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A thermodynamic approach for assessing agroecosystem sustainability

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ABSTRACT

By revisiting theoretical concepts in biogeography and the importance of thermodynamic laws in biosphere-atmosphere interactions, ecological sustainability in agricultural systems may be better defined. In this case study, we employed a multidisciplinary methodology for exploring agroecosystem sustainability by using eddy covariance (EC) data to compute thermodynamic entropy production (σ) and relate it to water, energy and carbon cycling in croplands and grasslands of the Central US. From 2002 to 2012, the biophysical metric of σ was compared across AmeriFlux sites, each with site-specific land management practices of irrigation, crop rotation, and tillage. Results show that σ is most correlated with net ecosystem exchange (NEE) of carbon, and when cropland and grassland sites are close to being carbon neutral, σ values range from 0.51–1.0 W K^{-1} m^{-2} for grasslands, 0.81–1.0 W K^{-1} m^{-2} for rainfed croplands, and 0.81–1.1 W K^{-1} m^{-2} for irrigated croplands. Irrigated maize stressed by hydrologic and high temperature anomalies associated with the 2012 drought exhibit the greatest increase in σ, indicating the possibility of decreased sustainability compared to rainfed croplands and grasslands. These results suggest that maximizing carbon uptake with irrigation and fertilizer use tends to move agroecosystems further away from thermodynamic equilibrium, which has implications for ecological sustainability and greenhouse gas (GHG) mitigation in climate-smart agriculture. The underlying theoretical concepts, multidisciplinary methodology, and use of eddy covariance data for biophysical indicators in this study contribute to a unique understanding of ecological sustainability in agricultural systems.

1. Introduction

The role of thermodynamics is inherent in the fields of ecology and physical geography, exemplified through abiotic–biotic or spatial interactions. Discussions concerning non-equilibrium dynamics and irreversible processes are seen in biogeography, climatology, geomorphology, and landscape ecology (Brunsell et al., 2011; Holdaway et al., 2010; Perry, 2002; Phillips, 1999, 2008; Smith, 2005; Steinborn and Svirezhev, 2000; Svirezhev, 2000) and are applicable to all natural and anthropogenic landscapes, including agricultural systems on varying temporal and spatial scales. In this study, we tie together thermodynamic laws, theories of complex ecosystem dynamics, and resilience theory to explore biophysical aspects of sustainability in agroecosystems. We propose that higher thermodynamic entropy production (σ) indicates higher stress and a move away from thermodynamic equilibrium and adaptive potential.

1.1. Thermodynamics and ecosystem evolution

Thermodynamic entropy has been explored for evaluating sustainability in various disciplines including industrial ecology, resource economics, and mechanical engineering (Gutowski et al., 2009; Hermanowicz, 2007; Krotscheck, 1997; Liao et al., 2012; McMahon and Mrozek, 1997). Different frameworks for evaluating systems and subsystems have been proposed, but complexities in applying these frameworks remain. The major difficulty in conducting and interpreting studies, manifesting in numerous debates and misunderstandings across disciplines and between Nobel Laureates (Gnaiger, 1994), relates to the terminology used in describing the systems studied and in identifying spatial and temporal boundaries. It is through identification of these system boundaries and improved understanding of abiotic–biotic or spatial interactions

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that the field of physical geography is ideally equipped to contribute to the future of sustainability science.

Based on the laws of thermodynamics, the physical boundaries for interactions between the Universe, the Earth and its ecosystems can be outlined as follows: the Universe is an isolated system that does not have inputs and outputs of energy; the Earth is a closed system that exchanges energy with the Universe but, for our purposes, not matter; and ecosystems are open systems exchanging both energy and mass within the Earth system. The second law of thermodynamics helps us understand ecosystems as open systems with dissipative structures far from thermodynamic equilibrium that evolve to maintain a high level of local organization resulting in a production of entropy (Schneider and Kay, 1994). Schneider and Kay (1994) argue that ecosystems, and the species that thrive within them, develop an increasing ability to degrade incoming solar radiation, which increases the total dissipation of heat from that ecosystem. This part of energy that is no longer available for work is also known as thermodynamic entropy.

Thermodynamic entropy results from non-equilibrium thermodynamic processes occurring in a system. It is produced by fluxes of heat, matter, and momentum and related to gradients of temperature, pressure, concentration, etc., which maintain systems away from equilibrium. Within the closed Earth system, solar radiation creates a large influx of energy and a gradient that open ecosystems will strive to reduce through all available chemical and physical processes. Ecosystems that are less stressed tend to exhibit a greater ability to degrade solar energy and reduce gradients than stressed ecosystems (Schneider and Kay, 1994).

From an ecosystem development perspective, entropy production may be at a maximum during three developmental stages due to: (1) early successional growth and rapid colonization by fast growing species, (2) sustained production during maturity of longer-growing species, and (3) extended maturity or delay of retrogression by stress-tolerant species (Holdaway et al., 2010). During the growth stage, species with rapid population growth may have a higher initial entropy production than slower growing species. The temporal and spatial scales of biogeochemical and biogeophysical processes involved add to the complexity of evaluating the maximum entropy production (MEP) hypothesis, which suggests that the maximum rate of entropy production in a system occurs when the influence of vegetation productivity on land surface albedo and the effect of solar radiation absorption on evapotranspiration result in maximizing the energy flux or dissipation from the system (Kleidon, 2009).

Changes in overall entropy of a system result from all the entropy production and entropy transfer processes associated with that system. Brunsell et al. (2011) quantified the overall thermodynamic entropy budget of a land surface, calculating both entropy production and entropy transfer, and found that a higher vegetative fraction results in increased entropy production and a decreased rate of change in overall entropy. It is important to note that the decrease in the overall entropy budget is related to the decrease of the Bowen ratio (the ratio of sensible to latent heat fluxes) or the increase of entropy transfer associated with latent heat flux during the daytime and sensible and soil heat fluxes during the nighttime. Brunsell et al. (2011) also applied their methodology to data from three eddy covariance (EC) flux towers in northeastern Kansas with different land cover types and land use management practices. Results suggest that the overall ecosystem entropy is related most to net radiation at the land surface, and that *entropy production* is driven by land cover and land management.

Land cover disturbance plays an integral role in the structure of ecosystems at multiple scales creating a mosaic where there are interactions between the heterogeneous surface properties or patchiness of the landscape and ecological processes (Perry, 2002). Phillips (1999, 2008) outlines the thermodynamic principles behind numerous theories of ecosystem structure, function, and development, where evolution itself can be thought of as a fundamental irreversible process. Phillips (2008, p. 56) states that “perhaps the most robust theory of evolution at the ecosystem and biospheric scale” is one presented by biogeographer Charles H. Smith, an expert on Alfred Russell Wallace.

Smith (2005) interprets Wallace’s view of evolution as one based on spatial interactions between species, versus adaptations within species. In Wallace’s perspective, Smith argues, there is no process of adaptation only the result of being adapted. In this paradigm, evolution of spatial interactions occurs between abiotic and biotic components in a systems framework, which contains both negative and positive feedback loops (Smith, 1986, 2005). “Adaptive structures” are part of a negative feedback loop where “deviation-countering” processes are maintained at the organismal level through biogeochemical cycling and dissipation of energy, hence the production of entropy. “Adaptive potential” and the selection of traits at the ecosystem level entails a positive feedback loop where “deviation-amplifying” processes occur and spatial interactions evolve. The divergence associated with evolutionary change and adaptive potential is a return toward instead of a move away from thermodynamic equilibrium. Using theoretical models, Kostitzin (1934) also described evolution as a series of unlikely events opposing the increase of thermodynamic entropy. Consequently, the energy and directionality that exist in working against change in the negative feedback loop may increase thermodynamic entropy production, and the randomness associated with genetic mutations and probabilistic spatial interactions related to evolutionary change in the positive feedback loop will correspond with lower entropy production (Phillips, 2008; Smith, 1986, 2005).

Organisms and ecosystems may also evolve in directions of lower stress (Smith, 1986, 1989, 2005). If we consider stress as spatial gradients related to the negative feedback part of the evolution framework described above, more intense gradients will require more work to maintain “deviation-countering” processes resulting in higher entropy production. Thus, thermodynamic entropy production can be an indicator of higher stress where the system is maintained in the negative feedback loop moving away from thermodynamic equilibrium versus entering the positive feedback loop where “deviation-amplifying” processes bring a system back toward equilibrium. It is important to recognize that living systems do not actually reach thermodynamic equilibrium because they are continuously exchanging energy and matter with their environments as open systems, as previously explained. However, it is the move back toward thermodynamic equilibrium that is crucial to Wallace’s evolutionary theory, the result of adaptation, and the metric we propose for evaluating agroecosystem sustainability.

Anthropogenic inputs of fertilizer and irrigation in agricultural systems can force organisms to remain in the negative feedback loop, creating larger gradients with their surroundings corresponding to higher stress and entropy production. Anthropogenic impacts on agroecosystems have previously been quantified with thermodynamic entropy metrics using data on agricultural inputs and outputs related to tillage, fertilization, pesticide use, harvest, etc. (Steinborn and Svirezhev, 2000; Svirezhev, 2000; Patzek, 2008). Energy inputs in agricultural systems can lead to an overproduction of entropy, and the greater the overproduction, the less sustainable a system is said to be (Steinborn and Svirezhev, 2000; Patzek, 2008).

1.2. Biophysical sustainability

With compounding pressures of a growing global population, increased food demand, and changing climatic conditions there is an urgent need to understand the geographic variability of sustainability in agricultural systems. Sustainability in agroecosystems has been defined as the maintenance of productivity over time