters, M. B. & Ellsworth, D. S. *Proc. Natl Acad. Sci. USA* **94**, 13730–13734 (1997).
- Meinzer, F. C. *Oecologia* **134**, 1–11 (2003).
- Reich, P. B. *et al. Int. J. Plant Sci.* **164**, S143–S164 (2003).
- Wright, I. J. *et al. Nature* **428**, 821–827 (2004).
- Kerkhoff, A. J., Fagan, W. F., Elser, J. J. & Enquist, B. J. *Am. Nat.* **168**, E103–122 (2006).
- Edwards, E. J. & Still, C. J. *Ecol. Lett.* **11**, 266–276 (2008).
- Cavender-Bares, J., Ackerly, D. D. & Kozak, K. H. *Ecology* **93**, S1–S3 (2012).
- Swenson, N. G. *Ecography* **37**, 105–110 (2014).
- Jetz, W. & Freckleton, R. P. *Philos. Trans. R. Soc. Lond.* **370**, 20140016 (2015).
- Schrodt, F. *et al. Glob. Ecol. Biogeogr.* **24**, 1510–1521 (2015).
- Asner, G. P. *et al. Proc. Natl Acad. Sci. USA* **111**, 5604–5609 (2014).
- Jetz, W., McPherson, J. M. & Guralnick, R. P. *Trends Ecol. Evol.* **27**, 151–159 (2012).
- Gelfand, A. E. *et al. J. R. Stat. Soc. Ser. C Appl. Stat.* **54**, 1–20 (2005).
- Keil, P., Belmaker, J., Wilson, A. M., Unitt, P. & Jetz, W. *Methods Ecol. Evol.* **4**, 82–94 (2013).
- Stanz, K., Mueller, A. & Heiden, U. in *Geoscience and Remote Sensing Symposium (IGARSS), 2013 IEEE International* 3502–3505 (IEEE, 2013); [www.ieeeexplore.ieee.org](http://www.ieeeexplore.ieee.org)

61. Stuffer, T. *et al. Acta Astronaut.* **61**, 115–120 (2007).
62. Iwasaki, A., Ohgi, N., Tanii, J., Kawashima, T. & Inada, H. in *Geoscience and Remote Sensing Symposium (IGARSS), 2011 IEEE International* 1025–1028 (IEEE, 2011); [www.ieeeexplore.ieee.org](http://www.ieeeexplore.ieee.org)
63. Green, R. O. *et al. in Proc. Int. Geoscience and Remote Sensing Symposium (IGARSS '12)* (NASA, 2012); <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120014260.pdf>
64. Space Studies Board, National Research Council *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (National Academies, 2007).
65. Turner, W. *Science* **346**, 301–302 (2014).
66. Reich, P. B., Ellsworth, D. S. & Walters, M. B. *Funct. Ecol.* **12**, 948–958 (1998).
67. Walker, A. P. *et al. Ecol. Evol.* **4**, 3218–3235 (2014).
68. Fourty, T. & Baret, F. *Int. J. Remote Sens.* **19**, 1283–1297 (1998).
69. Riaño, D., Vaughan, P., Chuvieco, E., Zarco-Tejada, P. J. & Ustin, S. L. *IEEE Trans. Geosci. Remote Sens.* **43**, 819–826 (2005).
70. Vohland, M., Mader, S. & Dorigo, W. *Int. J. Appl. Earth Obs. Geoinf.* **12**, 71–80 (2010).
71. Evans, J. R. *Oecologia* **78**, 9–19 (1989).
72. Loomis, R. S. *Proc. Natl Acad. Sci. USA* **94**, 13378–13379 (1997).
73. Serrano, L., Peñuelas, J. & Ustin, S. L. *Remote Sens. Environ.* **81**, 355–364 (2002).
74. Martin, M. E., Plourde, L. C., Ollinger, S. V., Smith, M.-L. & McNeil, B. E. *Remote Sens. Environ.* **112**, 3511–3519 (2008).
75. Knyazikhin, Y. *et al. Proc. Natl Acad. Sci. USA* **110**, E185–E192 (2013).
76. O'Brien, M. J., Leuzinger, S., Philipson, C. D., Tay, J. & Hector, A. *Nature Clim. Chang.* **4**, 710–714 (2014).
77. Asner, G. & Martin, R. *Remote Sens.* **7**, 3526–3547 (2015).
78. Govindjee & Rabinowitch, E. *Science* **132**, 355–356 (1960).
79. Grimm, B. *eLS* <http://dx.doi.org/10.1038/npg.els.0001310> (Wiley, 2001).
80. Gitelson, A. A. & Merzlyak, M. N. *Int. J. Remote Sens.* **18**, 2691–2697 (1997).
81. Siebke, K. & Ball, M. C. *Funct. Plant Biol.* **36**, 857 (2009).
82. Björkman, O. & Demmig-Adams, B. in *Ecophysiology of Photosynthesis* 17–47 (Springer, 1995).
83. Demmig-Adams, B. & Adams, W. W. 3rd. *New Phytol.* **172**, 11–21 (2006).
84. Melillo, J. M., Aber, J. D. & Muratore, J. F. *Ecology* **63**, 621 (1982).
85. Austin, A. T. & Ballaré, C. L. *Proc. Natl Acad. Sci. USA* **107**, 4618–4622 (2010).
86. Martin, M. E. & Aber, J. D. *Ecol. Appl.* **7**, 431–443 (1997).

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W.J. and J.C.-B. contributed equally to this work.