Journal of Ecosystem & Ecography

Evrendilek and Karakaya, J Ecosys Ecograph 2016, S5:1
DOI: 10.4172/2157-7625.S5-e101

Editorial Open Access

Monitoring of Ecosystem Metabolisms through Remotely and Proximally Sensed High-frequency Data toward Enhanced Sinks and Reduced Sources of Greenhouse Gases

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Received date: February 26, 2016; **Accepted date:** February 28, 2016; **Published date:** March 01, 2016

Ecosystem

The ability to predict the biogeochemical consequences of our actions for global climate failed as with the case of predicting many major natural, social, political or financial events throughout the human history. These unforeseen changes have been triggered by the interaction of many root causes such as unpredictable stochastic events, epistemological uncertainty, and lack of data to gauge the potential for changes to take place. In its constant and systematic search to be less wrong, however, the science strives for integrative and quantitative metrics and signals to better understand, monitor, predict and manage interdependencies and interconnections among society, environment, and economy.

Whether be terrestrial or aquatic, ecosystem metabolisms are a measure of ecosystem-scale input-output balances of energy budgets or stoichiometrically coupled biogeochemical budgets (e.g. solar radiation, carbon—C, nitrogen—N, water—H_2O, and oxygen—O) as a function of natural and anthropogenic degrading and aggrading processes. They are an ecosystem-level measure as they encompass all the related spheres (atmosphere, biosphere, hydrosphere, and pedosphere) of a terrestrial or aquatic ecosystem (Table 1). Ecosystem metabolisms for biogeochemical budgets are governed simultaneously by natural and human-induced production and loss rates of photosynthetic organic C (POC) and soil/sedimentary organic C (SOC), and ecosystem respiration rates. Ecosystem respiration rate (R_e) is the sum of heterotrophic (R_h) and autotrophic (R_a) effluxes of carbon dioxide (CO_2) to the atmosphere. Biological production can be expressed at the three organization levels of plant, ecosystem, and biome with and without accounting for respiratory C losses, a difficult distinction to make in practice due to the difficulty of *in situ* direct measurements of autotrophic respiratory losses, and for C losses due to natural and anthropogenic disturbance regimes. At the plant level are the two photosynthetic measures of net primary production (NPP), and gross primary production (GPP) without accounting for autotrophic respiratory losses, while net ecosystem production (NEP), or net ecosystem CO_2 exchange (NEE) is the ecosystem-level quantification where NEP = NEE = NPP - R_h = GPP - R_e. Net biome production (NBP), or net biome CO_2 exchange (NBE) takes into account natural and anthropogenic losses of organic C.

C Fluxes between Major Terrestrial and Aquatic Components	State Variables (Pools)	Rate Variables (Influxes/Effluxes)
Atmosphere to Phytosphere	Atmospheric CO_2 concentration	NPP and GPP
Biosphere to Atmosphere	Living community biomass	R_e, R_h and R_a
Lithosphere to Atmosphere	Soil (in)organic C [Sedimentary (in)organic C]	Rs/[sedimentary respiration and diffusion of dissolved C and bicarbonates]
Biosphere to Lithosphere	Dead community biomass	Litterfall/[sinking of particulate organic C]
Anthroposphere to Atmosphere	Ecosystem- or biome-scale C sources	NEE (NEP), NBE (NBP), burning of fossil fuels, transition to renewable energy sources, land-use/cover changes and management practices
Atmosphere to Anthroposphere	Ecosystem- or biome-scale C sinks	NEE (NEP), NBE (NBP), policy/land use decisions and management practices

The bracket sign "[ ]" was used to depict specific aquatic components. Terrestrial community biomass refers to the sum of aboveground and belowground plant and animal biomass, while aquatic community biomass refers to that of aquatic plant, phytoplankton, zooplankton and fish biomass. Rs = Soil (microbial + plant root) respiration. The term "anthroposphere" was used to denote human-induced regimes of both disturbances and rehabilitation/restoration practices. The term "lithosphere" " was used to denote the soil and bottom sediment conditions of the terrestrial and aquatic ecosystems, respectively.

Table 1: Major state and rate variables of C cycles in terrestrial and aquatic ecosystems.

The NEP and NBP estimates serve to determine if a given ecosystem acts as a sink or source. For example, net dissolved oxygen (DO) gain in a given aquatic ecosystem when NPP exceeds Rh, indicates that the ecosystem acts as a DO source (the increased degree of autotrophy), whereas net DO loss when R_h exceeds NPP means that the ecosystem acts as a DO sink (the increased degree of heterotrophy). What complicates the quantification of ecosystem metabolisms is the necessity of high-frequency (HF) data/signals to cover longer periods, bigger areas, and faster sampling rates and filtering techniques to extract useful information out of noisy HF data. The continuous monitoring of spatiotemporal changes in NEE through the use of HF eddy covariance (flux tower) data was made possible owing to many scientific and technological achievements reviewed chronologically by Baldocchi [1] and was first published by Monteith and Szeics [2] for a short period of time, and by Wofsy et al. [3] for a year. Data collected by multi- and hyper-spectral remote and proximal sensors have been related to flux tower and/or diel DO datasets for the purposes of interpolation, verification, and validation of terrestrial and aquatic ecosystem metabolism dynamics since the late 1990s.

Recent interests in ecosystem metabolism characterization have led to improvements in HF sensor data (e.g. Surface Water and Ocean Topography satellite mission to be launched in 2020) [4], technology (e.g. diel oxygen probes, and high-resolution digital cameras) [5], network (e.g. the Global Lake Ecological Observatory Network, the National Ecological Observatory Network, and the Ocean Observatory Initiative) [6] and data-filtering (e.g. continuous and discrete wavelet transforms) [7]. Denoised data from HF sensors play a pivotal role in not only better understanding and modeling of how ecosystem metabolisms work but also in better decision-making under uncertainties/stochastic conditions about how ecosystem metabolisms respond to and are affected by policy and management decisions. Any attempt at climate change resolution and mitigation involves the multiscale harmonization (or trade-offs among) of the private-to-state, individual-to-community and local-to-global regimes of behaviors toward enhancing productivity (efficiency), stability (resilience and resistance), security, sustainability, and equitability (distributive justice).

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This article was originally published in a special issue, entitled: **"Global Climate Change"**, Edited by Evrendilek