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Investigating trade-offs between water quality and agricultural productivity using the Land Utilisation and Capability Indicator (LUCI)–A New Zealand application

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ABSTRACT

Concern for the impacts of rural land-use intensification on ecosystem services is growing world-wide, especially with regard to water quality management. The Land Utilisation & Capability Indicator (LUCI) is a GIS framework that considers impacts of land use on multiple ecosystem services in a holistic and spatially explicit manner. Due to its fine spatial scale and focus on the rural environment, LUCI is well-placed to help both farm and catchment managers to explore and quantify spatially explicit solutions to improve water quality while also maintaining or enhancing other ecosystem service outcomes.

LUCI water quality and agricultural productivity models were applied to a catchment in the Bay of Plenty, New Zealand. Nitrogen (N) and phosphorus (P) sources, sinks and pathways in the landscape were identified and trade-offs and synergies between water quality and agricultural productivity were investigated. Results indicate that interventions to improve water quality are likely to come at the expense of agriculturally productive land. Nonetheless, loss of agriculturally productive land can be minimised by using LUCI to identify, at a fine spatial scale, the most appropriate locations for nutrient intervention. Spatially targeted and strategic nutrient source management and pathway interception can improve water quality, while minimising negative financial impacts on farms. Our results provide spatially explicit solutions to optimize agricultural productivity and water quality, which will inform better farm, land and catchment management as well as national and international policy.

1. Introduction

Understanding of the importance of ecosystem services and a concern for their degradation has increased globally in recent years (Braat and de Groot, 2012; MEA, 2005). The impacts of agricultural land use on ecosystem services associated with freshwater and nutrient cycling are of particular concern (MEA, 2005; Muller et al., 2015). New Zealand's economy relies heavily on primary agricultural production (Govt, 2015), yet these industries are implicated in a decline of key environmental indicators. Recently public attention has focused on deteriorating fresh water quality of streams, rivers and lakes, leading to new and pending local government legislation and regulation (MFE, 2013; Govt, 2014; PCE, 2013). These policies put farmers and land managers under increased pressure to reduce farm nutrient losses to the environment while ensuring production and profitability goals are met. However, paths linking diffuse nutrient loss at the farm scale to downstream water quality can be varied and uncertain. Models and decision support tools are useful for assessing and communicating nutrient movement through landscapes, as well as determining their impacts and potential mitigations (Heathwaite, 2003).

LUCI (the Land Utilisation and Capability Indicator), an extension of the Polyscape framework described in Jackson et al. (2013a), aims to investigate the cumulative impact of individual sub-field ecosystem service interventions within larger catchments. It shares a number of features in common with other decision support frameworks, but also has unique features that make it particularly suitable for evaluating the impacts of small-scale management at larger scales. Bagstad et al (2013) identified LUCI as the only tool suitable for both landscape and site scale modelling in a recent comprehensive international review of generalizable ecosystem service models.

The LUCI framework considers impacts of land use on multiple ecosystem services in a holistic and spatially explicit manner. A number of ecosystem service stocks and associated indicators and processes are considered by LUCI and it determines how the configuration and

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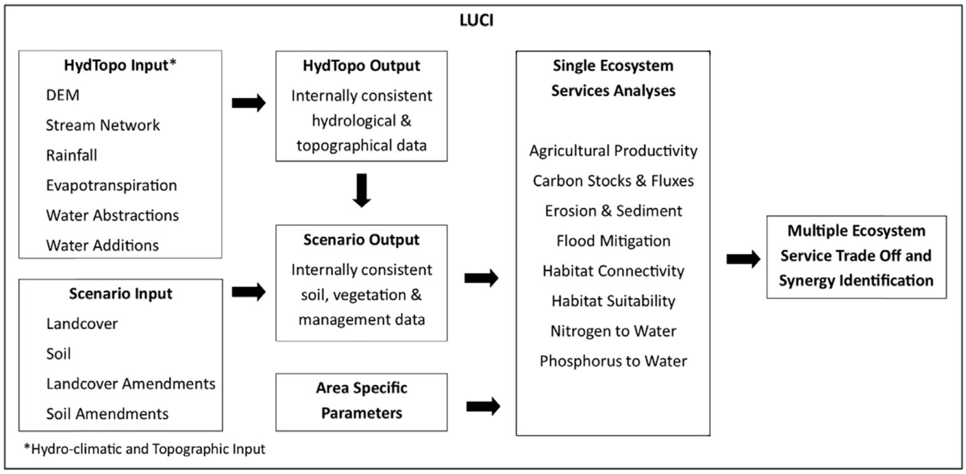

Fig. 1. LUCI Process Diagram.

placement of landscape features affect each of these. Individual ecosystem services can be assessed and the interrelationships between ecosystem services can be analysed to identify trade-offs and synergies between them (Fig. 1). LUCI uses readily available national data and is computationally efficient, accomplishing highly spatially explicit catchment-scale analyses within minutes to hours. Minimum data requirements for LUCI are a digital elevation model (DEM), land cover and soil data. However, applications can be easily supplemented with additional national or local data if it is available. LUCI is readily applicable to a number of countries and a wide range of environments, and it has been extensively applied in New Zealand (eg. Ballinger, 2011, Scott, 2015, Jackson et al., 2016, Marapara, 2016, Trodahl et al., 2016), Wales (e.g. Jackson et al., 2013a, Robinson et al., 2013, Emmett et al., 2014, Emmett et al., 2015, Emmett et al., 2016), and elsewhere (Benavidez et al., 2016; Bhatterei, 2009; Jackson et al., 2013b).

This paper reports the first application of LUCI in a groundwater dominated catchment, which is also the first application to use both nitrogen (N) and phosphorus (P) water quality and agricultural productivity tools in conjunction with a trade-off analysis. Additionally, newly developed, novel algorithms that update the N and P predictions to account for impacts of detailed farm management are applied. The study is a result of a collaboration between LUCI developers and a New Zealand farmer-owned co-operative (Ravensdown), which is incorporating farm management information into the framework to enhance LUCI's capabilities to support on-farm decision making (Jackson et al., 2016; Trodahl et al., 2016). The objectives of this study were to identify nitrogen and phosphorus sources and sinks in a complex landscape and to investigate trade-offs and synergies between water quality outcomes and agricultural productivity.

2. Study site

Lake Rotorua is situated in the Bay of Plenty, North Island, New Zealand (Fig. 2). The lake is a volcanic caldera with significant geothermal resources and springs in the surrounding catchment. The contributing surface water catchment is 502.1 km^2. In addition, there are significant groundwater resources. It is estimated that an additional area of 35 km^2 to the north-west of the catchment also contributes groundwater to the Lake Rotorua system (White et al., 2014). The catchment is largely comprised of porous allophanic and pumice soils, although the west of the catchment consists of less porous podzol soils. Smaller areas of recent, organic and raw soil are also present. See Hewitt (2010) for New Zealand soil order descriptions.

Land cover within the catchment is largely agricultural (210 km^2). 1% of agricultural land cover is crops and orchards. The remaining agricultural land is pastoral with 25% of this in dairy farming and 75% in dry stock (sheep and beef) farming (BoPRC, 2012a). There is negligible irrigation or artificial drainage on agricultural land within the catchment due to high rainfall and porous soils. Commercial forestry covers 74.9 km^2, and non-commercial forest and shrubland 95.8 km^2. The largest urban area in the catchment is the city of Rotorua (20.8 km^2) with a population of just over 53 000 (TeAra, 2016).

Lake Rotorua has suffered from well-documented reductions in water quality in recent decades. Past and present anthropogenic drivers of declining water quality include intensification of pastoral farming, septic tanks and sewage treatment plant discharge. However, natural sources of N and P are also present due to the area's geology and volcanism and, in some sub-catchments, these represent a significant proportion of the nutrient load (Rutherford et al., 2011; Tempero et al., 2015; Williamson and Cooke, 1982).

Land management strategies to reduce nutrient input to the lake are used to varying degrees and include riparian protection from stock (fencing and planting), efficient fertiliser use, detention dams, tree planting for erosion control, land use change and improved septic and sewage treatment (Rotorua Te Arawa Lakes Strategy Group, 2016). Recent local government regulation now limits nitrogen and phosphorus export to a 2001–2004 benchmark for properties over 4000 m^2. This benchmark is established for each property using OVERSEER®, a New Zealand, non-spatial farm nutrient budgeting model with widespread use amongst farmers, farm consultants and local government (BoPRC, 2012b; OVERSEER, 2016; Wheeler and Shepherd, 2013).

Despite the hydrological complexity and diverse nutrient sources in the Rotorua catchment, we chose it for the application of the LUCI models in this study because of the availability of long term, comprehensive hydrological and nutrient data. In addition, farmers are concerned that the new regulatory measures to limit nutrient losses to waterways within the catchment will negatively impact the viability of agricultural enterprise in the region (McRae, 2015). LUCI can assist with decision making around this complex issue by providing information to stakeholders, and farmers respond positively to the visual, spatially explicit nature of the LUCI framework (Scott, 2015). We applied LUCI's *Nitrogen to Water*, *Phosphorus to Water* and *Agricultural Productivity* models to the Lake Rotorua surface catchment.

3. Method

3.1. Base data

Base data for this application included a 5 m by 5 m DEM derived from LiDAR data from Bay of Plenty Regional Council (BoPRC), land