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ISS observations offer insights into plant function

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In 2018 technologies on the International Space Station will provide ~1 year of synchronous observations of ecosystem composition, structure and function. We discuss these instruments and how they can be used to constrain global models and improve our understanding of the current state of terrestrial ecosystems.

Space-based observations are increasingly central to global ecology, opening windows to address questions pertaining to the carbon cycle, biodiversity, productivity and disturbance. Until recently, satellite observations provided a limited range of observations, albeit critical ones, relating light absorption to support plant growth, disturbance and land use/cover change. These observations have revolutionized our knowledge of global ecology, but have not addressed a series of critical questions about ecosystem process that must be resolved in order to reduce uncertainty in future climate and ecosystem service projections. These key questions have been addressed in local studies, but the findings of these local experiments cannot be tested across broad landscapes with observations from existing satellite technologies. For example, normalized difference vegetation index (a metric of vegetation greenness often used as a proxy for ecosystem productivity or carbon storage) influences estimates of absorbed photosynthetic active radiation (fPAR) and leaf area index (a metric of one-side leaf area per ground surface area)[1]. Thus, more direct observations of functioning and structure are needed to enable distinct testing and improvement of modelled representations of ecosystem processes.

Questions include:

- How sensitive are ecosystems to temperature and water availability and how will this affect future carbon and energy balances?
- Do diverse plant communities respond to climate change differently from simpler communities?
- Does diversity lead to ecosystems responding non-linearly to change, in ways we cannot predict now?
- How does land management interact with climate to control future disturbance regimes?

Common to all these questions is that they require multiple observations to test specific hypotheses, and reject incorrect model formulations. Fortunately, there are many exciting new developments in remote sensing that will provide key observations of the land (for example, Sentinel series, BIOMASS, NISAR).

Although new technology makes many key observations feasible, it's uncommon to have observing platforms with multiple instruments collecting a variety of parameters at synergetic spatial resolutions and coordinated temporal acquisition, particularly at scales needed for management. Yet this is exactly what is needed to resolve how plant function affects ecosystem processes at landscape scales in different regions across the globe.

Box 1 | Description of ISS instruments.

The instruments for deployment on ISS are: GEDI, ECOSTRESS, OCO-3 and HISUI. Each instrument is being designed independently, but the nature of the observations offers an unprecedented opportunity to resolve regional and global scale understanding of ecosystem process and function.

GEDI. A geodetic-class LIDAR that will measure canopy heights and foliar vertical profiles to establish a baseline of vegetation structure and global terrestrial biomass. GEDI observations leverage a sampling scheme that is then interpolated to produce a map. The sample scheme uses three lasers (at 242 pulses per second) to produce observations in 25-metre footprints along ten parallel tracks. The tracks are separated by ~600 m each, and footprints are separated by 25 m along the tracks.

ECOSTRESS. Because transpiration performs the same cooling function as sweat, when plants close stomata their leaf temperatures increase. This rise in temperature can be detected and such observations at different hours throughout the day are crucial for mapping vegetation water-use efficiency, represented by the ability of vegetation to close stomata in the afternoon to avoid transpiration that would exceed water uptake from the soil.

OCO-3. A pointing instrument that will use three high-spectral-resolution grating spectrometers to measure solar-induced fluorescence, a measure of photon emission during photosynthetic partitioning that provides a direct proxy for gross primary productivity, and atmospheric column CO_2, with high precision (±1 ppm).

HISUI. Will provide contiguous visible to shortwave infrared (400–2,500 nm) surface reflectance at very high spectral resolution (400–979 nm at ~10 nm average per band for 57 bands and 900–2,500 nm at ~12.5 average per band for 128 bands).

Table 1 | A list of high-level data products that will provided by each instrument expected for deployment to the ISS starting in 2017.

Data product level	ECOSTRESS (40–60 m pixels, 20–30 samples per hour of the day collected throughout the year)	OCO-3 (5 km^2 footprint, capable of mapping up to one hundred 1,000 m^2 areas per day)	GEDI (~500 m^2 footprint spaced 60 m along a track with no temporal repeat)	HISUI (30 m pixels with 20 km swath and 10 nm spectral resolution over 0.4–2.5 μm spectral range)
2	Surface temperature Emissivity	Atmospheric column CO_2 Solar-induced fluorescence	Height metrics Canopy metrics	Atmospherically corrected surface reflectance with quality assurance (not validated)
3	Evapotranspiration	Gridded level 2	Gridded level 2	
4	Water-use efficiency Evaporative stress index		Aboveground biomass (footprint and gridded)	

Fortunately, with a coordinated strategy, such an opportunity will arise for ecologists in the next few years.

Novel Earth observations

The International Space Station (ISS) will host four instruments from JAXA (Japan Aerospace Exploration Agency) and NASA (Box 1) in 2018 that will advance our ability to monitor and model terrestrial ecosystems between latitudes ~50° North and South. Three of the instruments are from NASA and include: the Global Ecosystem Dynamics Investigation (GEDI), the Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), and the Orbiting Carbon Observatory 3 (OCO-3). All three are being developed for deployment to the ISS in 2018 and will distribute the free data products listed in Table 1. The fourth instrument, also for deployment in 2018, is the Hysperspectral Imager Suite (HISUI) from JAXA[1,2]. Complementing HISUI is the German Aerospace Agency (DLR) EnMAP[3], for which the observational plan has already been established, thus it is not the focus of the imaging spectroscopy discussion henceforth. These four instruments will make observations of three-dimensional structure (GEDI) that can be used to scale biochemical signals[4–6] to the canopy level (HISUI) and derive estimates of ecosystem composition, productivity (solar-induced fluorescence from OCO-3), and water-use efficiency (a product of ECOSTRESS) at landscape scales. This instrument suite offers a unique opportunity because the drifting ISS platform and pointing capabilities of some of the instruments enable co-location of high-spatial-resolution measurements in space and acquisition times covering the diurnal cycle throughout the year (that is, more than 20 observations per hour of the day throughout the year).

Call for coincident observations

Coordinating the spatial and temporal coincidence of measurements from GEDI, ECOSTRESS, OCO-3 and HISUI would be an opportunity to address ecosystem dynamics questions that cannot be answered from any one instrument and that have the ability to substantially enhance our understanding of ecosystem responses to global change. For example, an estimation of carbon sink potential (Fig. 1) can be estimated using observations of carbon flux (OCO-3) and carbon storage (LIDAR-derived biomass from GEDI), both of which can be affected by the efficiency of individual plant species (HISUI) to sequester carbon under variable access to water (ECOSTRESS).

Despite added information value from synergistic observations, the protocols and measurement strategies for any one of these instruments do not currently consider the other instruments. Thus, there is an argument and need for collaboration during mission development to coordinate observation strategies and maximize scientific returns on investment. Coordinated observations can include using aircraft versions of these spaceborne instruments (for example, LIDAR for GEDI, PhyTIR for ECOSTRESS, CFIS for OCO-3, and AVIRIS for HISUI) both before and after launch. Airborne campaigns with instruments analogous to those deployed for space are frequently used for calibration and validation activities of delivered data products both leading up to and after launch. Furthermore, these instruments may help to scale understanding of ecological processes between ground-based and spaceborne observations. Additional consideration for integration with airborne (high spatial resolution) and ISS (unique temporal acquisition) observations is the use of other spaceborne observations (for example, Sentinel series and Landsat), as these can provide additional information for

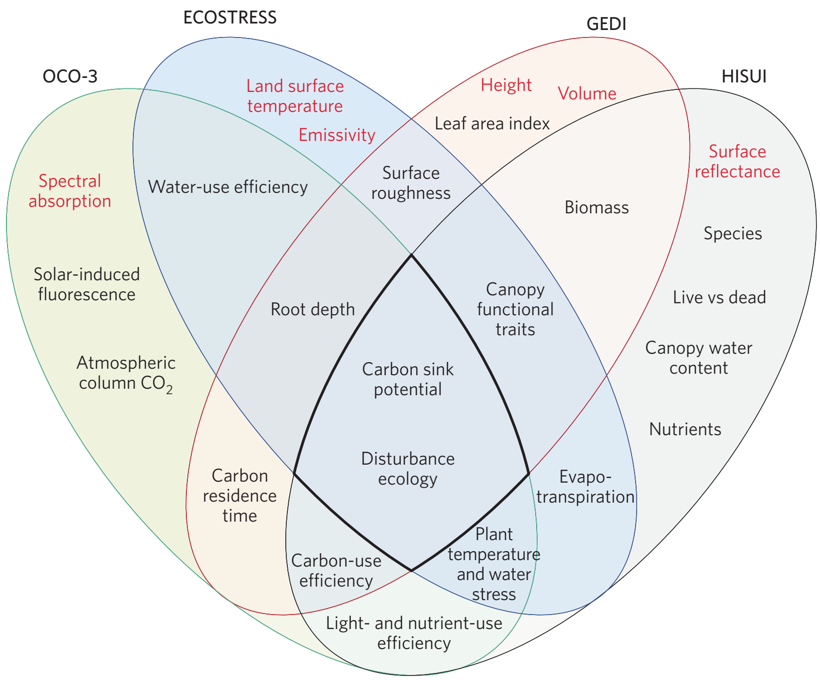

Figure 1 | Spatial and temporal synergy of observations and their applications. A pretzel diagram of observations (red text) from each instrument (coloured shapes) and the synergistic physical parameters that can be derived (black text) when observations are taken at synchronous and complementary spatial and temporal resolutions.

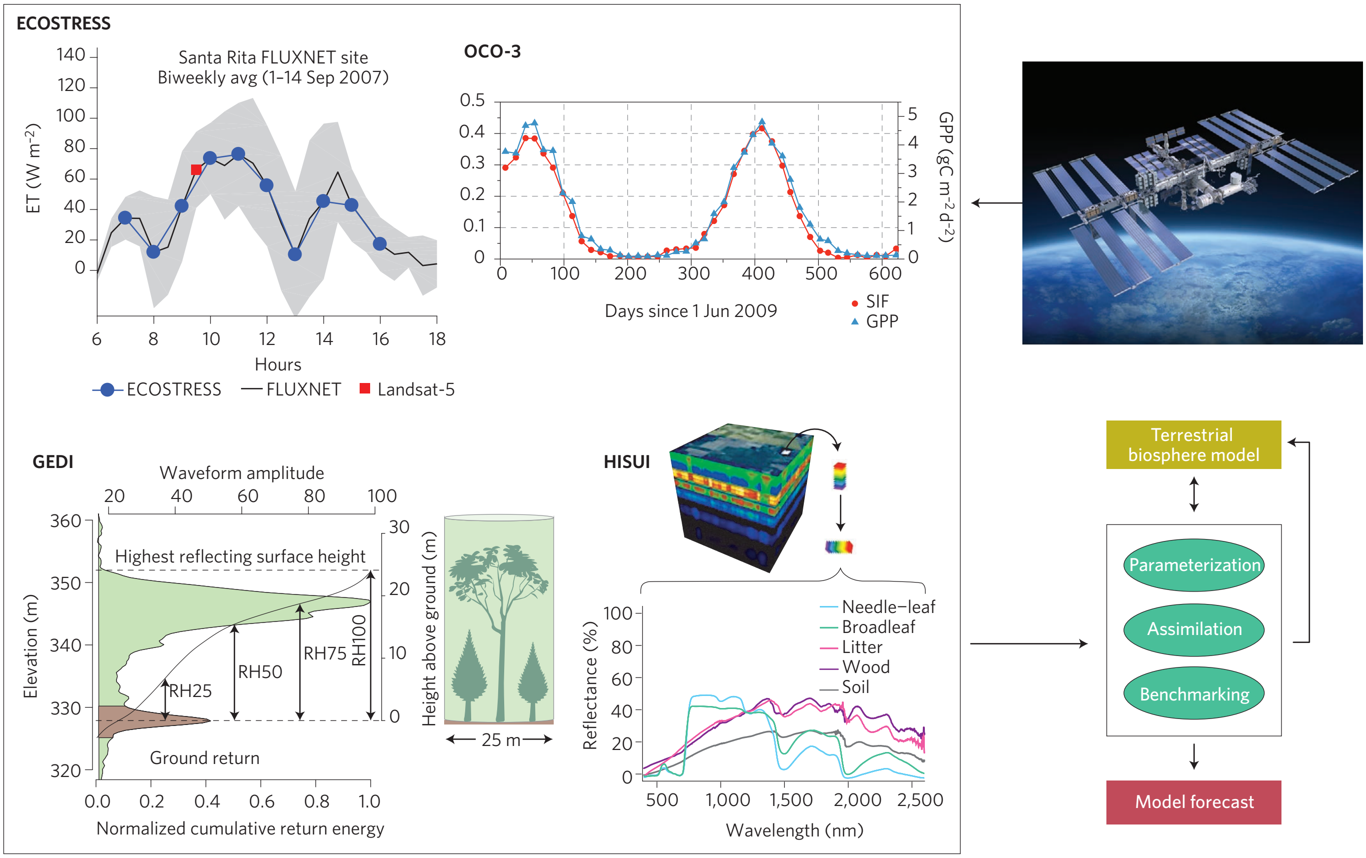

Figure 2 | A conceptual framework for how different data, observed from each ISS instrument, can be integrated into terrestrial biosphere models to improve their ability to represent and predict ecosystem processes. ECOSTRESS shows the 14-day average evapotranspiration (ET) from Santa Rita Fluxnet against the expected annual average value of ET from ECOSTRESS for each hour of the day. OCO-3 shows GOME solar-induced fluorescence data compared to the MPI-BGC gross primary productivity product. GEDI shows airborne LIDAR waveform from La Selva Biological Research Station, Costa Rica. HISUI shows an imaging spectroscopy/hyperspectral image cube and different spectra for different spectral classes. ISS image credit: Getty Images/scibak.

scaling understanding of ecosystem process and function. Thus, efforts to coordinate synergistic observations between the ISS instruments should also consider the utility of and coordinated efforts needed for airborne campaigns and how their observations link with existing and upcoming satellites.

Organizing synchronous observations in space and time at varying scales of resolution will be most useful if future research uses these data by integrating them with existing information system infrastructure (that is, models) in order to contextualize the information gleaned from the relatively short period of overlapping observations (approximately one year). Specifically, future research can use the ISS observations to establish a baseline for monitoring that can be used to attribute and improve predictions of terrestrial ecosystem changes through time. To do so will require systematic evaluation of processes and ecosystem dynamics, which can be done using models[7]. Terrestrial biosphere models are the primary tool for quantifying the impacts of climate variability, disturbance, and global change on terrestrial ecosystems[8,9]. These models incorporate semi-empirical and mechanistic descriptions of the physiological and biophysical processes and properties of terrestrial ecosystems that drive land–atmosphere fluxes and storage of carbon, water and energy across space and time. In addition, terrestrial biosphere models provide the mechanistic framework necessary for integrating various types of data because they can represent ecological processes and functional responses at multiple spatial and temporal scales in a way that leverages our best understanding[10]. In order to improve terrestrial biosphere model parameterizations[11], benchmark model forecasts[12], improve process representations, and evaluate alternative model structures, models may need to be adjusted to integrate the ISS observations at the relevant spatial and temporal scales for the processes and functional responses of interest (Fig. 2).

Although these flight projects can work together to coordinate observations strategies, there are many logistical issues (for example, explicit priority of observation areas) for coordinating observational strategies that remain undetermined. Specifically, which areas are of highest priority to image given downlink constraints of instruments on the ISS? And, who is responsible for organizing this across missions? Each instrument system and team is limited and constrained by their budgets and the mandate to deliver on their individual mission requirements first. Thus, it will be necessary for the community to make additional efforts in order to seize this opportunity and take full advantage of this spectacular convergence of technical advances that offer a means for constraining our mechanistic understanding of ecological systems across scales suitable for management and regional analyses. Importantly, although each instrument is largely developed and provides significant value independently, in aggregate, the contemporaneous observations from all four instruments could provide observations to support major advances for understanding the carbon and water cycles, and how ecosystem structure, function and diversity interact with them. ❐

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Author contributions

E.N.S. is the lead writer for the manuscript, D.S. led discussions and helped articulate the key points of discussion for the manuscript, R.P. provided HISUI and OCO-3 information and panels in Fig. 2 as well as with edits for the manuscript, S.S. helped edit the general text, developed Fig. 2 and provided text for terrestrial biosphere models section, A.S. helped edit the general text and provided text for terrestrial biosphere models sections, L.D. provided the GEDI panel in Fig. 2 and text describing GEDI, J.B.F. helped with general editing and provided the ECOSTRESS panel in Fig. 2, F.F. helped with general editing, S.U. helped develop the original manuscript outline, R.D., A.S. and P.W. were key in contributing ideas for the manuscript.

Competing interests

The authors declare no competing financial interests.