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Assessing resource-use efficiency of land use

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ABSTRACT

We introduce an explicit indicator and the Land Use Management Support System to assess the resource-use efficiency of land use (RUE) at the landscape scale. To estimate RUE, we relate land-use performance with regard to ecosystem services indicators to the maximum possible land-use performance based on an optimised land-use configuration. The test application of the RUE assessment in the Haean catchment, South Korea, shows that the land-use system's RUE could be increased by 11% for both nitrate and sediment loss. The estimated headroom could indicate whether potential contaminant reduction targets for the downstream water reservoir Lake Soyang could be achieved with the current land-use system. The recurring RUE assessment for a given region might indicate the effectiveness of spatial planning and policy measures to improve the RUE in that region. Future work should address the integration of RUE into a participatory spatial planning or resource-management framework.

Software and data availability

Land Use Management Support System (LUMASS)

Software: LUMASS.
Developer: Alexander Herzig (s. Corresponding author)
Year first available: 2012.
Hardware: PC, notebook; 4 GB RAM; 1 GB disk space.
Software required: Windows (64bit) or Linux.
Program language: C++
Program size: 30 MB (source); 312 MB (Windows 64bit, installed)
Licence: GNU General Public Licence v3 (GPL)
Availability: Source code; Windows (64 bit) binaries.
Download: https://bitbucket.org/landcareresearch/lumass.

Haean dataset (LUMASS spatial Optimisation HowTo)

The Haean dataset and the LUMASS spatial optimisation settings files used to compute the data discussed in this paper are available as part of the LUMASS spatial Optimisation HowTo

Authors: Optimisation HowTo: Alexander Herzig; Haean dataset: Ganga Ram Maharjan, Trung Thanh Nguyen, Sebastian Arnhold, Bumsuk Seo, Thomas Koellner, John Tenhunen.
Licence: Optimisation HowTo: Creative Commons Attribution (CC BY 4.0); Haean dataset: Creative Commons Attribution-NoDerivs (CC BY ND 4.0)
Download: https://bitbucket.org/landcareresearch/lumass.

1. Introduction

Human population increase and economic growth agendas (e.g.

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MBIE, 2015) increase the pressure on natural resources and ecosystems around the world (MEA, 2005). Ever more production needs to be realised from the same finite amount of natural resources. At the same time, environmental conditions need to be improved or at least maintained (e.g. NZGOVT, 2012). Hence, natural resources have to be used more efficiently to maximise the provisioning of ecosystem goods and services (*ecosystem services*, MEA, 2005).

But how efficiently are we using natural resources in a given landscape? How do we measure resource-use efficiency at the landscape scale? In resource and ecological economics in particular, different approaches have been developed to assess and analyse the environmental efficiency of production processes with regard to natural resources. These include simple ratios, relating resource-use or environmental impact to production output or net revenue (often referred to as eco-efficiency indicators) (Tyetca, 1996; OECD, 1998; WBCSD, 2000), material or energy and exergy balances (Coelli et al., 2007; Lauwers, 2009; Hoang and Alauddin, 2012), and frontier-based efficiency analyses (Lansik and Wall, 2014; Berre et al., 2015). Coelli et al. (2011) proposed a modified Data Envelopment Analysis (DEA, Charnes et al., 1978) to assess the environmental efficiency of Italian provinces. More recently, Nguyen et al. (2012) have used this DEA approach to assess the environmental efficiency of South Korean rice farms and to determine the trade-offs between economic efficiency (maximized profit or minimize production costs) and environmental efficiency (minimize negative environmental impacts).

While frontier-based approaches are often used to analyse and compare the environmental efficiency of individual enterprises of a particular business sector (e.g. Coelli et al., 2007; Hoang and Nguyen, 2013), eco-efficiency indicators are often used to compare the environmental impact of economic growth of different regions or countries (e.g. UNESCAP, 2009). Despite their success in fostering resource-use reduction and decreasing environmental impact of businesses (McDonough and Braungart, 1998), Huppes and Ishikawa (2007) point out that there is a disconnection between environmental targets at larger scales and eco-efficiency improvements at smaller scales. McDonough and Braungart (1998) argue that the concept of eco-efficiency does not overcome the conceptual ill-design of industrial production. Therefore, eco-efficiency could only slow-down environmental degradation rather than actually lead the way towards sustainability (McDonough and Braungart, 1998).

In fact, eco-efficiency indicators and environmental efficiency measures as mentioned above (henceforth simply referred to as eco-efficiency indicators) solely represent the demand for natural resources and ecosystem services. They are not linked to the landscape ecological processes delivering the ecosystem goods and services consumed in the production process. Eco-efficiency indicators do not account for the stock of natural resources or the ecosystem's potential to provide ecosystem services, for example, the abatement of adverse effects of the production process on the environment. Likewise, Coelli et al. (2007, p. 10, note 17) point out that their farm-level environmental efficiency score calculated for Belgian pig-finishing farms does not directly correspond to environmental damage because of the different locational characteristics of the analysed farms, such as soil type and topography.

It is impossible to infer the state of the environment in a particular region from the eco-efficiency of the businesses in that region. Even if all businesses in a particular region improve their eco-efficiency, the region's natural resources may still be unsustainably used. Hence, eco-efficiency indicators provide little information on the resource-use efficiency in a given region. The challenge is to link farm-scale management and technological aspects with landscape-scale environmental and socio-economic objectives. To address this issue, several case studies have been presented that employ land-use optimisation algorithms to achieve landscape-scale environmental and economic objectives, while explicitly accounting for farm-scale management and technological aspects, such as fertiliser regimes, crop rotations, and irrigation, respectively (e.g. Seppelt and Voinov, 2002; Roetter et al., 2005; Lautenbach et al., 2013; Herzig et al., 2016). Land-use optimisation is driven by the spatially varying ecological conditions across the landscape and optimises the match of land use with the landscape's potential to provide ecosystem goods and services. Thereby, it implicitly improves the productivity of the landscape and also the efficiency with which the landscape's natural resources are used to provide benefit to human well-being[2] (e.g. Polasky et al., 2008; Bryan et al., 2015; Herzig et al., 2016). However, to our knowledge, there is no explicit measure available that quantifies resource-use efficiency of land use. Consequently, if we cannot measure resource-use efficiency, it is difficult to assess whether any land-use changes improve resource-use efficiency or not. Moreover, it is impossible to estimate the potential headroom for efficiency increases.

In this paper, we introduce a new indicator to explicitly estimate the resource-use efficiency of land use (RUE) at the landscape scale (Sections 2.1 and 2.2). Additionally, we introduce a sequence of analysis steps to support the exploration of land-use performance by multi-scenario analysis reflecting different regional objectives and expectations (Section 2.6). The information derived from this analysis might be used to support regional planning, for example, to assess the impact of agricultural intensification on the land-use performance potential (Herzig et al., 2016) or the impact of urban expansion on the provisioning of ecosystem services (Curran-Cournane et al., 2014). To facilitate the assessment of RUE and multi-scenario analysis, we introduce the free and open source Land-Use Management Support System (LUMASS) (Section 2.3). It is intended to enable planning professionals with geo-data processing skills to assess RUE and conduct multi-scenario land-use performance analysis.

We demonstrate the assessment and evaluation of the indicator through an academic case study using a test data set of modelled ecosystem services indicators for the Haean catchment, South Korea (Sections 2.4 and 2.5). Additionally, we indicate at which stages of the assessment stakeholder input is required to potentially inform spatial planning or policy development. Nevertheless, stakeholder engagement and strategies to incorporate RUE assessment into spatial planning and policy development processes are beyond the scope of this paper and subject to further research.

Intensive agriculture in the Haean catchment has been identified as a major source of sediment and nutrient contamination in the downstream water reservoir Lake Soyang. We use the Haean test data set to demonstrate in general how the assessment of RUE can be applied to i) assess the land-use performance limits with respect to individual ecosystem-services, ii) assess the potential maximum environmental and iii) socio-economic land-use performance, as well as iv) identify potential trade-off scenarios between environmental and economic land-use performance (Section 2.6). More specifically, in the context of the Haean test application, we show that the RUE assessment provides estimates of the maximum possible individual and combined reduction of sediment and nutrients for the current land use. This could inform spatial planning and policy development whether the current land-use system provides enough headroom to achieve potential sediment and nutrient reduction targets for Lake Soyang, while maintaining or enhancing the livelihood in the Haean catchment.

[2] We understand human well-being as defined by MEA (2005, p. v): "Human well-being is assumed to have multiple constituents, including the *basic material for a good life*, such as secure and adequate livelihoods, enough food at all times, shelter, clothing, and access to goods; *health,* including feeling well and having a healthy physical environment, such as clean air and access to clean water; *good social relations,* including social cohesion, mutual respect, and the ability to help others and provide for children; *security,* including secure access to natural and other resources, personal safety, and security from natural and human-made disasters; and *freedom of choice and action,* including the opportunity to achieve what an individual values doing and being."