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Recognizing the Scientific Mission of Flux Tower Observation Networks—Lay the Solid Scientific Data Foundation for Solving Ecological Issues Related to Global Change

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Abstract: As the Earth entering into the Anthropocene, global sustainable development requires ecological research to evolve into the large-scale, quantitative, and predictive era. It necessitates a revolution of ecological observation technology and a long-term accumulation of scientific data. The ecosystem flux tower observation technology is the right one to meet this requirement. However, the unique advantages and potential values of global-scale flux tower observation are still not fully appreciated. Reviewing the development history of global meteorological observation and its scientific contributions to the society, we can get an important enlightenment to re-cognize the scientific mission of flux observation.

Key words: flux tower observation; ecological research; scientific data accumulation; global sustainable development; ecological prediction.

Earth is now in a new era – the Anthropocene (Crutzen and Steffen 2003). Human beings in the Anthropocene have surpassed all other creatures in excessively exploiting natural resources (food, fresh water, timber, and fuel, etc.), resulting in substantial potentially irreversible changes to the planet and threatening the maintenance of human society (Millennium Ecosystem Assessment 2005). Planning for a sustainable future of human must be underpinned by new ecological research that has the capacity to make large-scale, quantitative prediction and give early-warnings for eco-catastrophe (Barnosky *et al.* 2012; Mace 2013). A revolution in both ecological observation technology and scien-

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tific research that values long-term accumulation of data is imperative. Gratefully, the developing ecosystem flux tower observation technology can provide solid scientific data foundation. Yet, the unique advantages and potential values of global-scale flux tower observation are still not fully appreciated. By referring to the development history of global meteorological observation and its scientific contributions to society, we can be enlightened to re-cognize the scientific mission of flux tower observation networks.

1 Ecology needs turning into a new era

Ecology, as a branch of biological science, has experienced a long-term incubation, episodic leaps, and incessant development. Traditionally, ecology mainly focuses on biological interactions between organisms and their living environment at local scale. Since the 1960s, the development of the concept of ecosystem has led to ecological research gradually shifting its focus to regional and global ecological issues with the guide of several international programs (e.g. International Biological Program (IBP), Man and Biosphere Program (MAB), International Geosphere Biosphere Program (IGBP), etc.,).

Increasingly, regional and global ecological issues receive greater attention. Ther large consumption of natural resources by human beings has fundamentally influenced the supporting biological and environmental systems (Fig. 1). Accompanied with the world's population keep expanding, it will exacerbate the ecological and environmental issues associated with global climate change, biodiversity, biogeochemical cycles and ecosystem services (Barnosky *et al.* 2012; IPCC 2014) (Fig. 1). To tackle these global problems that requires a new framework of ecology: large-scale, quantitative, predictive and capable of providing long-range early warnings for eco-catastrophe. This new framework must be able to not only provide comprehensive and predictive information on how ecosystem structure and function, pattern and process will change at a given place and a given time (Mace 2013),but also quantify and predict the impact of human activities and climate change on ecosystem and society sustainable development, specifically (i) could cognize the relationships among ecosystem change, climate change and Earth system change, (ii) evaluate the effect of human activities on those relationships, (iii) synthetically quantify and predict the impact of human activities on sustainable development in the context of global environment change.

To achieve this goal, we must overcome some constraints. Most ecologists focus on ecological phenomenon observation and its explanation and conduct researches in isolation with a label of "personal ownership" (Mace 2013; Reichman *et al.* 2011). In addition, a more important constraint is the absence of direct integrated observation system of ecosystem structure and function. If these constraints are not overcome, ecology would be hard to make the step changes from qualitative to quantitative, from local to region/global scale, and from phenomenon analysis and mechanism interpretation to scientific forecasting.

2 Global Flux Observation Networks have unique advantage and great potential value

Modern science and technology provide good opportunity for ecology to enter into an era of new measurements

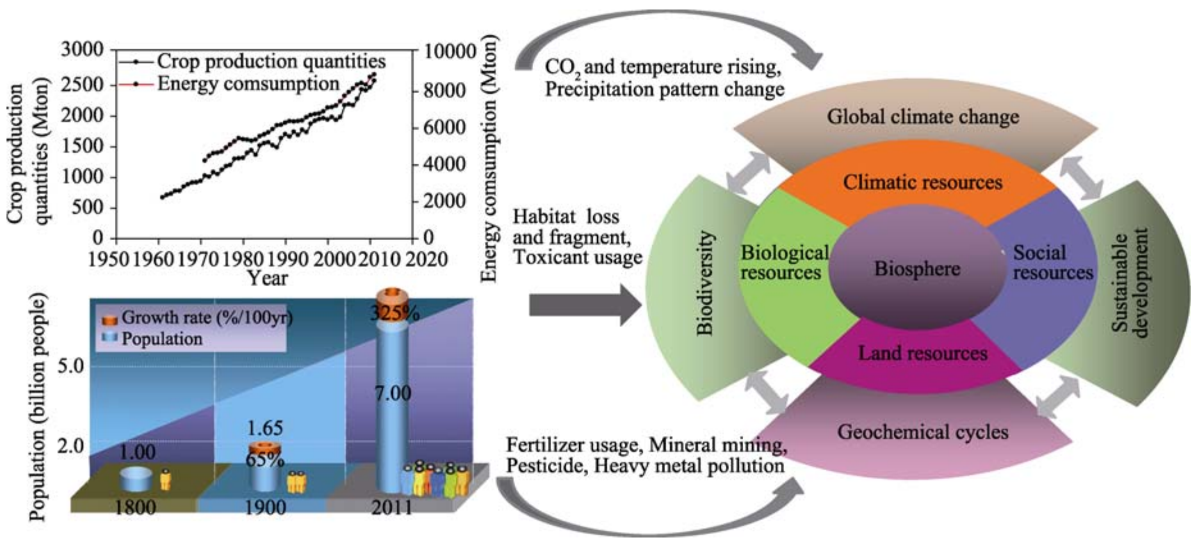

Fig.1 Human footprint on the Earth system

Note: The interactions between human activities, biological and environmental systems and sustainable development. Population, energy consumption and crop production quantities changes on the left and its influences on climatic, biological, land and social systems on the right. Population data is from United Nations (UN) (World Population Prospects 2013). Energy consumption data is from International Energy Agency (IEA) (Key World Energy Statistics 2014). Crop production quantities data is from Food and Agriculture Organization (FAO) (FAOSTAT 2014).

(Chave 2013). The invention of eddy covariance flux measurement (EC) has undoubtedly created a great technological revolution in ecological observations at ecosystem scales because it allows direct in situ measurements of the fluxes of material and energy and ecosystem productivity (Wofsy *et al*. 1993). Continuous and synchronous flux measurement of CO_2, H_2O, and energy at the ecosystem-scale can now be steadily and reliably conducted with EC. Measurements on fluxes of CH_4, N_2O, other trace gases and stable isotope are also successfully incorporated into the EC systems (Baldocchi 2014). As the EC technique further develop and the cost of EC equipment economize with the technology advance, EC observational systems will be more broadly applied worldwide. As Baldocchi said, EC measurement provides a promising approach to examine how ecosystem carbon and water fluxes may change in response to biotic and abiotic factors, and is adept at discovering the emergent properties of ecosystems (Baldocchi 2014). As the fluxes of water, energy and greenhouse gases (GHGs) can be assumed as the proxy for the responses of ecosystem structure and function to global change, EC has become the core technique in the comprehensive monitoring system integrated with ground survey and remote sensing for changes in ecosystem structure and function (Fig. 2), which facilitates our understanding and prediction on the 'breathing' of the biosphere under global change (Baldocchi 2008). The gradual accumulation of data from the flux tower observation has become the essential resource for analyzing the dynamic changes in ecosystem GHGs exchange and energy budget , revealing the biogeographic mechanism, assessing ecosystem productivity and carbon source/sink capacity, and evaluating the impacts of global climate change and human activities, across regional, continental and global scales.

However, the unique advantage and potential value of flux data for macro-ecological research and global sustainable development has not yet been fully appreciated by the research community, the general public and the governmental agencies. Although some researchers have paid attention to the large-scale macro-ecological issues, majority of flux communities still focus on the progress of the observation theories and knowledge of ecological phenomenon at a small or individual-site scale. Therefore, the general public and government agencies have not fully realized the potential value of the flux network observation in addressing the

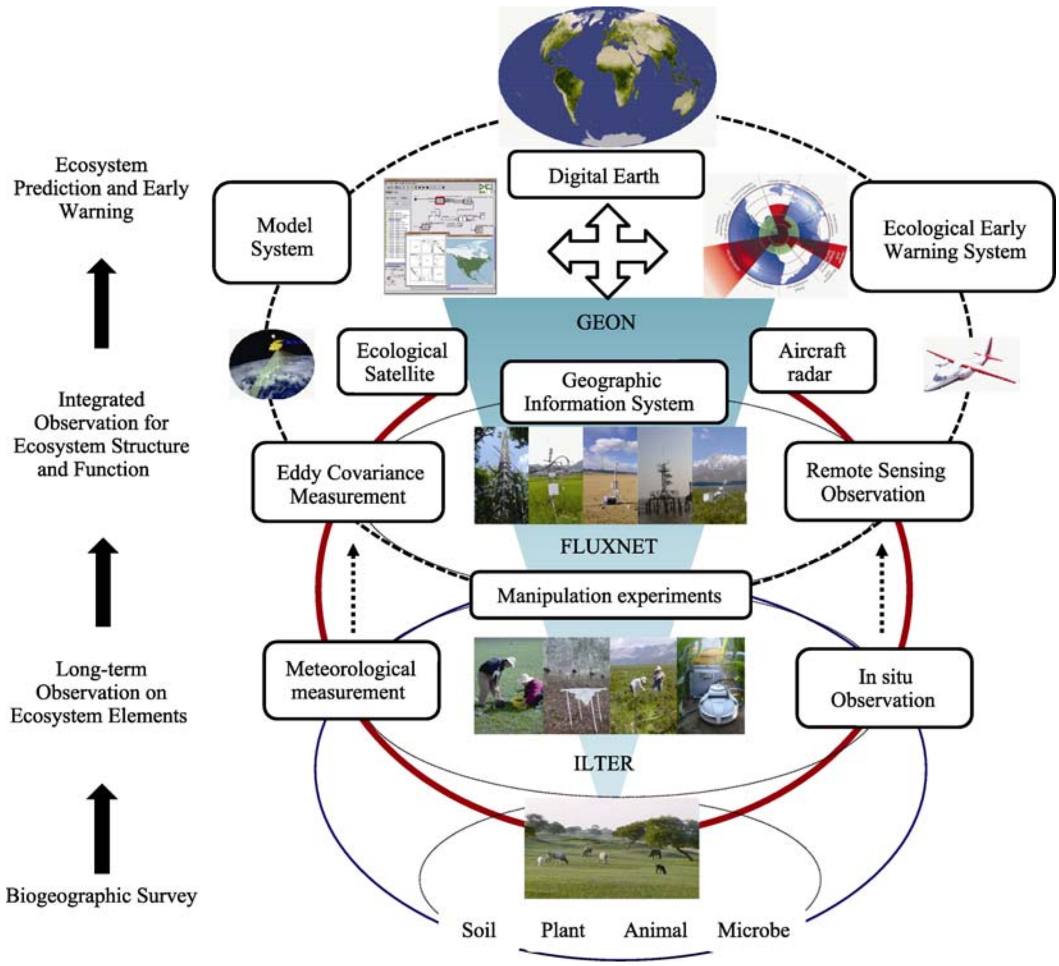

Fig.2 Blueprint and framework of ecology development stages, technology systems and networks

ecological issues related to global change and human welfare. This under-evaluation results in tremendous difficulties in expanding the global network of flux observation, developing a standardized observation system and achieving the data sharing.

3 Development of meteorology science provides a valuable enlightenment

The development of meteorology provides good enlightenment for us to re-cognize the scientific mission of networked flux observation. Meteorology started to accumulate knowledge around the 16th century and gradually advanced its development at each stage of technology innovation (Fig. 3a). After entering the 1950s, some new atmospheric detection technologies such as radar, rockets and satellites, etc. were applied in monitoring the meteorological environment and its changes at different spatial and temporal scales. Meteorological data is made freely available in near real-time, allowing high-speed computers to be applied in automatic and large-volume data processing. With the continuous promotion of World Meteorological Organization (WMO), meteorological observation has transformed from pure scientific research to routine operation, and such transformation has greatly accelerated the development of numerical weather forecasting and atmospheric science.

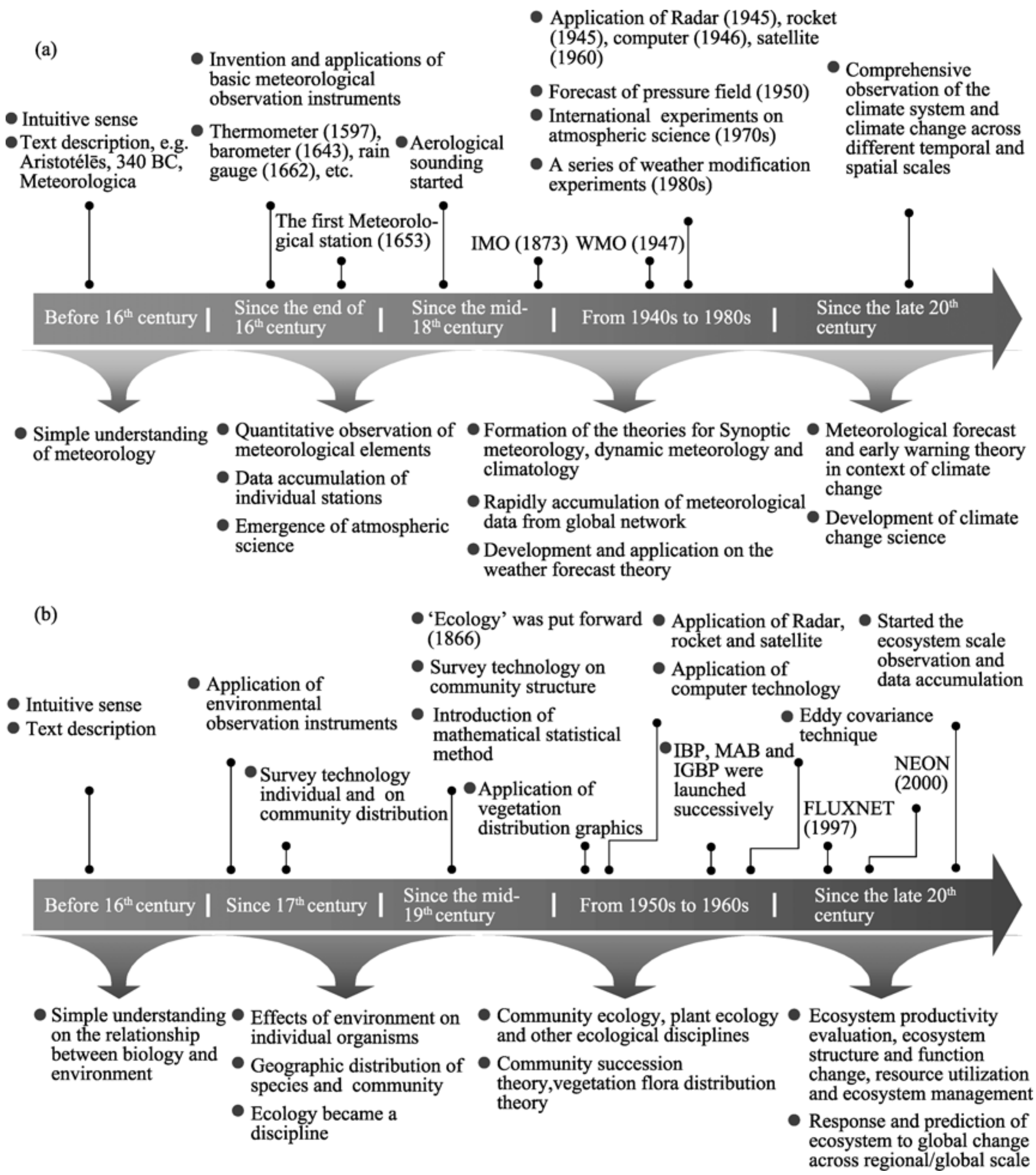

Fig.3 The historical development of meteorology science (a) and ecology science (b), and their technology system and scientific mission

The progress of meteorology illustrates that after hundreds of years' development, the meteorological observation has gradually advanced from manual observation of major meteorological elements to an automated multi-elements satellite and radar stereoscopic observation. The meteorology accordingly advances to global-scale weather forecasting, and thus allows the parallel rapid development of climate change science (Fig. 3a).

Ecology is experiencing a similar development process as the meteorology does (Fig. 3b). It has developed from the ecological phenomenon observation, stand inventory, and site-level ecological elements measurement, to ecosystem-scale observation. Ecological data acquisition also has experienced the step stages from traditional field investigation, positioning and discrete observation to long-term, in-situ coordinated observation (Fig. 3b). However, the development of weather forecasting and climate science reminds us that without 50-100 years accumulation of network observational data, achieving the capacity of ecological forecasting and prediction may still be a footless "dream".

4 Following the developing roadmap of meteorology, achieving ecological prediction and security warning

"A thousand mile journey begins with a single step, and the century-dream entails generations to struggle for". For ecological science to prosper, we need to grasp the current historical opportunity presented by the revolution of observation technique and the new "big data and big science" era of ecology. (Boyle 2013; Marx 2013; Michener and Jones 2012). We must promote the transition from the traditional observation of ecological elements to the integrated observation of ecosystem structure and function, and promote transition from individual site study to large-scale synthesized studies across vast geographic zones and time periods. At the same time, we need to enhance our capability for scientific prediction on ecosystem change and ecosystem service, which is a prerequisite for solving ecological issues related to sustainable development at regional and global scales.

To achieve this goal, a series coordinated actions have to be adopted. First, a World Ecological Organization (WEO), similar to the World Meteorological Organization (WMO) is needed. The WEO will make efforts to unite the global-scale network resources involving the International Long-Term Ecological Research network (ILTER), FLUXNET and the aircraft and satellite remote sensing observation networks, and other regional/national-scale networks to construct a Global Ecological Observation Network (GEON) (Fig. 2). Second, due to the unique role of EC data for understanding the mutual effect of biotic and abiotic factors on ecosystem processes and functions, the flux-centric integrated observation system combined ground-based ecological measurement and space-based observation should be established to create an automatic, standardized three-dimensional observatory system. Third, an advanced model system combined the ecosystem processes and biogeochemical cycles should be develop and optimized with the multi-source data through model-data fusion. Finally, we use the approach of "multi-scale observations, multi-method validation, multi process integration, cross-scale cognition, cross-scale simulation" to explore the principles of ecosystem structure and function, and how ecosystem pattern and process changes in the context of global climate cha

Only if 50–100 years of continuous effort in advancing fluxes observation technology and a long-term accumulation of scientific data from the united constructed GEON, ecological science could finally achieve the transitions from being qualitative to quantitative, and from ecological analysis to ecological forecasting. Such an ecological science can provide more efficient services for global sustainable development in fields of scenario analysis, scientific forecasting, ecological safety warning and decision-making. This is a universal expectation of ecologists, and is the scientific mission for the world's flux tower observation network community.

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通量观测事业的科学使命再认知--为解决全球可持续发展的生态学问题奠定坚实的数据基础

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摘　要：自地球系统进入人类世，要解决全球可持续发展问题，生态学研究需要进入一个大尺度、定量的和可预测的新时代。生态学观测技术的革命和科学数据的长期积累是实现生态学研究跨时代发展的必需。生态系统的通量观测技术是生态学观测技术上的一次重大革命。然而，全球规模的通量观测事业的独特优势和潜在价值仍未被充分认识。回顾全球气象学观测事业的发展历史及其对社会的科学贡献，很好地启示我们再认识通量观测事业的科学使命。

关键词：通量观测；生态学研究；科学数据积累；全球可持续发展；生态预测