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Abstract:

This report provides a brief set of recommendations, from a modeling point of view, on the monitoring of ecosystem biogeochemical and hydrological cycles and biodiversity, including the need to push for recent measurement techniques (water, carbon fluxes/stocks), for comprehensive measurements including all components of a system and for more global data-bases.

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Contributors: Philippe Peylin, Natasha MacBean, Vladislav Bastrikov, Fabienne Maignan, Harrie-Jan Hendricks-Franssen, Hanna Post, Albert Porcar, Franck Berninger, Leslie Firbank, Ingolf Kuehn, Bill Kunen, Carl Gudrun

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PP Restricted to other programme participants (including the Commission Services)	**[ ]**
RE Restricted to a group specified by the consortium (including the Commission Services) (precise to whom it should be addressed)	**[ ]**
CO Confidential, only for members of the consortium (including the Commission Services)	**[ ]**

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1. Executive summary

This report provides a brief set of recommendations, from a modeling point of view, on the monitoring of ecosystem biogeochemical and hydrological cycles as well as biodiversity. This is not a comprehensive description of all possible improvements that could be made but rather a specific point of view from few modeling groups that have used in situ data to validate and calibrate process-based ecosystem models or to estimate biodiversity. The main suggestions for the biogeochemical cycle and especially the carbon cycle are:

- Recent measurements such as the Solar Induce Fluorescence (SIF) seem to provide new insights on photosynthetic activity that will potentially outmatch the classical vegetation indices (fAPAR, NDVI); Given the recent availability of satellite SIF global product, in situ measurement of SIF should be reinforce;
- Carbon stock measurements as well as carbon stock changes should be measured more comprehensively, along with the flux measurements so that a full range of model processes, from fast to slow processes, could be evaluated simultaneously.
- Ecosystem Manipulative Experiments (EME) provide new test beds of model processes; in this context, multi-variable experiments (combinations of Precipitation, temperature, CO2 and nitrogen changes) should be promoted in order to evaluate the non linearity of model responses and feedbacks.
- Gathering the different data streams into comprehensive data-bases (such as TRY) needs to be pushed forward; for each site, ancillary data including site history (land use and land management) and soil/plant traits measurements should be gathered.

For the hydrological cycle, our main suggestions are:

- It is crucial to monitor the whole water balance of a catchment of interest (including lateral flows) rather than the water balance of few arbitrary plots.
- We should consider all components of the water balance at the same time: precipitation, evapotranspiration components (transpiration, bare soil evaporation, interception loss), storage in soil, runoff, drainage, river flow, …
- New techniques to measure soil moisture content on a scale similar to that of a flux tower, such as cosmic ray probe, should be promoted. These measurements could also be used to further validate upcoming soil moisture satellite products.
- The separation of evapotranspiration between ground evaporation and transpiration is crucial; new techniques using isotopic measurements should be promoted.

For biodiversity, our main suggestions are:

- New techniques, such as wavelet statistical analyses, offer when the data density is high enough, new possibilities to diagnose the dynamics of biodiversity change over a range of spatial and temporal scales
- Measurements of biodiversity along with ecosystem function at the same site should be reinforced to assess more easily multi-scale ecosystem functions.

2. Monitoring improvements for biogeochemical cycles

2.1. Photosynthesis and carbon allocation: the potential of new and combined measurements

Photosynthesis controls the uptake of carbon within plants. Its sensitivity to variations in temperature, precipitation, radiation and CO2 regimes is still not well captured by current global ecosystem model; which thus prevents accurate predictions of the fate of the terrestrial carbon budgets. Although a large number of observations exist, from leaf scale to plot scale (FluxNet observations), only few proxies are available at large scales (regional to global) with vegetation activity indexes (fAPAR, NDVI, EVI). The relations between these proxies and photosynthesis activity are still complex and associated with large uncertainties. However, recent observations open new perspectives like fluorescence observations, tree ring isotopes, etc, especially when combined in a multi-data approach. We thus advise here to push forward these recent measurements, providing few examples.

2.1.1 Fluorescence measurements

We first compare different “proxies” of GPP. The midday ground-measured sun-induced fluorescence (SIF) and Vegetation indices were compared with the eddy covariance tower-measured GPP for a cropland site near Avignon (Figure 1) as a preliminary investigation to assess the potential of fluorescence at canopy-level to improve a global model like ORCHIDEE. SIF at 760nm (F760) shows a clear linear response to GPP; on the contrary the Normalized Vegetation Index (NDVI) shows a positive relationship but with saturation at high GPP. SIF at 687nm (F687) and Photochemical Reflectance Index (PRI) show no clear relationship to GPP. This comparison thus suggests that the conventional vegetation indices would not be useful to improve our understanding of the processes controlling GPP for this cropland. Note that no particular relationship for the fluorescence at 687nm is obtained.

Currently, the GPP simulated by ORCHIDEE shows moderate agreement with the measurements for this cropland site (Figure 1e). However, it is expected that the strong relationship of F760 to measured GPP (Figure 1b) could be used to improve the process descriptions in ORCHIDEE after having incorporated the calculation of SIF in the model (with the implementation of a radiative transfer scheme accounting for fluorescence; van der Tol, 2009). The objective is not only to assimilate in-situ SIF data but more importantly the upcoming global SIF satellite products.

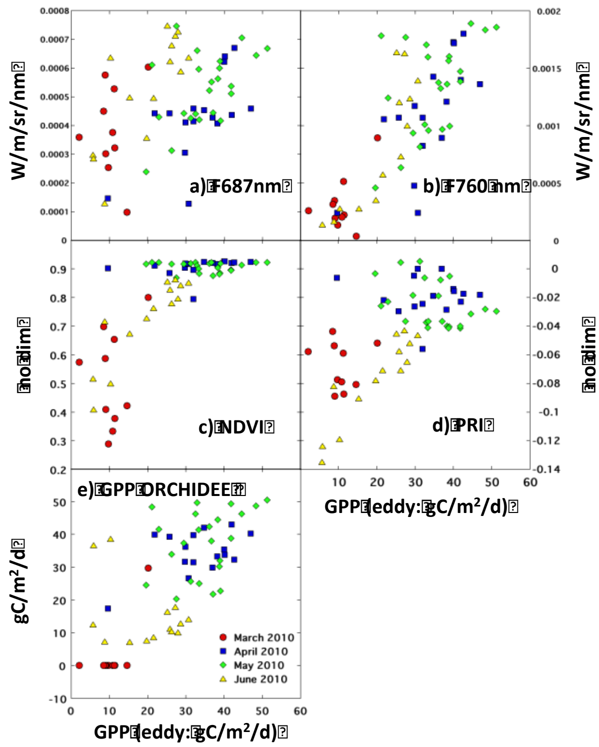

Figure 1: Seasonal change in the relationships at midday (11h30-13h30) between eddy tower measured GPP and a) 687nm fluorescence, b) 760nm fluorescence, c) NDVI, d) PRI and e) GPP simulated by ORCHIDEE with original setting in cropland in Avignon. a-d are measured at ground eddy flux site.

New satellite products of SIF derived from the GOME-2, GOSAT and OCO-2 instruments are indeed becoming increasingly available (Frankenberg et al., 2011; Guanter et al., 2012; Joiner et al., 2013; Kohler et al., 2014; Frankenberg et al., 2014). These products have shown high correlations with process and data driven model-based products (Figure 2) demonstrating, as for ground-based data, that SIF data may be useful for evaluating and optimizing the photosynthesis processes encoded in land surface models. First however, measurements of leaf- and canopy-level fluorescence at the site-based level are crucial for evaluating the satellite products and for model-data fusion feasibility studies. From these first tests we would thus recommend to i) promote the SIF measurements at site level and ii) perform these measurements along with other conventional observations (GPP, LAI, soil water content, ..).

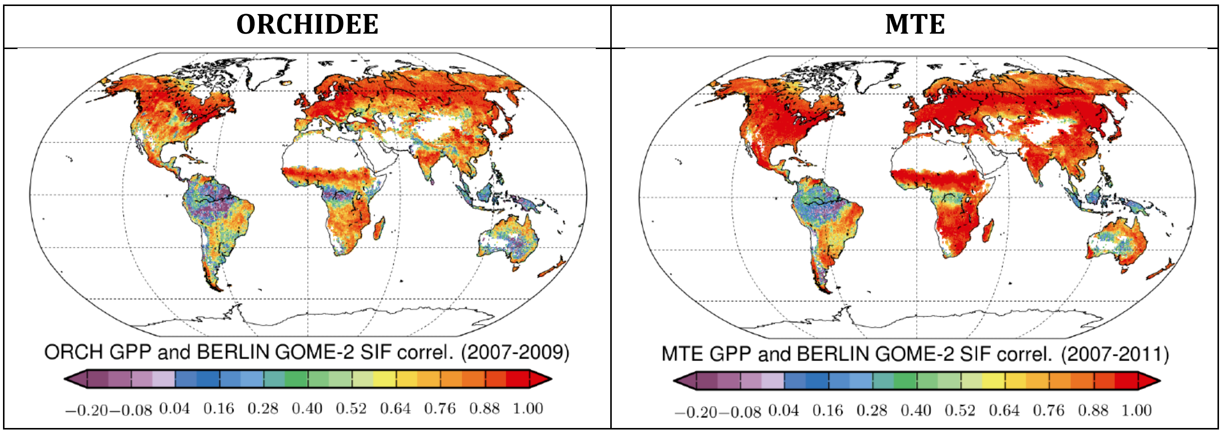

Figure 2: Global correlation maps between GPP products (left: ORCHIDEE LSM, right: JUNG MTE) et satellite-derived SIF data from GOME-2 produced by the University of Berlin (Köhler et al., 2014)

2.1.2 Tree ring width and isotopic measurements

Measurements of tree ring width have recently been used to diagnose the year-to-year variations of tree growth and carbon allocation in the plant. Isotopic C13 and O18 of the cellulose have been also measured but primarily to reconstruct paleo-climate from long tree ring chronology. However, there is a strong potential in these measurements to constrain the ecological functioning of trees and in particular the photosynthetic activity and how carbon is allocated in the different plant reservoirs. Recently, several papers have estimated the change in water use efficiency in the past decades using tree ring measurements (Franck et al., 2015)

As an example, we provide below a first comparison (figure 3) of tree ring width and isotopes (13C and 18O of cellulose) obtained at Fontainebleau (Sessile Oak) with the ORCHIDEE global ecosystem model. The correlation between the modeled and observed yearly quantities varies between the tracers (from 0.46 for 13C to 0.59 for the width) as well as the normalized standard deviation.

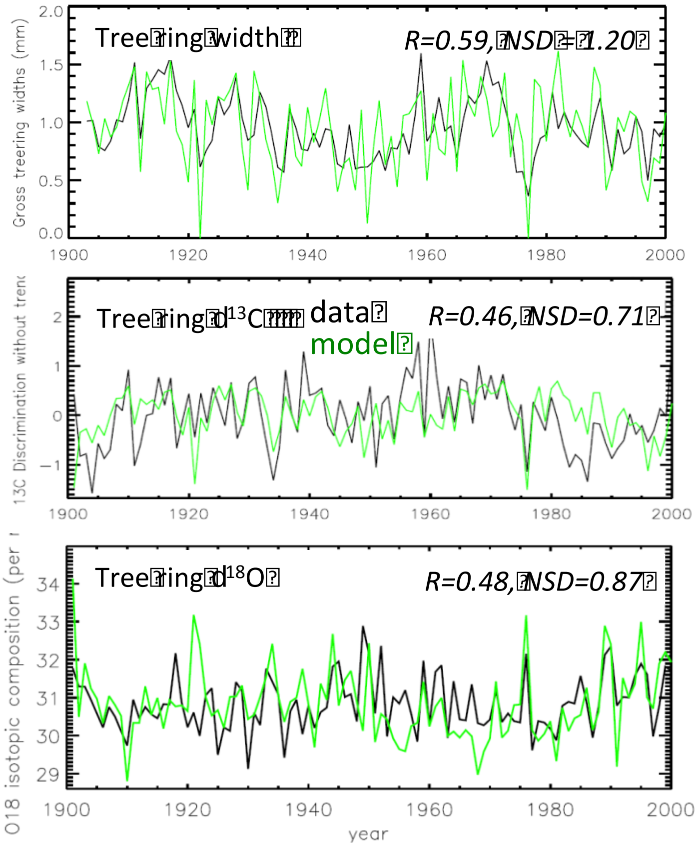

Figure 3: Modeled and observed year-to-year variations of the tree ring width, δ13C, and δ18O for the Fontainebleau site. Correlation (R) and normalized standard deviation (NSD) are reported for each tracer.

From this example and given the recent development in dendrochronology, we would like to draw few recommendations:

- Multiple-tracers tree ring chronologies (width and isotopes) can be used to calibrate model processes and especially the sensitivity of photosynthesis to drought and the changes of carbon allocation with climate conditions.
- Measuring the three tracers (width, 13C and 18O) offers different constraints to evaluate and optimize the processes represented in global models.
- These measurements should be performed at sites where intensive measurements are taken and where the soil hydrology is also well characterized; this will provide a large ensemble of constraints: from instantaneous flux measurements to more integrated observations.

2.2. Need for more comprehensive carbon stock-changes measurements

Carbon fluxes due to respiration are usually modeled as first order kinetic equations where the flux is proportional to the stock using a decay rate depending on climate (temperature and moisture) and soil conditions. It is thus difficult to validate any parametrization based solely on flux measurements and we thus need at the same time carbon stock measurements. We thus would like to make few recommendations:

- There is a strong need to measure carbon stock but also stock changes for both below ground living biomass and soil organic matter and also for above ground living biomass. Stock changes are integrated quantities that would be crucial to validate long term processes embedded in current models (mortality, soil organic turnover rates, …).
- History of the sites should be also provided at the same time than carbon stocks in order to fully reconstruct the past carbon dynamic that led to the current stocks. For instance, forest disturbance (human thinning), harvest for crop system, land cover changes or any changes in management practices (type and intensity) are crucial information.
- Uncertainties about stock and stock changes should be reported with great care.

2.3. Need for more multi-variable ecosystem manipulation experiments

Ecosystem manipulative experiments (EME) are crucial to understand the ecosystem response (carbon and water cycles) to climate changes; but they are still too few and not widely used by global ecosystem modelers. We recall below few important features to be considered.

- EME are probably the best way to test the model responses to climate changes, especially drought and CO2 increase. Their design should thus be plan more often together with modelers, in order to make sure that the model needs, in terms of forcing data and parameters, will be effectively measured.
- EME are crucial to test the sensitivity of model GPP to increasing CO2; for instance most DGVM have very different sensitivity to CO2 (mean annual GPP response) although they use mainly the Farquhar, et al. (1980) and Ball and Berry model. Specific insight on the model differences would be gained by additional manipulative

experiments where a large number parameters would be measured (vcmax, vjmax, soil water stress, hydraulic conductivities for trees, …).

- Multi-factorial EME should be developed as a unique way to test all feedback and relations between the different driving factors that are manipulated. Below is an example at one site that is useful to assess the complex response of combine drought, warming and CO2 changes.

Exemple with Brandbjerg ecosystem manipulation experiment:

Using the manipulative experiments at Brandbjerg, a shrub ecosystem, we made a first attempt to calibrate the ORCHIDEE global terrestrial model. The objective was to see whether the model is able to represent the sensitivity of the above ground biomass, soil respiration and total respiration to different manipulations: Drought, Warming, CO2 increase, and several combinations of these factors. The figure below shows the observed changes for the three measured quantities to the different treatments (applied during a restricted period in summer) as well as the model changes with standard parameters (prior) and after a “Bayesian” parameter optimization (poste). The main results are:

- The calibrated model is able to reproduce at least the direction of change for both the above ground biomass and the soil respiration and to a lesser extend for the total ecosystem respiration.
- However, there are some combinations of factors where the model provide opposite responses (mainly for TER); when the response is in the same direction than the observations, the amplitude of the simulated changes are not always of the right magnitude.
- The optimization of model parameters largely improves the model skill.

COMPARISON TO CONTROL

ABOVEGROUND BIOMASS (g/m2)

	Obs	Prior	Posterior
Drought (D)	-70	-32	-80
Warming (T)	-33	-58	-68
TD	-105	-98	-111
CO2	+42	+54	+17
DCO2	-37	+22	-31
TCO2	+7	+3	-18
TDCO2	-122	-46	-108

SOIL RESPIRATION (g/m2/d)

	Obs	Prior	Posterior
Drought (D)	-0.11	+0.02	+0.60
Warming (T)	+0.24	+0.25	+0.66
TD	-0.18	+0.25	-0.06
CO2	+0.55	+0.06	+0.34
DCO2	+0.51	+0.03	+0.56
TCO2	+0.85	+0.26	+0.66
TDCO2	+0.17	+0.28	+0.88

TER (g/m2/d)

	Obs	Prior	Posterior
Drought (D)	-0.86	-0.21	+0.59
Warming (T)	+0.30	-0.06	+0.57
TD	-0.53	-0.26	-0.71
CO2	+0.73	+0.40	+0.72
DCO2	-0.22	+0.38	+1.04
TCO2	-0.67	+0.26	+0.94
TDCO2	+0.01	+0.15	+0.95

Figure 3: Results of the ecosystem manipulation experiment

This comparison further highlights that combinations of factors are important to fully diagnose model responses. Note finally that ancillary data associated to the experiments (soil properties, vegetation structure, soil hydrology) should be gathered and provided with the main results of the EME in order to facilitate model evaluation.

2.4. Need for integrated data bases

From a modeler point of view, it is important to have access to a large ensemble of ecosystem measurements that cover various plant functional types under different soil and climate regimes. However, currently the information is still fractionated and only available through different organisms/projects. The trait database, "TRY", represents a great attempt in the direction of providing comprehensive observations to modelers but it does not gather all possible and needed observations. We would thus recommend to:

- Reinforce global data base infrastructure and facilitate their access through simple registration procedures.
- Build similar data-bases for ecosystem manipulative experiment so that an easy access to the different experiment and an easy collaboration with the site PIs could be establish.
- Gather ancillary data with any flux/stock measurements such as the site history, the type of management practices and their change in the recent past.

3. Monitoring improvements for the hydrology cycle

In order to monitor the hydrological cycle, a water balance for the catchment of interest has to be made. This is related to the fact that a significant amount of water is transported laterally, both in the form of direct surface runoff (especially after intense precipitation) and groundwater flow in the subsurface. Lateral flow in soils plays a more marginal role, except for steep topography. Therefore it is often less meaningful to derive a water balance for an arbitrary plot, and we have to consider the complement catchment.

A further complication in hydrological monitoring is the fact that we are dealing with several processes, which act on very different temporal scales. Precipitation is a main driver and it is important to have high resolution information about it. Evapotranspiration, with separate contributions by soil evaporation, plant transpiration and evaporation from intercepted water, is after precipitation the largest hydrological flux. River discharge is a much smaller flux, but with a large impact on society given its hazardous potential (floods). Groundwater is the main drinking water resource and long term changes in groundwater recharge are important to monitor in order to establish the impact on sustainability of groundwater extraction. Storage in soil (soil moisture) is important to monitor for its important relation to other main hydrological fluxes like recharge, discharge and evapotranspiration. In addition, soil moisture is essential for plant growth. Hydrological monitoring that allows establishing the water balance at the catchment scale and allows more insight in the hydrological cycle therefore needs to consider all compartments and processes simultaneously. Many monitoring networks in Europe are designed for a specific flux (precipitation, discharge, groundwater) without considering the complete hydrological cycle. We would advocate the establishment of more hydrological networks where all mentioned fluxes and states are monitored, in addition to vegetation and carbon and nitrogen cycles, given the important relations between biogeochemical cycles and the water cycle. In general, this implies that groundwater should be better included in the monitoring programs at hydrological sites, and the same is the case for vegetation.

Apart from the general recommendation to establish more hydrological observatories for small catchments where many types of data are measured, there are additional specific points to improve hydrological modelling with help of monitoring:

- The relation between evapotranspiration (ET) and soil moisture content has still a strong empirical character in land surface models, and shows sometimes large differences from observed ET-soil moisture relationships. Measurement data are also lacking to gain more insight because soil moisture is often measured at only a few locations. A possible alternative is the cosmic ray probe, which allows the estimation of soil moisture content on a scale very similar to the footprint of an eddy covariance measurement. We advocate therefore the installation of couples of eddy covariance systems and cosmic ray probes, to obtain evapotranspiration and soil moisture estimates at similar spatial scales, which would allow more insight in the relation between soil moisture and evapotranspiration reduction. However, this installation makes mainly sense for cropland

and grassland with shallow root systems, as the cosmic ray probe will not measure soil moisture content below 50cm even under dry conditions.

- In general, for use of remotely sensed surface soil moisture contents in land surface models it is important to have calibration/validation sites. Although a number of these sites has been established, the relation between remotely sensed coarse scale brightness temperature and soil moisture contents at the land surface is still subject to large uncertainty. More measurement sites which cover larger areas and making use of cosmic ray probes, gravimetry and hydrogeophysical methods at the calibration/validation sites is expected to help and ultimately would increase the value of remote sensing information (Vereecken et al., 2015).
- Land surface models differ also largely in the ratio of plant transpiration with respect to soil evaporation. Currently most measurement types do not provide further information on this ratio. An alternative is stable isotope analysis of water in soil and plant which allows for separation of transpiration and evaporation. A non-destructive method on the basis of gas-permeable tubing and infrared laser spectroscopy is now available for this (Rothfuss et al., 2013) and also eddy covariance based isotopic flux measurements will be possible in the future. It would be important that at existing EC-sites such measurements would be carried out, starting with a number of selected sites (Vereecken et al., 2015).
- For process understanding and also for large scale land surface modelling activities, it is important that many existing combinations of land use and soil types and climate zones are investigated. It is therefore important that arid and semi-arid regions, as well as boreal and tropical regions are captured better by a network of hydrological observatories than is the case until now.

4. Monitoring improvements for biodiversity studies

4.1. Introduction

Biodiversity monitoring is already very well established, with standard procedures for data collection and reporting for the inevitably wide range of taxa and geographic scales underpinning reporting (e.g. EU BON, Convention of Biological Diversity, EEA Biodiversity Data Centre, Euring etc). The challenge for ExpeER was to collect and analyse biodiversity data in ways that can be related to changes in environmental drivers and responses that can inform models. Again, this is far from a new objective; models relating species occurrence to environmental change and ecosystem function are legion (e.g. (Phillips et al., 2006, Hooper et al., 2005, Pearson and Dawson, 2003). However, methods of biodioversity assessment that cross scales are somewhat scarcer.

4.2. The use of wavelet statistical analysis

One of the possible approaches is the use of ‘wavelet’ analysis for studying the dynamics of biodiversity change over a range of scales of space and time (Kumar and Foufoula-Georgiou, 1997). A function that describes a multi-scale process can be described using combinations of wavelets. A wavelet is an oscillating function whose amplitude diminishes to zero within a certain interval of space or time. Any function can be produced by a combination of wavelets, which can be visualized to reveal behaviours at the selected scales of space and time; knowledge of the wavelet coefficients gives perfect knowledge of the original function. Spatial patterns can be transformed into a matrix of wavelet coefficients, which show patterns of variation horizontally, vertically and diagonally. Once calculated, the wavelet coefficients are powerful tools for relating environmental change to ecological response.

The challenge with wavelet analyses is that data are required over either a large contiguous grid or a long continuous time series. Thus, within ExpeER, on the one hand, land cover and climate were related to the ecosystem process of vegetation greening at scales from 0.01 x 0.01^{o} resolution (approx. 1 x 1 km), covering an area of 1024 cells square. On the other hand, temperature and phenology data for a beech forest were co-analysed across multiple time scales to reveal that the expected relationship between greening and temperature is actually delayed by a year (Carl et al., 2013). Very few such data sets are currently available that are tractable in this way, and without advances in sensing of particular taxa across large numbers of contiguous cells, this technique is unlikely to prove practicable for all but a small number of specialist applications, at least in the near term.

4.3. The use of nested quadrats

A far less labour-intensive way of collecting biodiversity data is by using nested quadrats, where species presence / absence is recorded at a series of spatial scales a common points. The UK Countryside Survey, for example, uses nested vegetation quadrats (Smart et al., 2003). Analysis of such data is subject to autocorrelation across scales, but nonetheless is achievable with a reasonable extent of human effort. Within ExpeER, biodiversity assessments were made using a nested quadrat design that counted species from $0.01m^2$ to $1000m^2$ in tenfold increments.

The challenge for ExpeER was not the recording of plant diversity across this range of scales, rather it concerned the acquisition of data on ecosystem functions across a comparable range. Many such data are based at single sampling point (e.g. the location of a sensor) or integrated over a larger area (e.g. a flux tower). Integration across technologies faces the problem that they may measure slightly different aspects of the environment. It is possible to estimate a surface for a particular ecosystem function or state (e.g. soil moisture) from a large number of sample points. As we found in ExpeER, few experimental locations are currently instrumented at sufficient intensity to allow such interpolation.

4.4. Looking ahead

The development of DNA barcoding and similar techniques opens up the possibility of multi-scale biodiversity sampling using soil samples.

The challenge of relating biodiversity data with ecosystem process data remains. However, the co-location of such data is clearly of high value. Currently, the installation of multi-scale measurement of ecosystem function data is far more costly than recording multi-scale plant diversity data. It would therefore be appropriate for the design of such ecosystem monitoring systems to include biodiversity assessment protocols to facilitate future joint analyses.

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