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The 5M Principles of Sustainability Dynamics: Ecosystem-Level Measuring, Monitoring, Mapping, Modeling and Managing of Natural Capital

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"The world has quietly transitioned into a situation where water, not land, has emerged as the principal constraint on expanding food supplies." — Lester Brown, *The Observer* 2013

Ecosystems are interacting open systems of abiotic and biotic components at a given spatio-temporal scale that function in a self-sustaining and -organizing manner in the absence of major anthropogenic disturbances and provide humans with life-support productive, regenerative, protective, regulative and informative services (aka ecosystem services) [1]. The root causes of endangered sustenance of ecosystem services include rapid growth of human population and consumption, poverty, unequal economic growth, uses of ecologically incompatible technologies, and misuse, overuse and undervaluation of natural capital [2]. The basic premise of ecosystem sustainability regardless of how it is *defined* is the inevitable dependence of humans on the natural capital as the source and sink of ecosystem services, and thus, is to keep socio-economic throughput load within the biophysical limits of the continued productivity of the earth's natural capital [3,4]. The global value of total ecosystem services in 2011 was estimated at $125 trillion yr-1 based on the monetary terms of 2007 $US [5]. Building and securing ecosystem sustainability call for not only living in harmony with but also enhancing carrying capacity (biophysical limits) of local, regional and global natural capitals [1]. However, with the globally increasing magnitude and severity of human-induced disturbances of the environment, nations have been facing great challenges of adopting better yardsticks than Gross National Product (GNP) that would signal trade-offs and uncertainties inherent in all public decisions and/or valuation towards ensuring sustainability [2,4,6].

Even though we need diverse indicators of sustainability to be tested across the world on the way to maturity in finding a common sustainability measure, the process of assessing sustainability dynamics at the ecosystem scale consists mainly of five coupled principles/ components that continuously feedback to one another in a cycle. In other words, the extent to which sustainability of natural capital changes over given space and time scales can be mainly described in 5Ms thus: measuring, monitoring, mapping, modeling, and managing. Measuring provides a full snapshot accounting of marketed and non-marketed costs and benefits associated with natural capital and public policies at the time, location, and resolution of measurement. Monitoring and mapping go far beyond measuring by estimating spatio-temporal distribution patterns of changes in natural capital at a desired spatio-temporal resolution in response to natural and human-induced processes and their impacts on different generations, income groups and regions. Furthermore, empirical and mechanistic modeling allows for the better understanding and prediction of effects of human interventions on the degradation or rehabilitation of ecosystem services under "what-if" or "trade-off" scenarios, and thus, for the formulation of adaptive public policies and management practices in the face of uncertainty towards the paths of sustainability.

Uncertainty refers to a lack of complete understanding, knowledge and predictability of the system to be managed. Adaptive public policy and management explicitly consider implications of uncertainty for the decision-making process and coping with environmental issues in ecologically compatible, economically viable, and socially acceptable ways [7]. Adoption and implementation of the 5M principles demand flexible, responsive and collective institutional regimes so as to learn from past and present failures whether be policy-, market- or governance-related which distort the locally, regionally and globally intertwined relationships among such domains as economy, ecology, energy, and ethics (4Es).

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