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Analysis

The Impact of Land Use Change on Carbon Stored in Mountain Grasslands and Shrublands

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1. Introduction

Mountain grasslands and shrublands (MGS) provide numerous ecosystem services including plant and animal biodiversity, the provision of clean water (for drinking, sanitation, irrigation and energy), food, culture and recreation, and as is the focus here, climate regulation through the continued storage of existing carbon (C) stocks and sequestration of carbon dioxide (CO_2) in high-altitude vegetation and soils (Korner et al., 2005; Ward et al., 2014). Ward et al. (2014) estimated that between 60.5 Pg C and 82.8 Pg of C was stored across 64 mountain countries in the year 2000 (excluding Antarctica). This C pool plays an important role in international-level carbon budgets and climate regulation, and has a substantial economic value (Ward et al., 2015). Likewise, any net sequestration of CO_2 by MGS over a period of time will also have an economic benefit to society through mitigating climate change.

Ecological economics-based valuations have been made for forests, lowland grasslands and marine ecosystems (e.g. mangrove forests and seagrass meadows) with the aim of building more robust environmental accounts and drawing attention to the climate regulating importance of these areas. Proponents also advocate that such estimates enable more effective natural resource management (NRM) decision-making through the use of spatial targeting to determine where to best focus limited financial and technical resources, enabling climate finance to be used to fund more sustainable land use (Costanza et al., 2014; Braat and de Groot, 2012; Lin et al., 2013; Pendleton et al., 2012; TEEB, 2010). However, unlike for other ecological assets, an economic value for both C in-situ stocks (the C that is there now) and net CO_2 sequestration (the additional C that is stored over time) has not been estimated for MGS at any national level, let al.one at the global scale. Climate change is global policy challenges which require studies of sufficient scale as to not miss the influence of relevant biophysical and socioeconomic circumstances (Soroos, 1990; Millennium Ecosystem Assessment, 2005).

In this regard, a lack of understanding of trends in land use and land use change (LULUC), CO_2 flux, and the associated ecological economic values, has potential for adverse decision-making implications for the management of MGS (Costanza et al., 2014; TEEB, 2010). Advocates of ecosystem valuation argue that such studies help make sense of complex socioecological interactions, allowing for the incorporation of the value of natural capital into public decision making processes (TEEB, 2010). Perhaps more critically, unsustainable LULUC practices more often than not exert a negative impact on ecological assets, associated C pools, and in addition, the ongoing capacity of vegetation and soils to sequester CO_2. This is particularly the case for MGS, which are fragile and slow to recover from degradation (Beniston, 2003). Such degradation has the potential to undermine international climate change mitigation targets, such as the recent *Paris Agreement*, whereby the degradation of C stocks and CO_2 biosequestration capacity (be it forests, marine or MGS ecosystems) offsets greenhouse gas (GHG) reduction gains in other areas e.g. energy generation using low emissions technologies. To this end, avoiding emissions from unsustainable LULUC practices can be considered both logical and desirable. Avoiding emissions may also offer previously unrecognised carbon mitigation potential through mechanisms such as the Reduced Emissions from Deforestation and Degradation (REDD) and the Verified Carbon Standard which provide a financial incentive to manage MGS more sustainably (Ward et al., 2015).

Critical knowledge and data gaps impede the resolution of many mountain-related issues, including for LULUC in MGS and associated CO_2 dynamics (Jansky et al., 2002; Ward et al., 2015). There are only a handful of ecological economic orientated studies for mountain forests, and even fewer focused on MGS ecosystems. At the local scale, ecosystem valuation studies have been completed for a number of locations

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in the European Alps (Gret-Regamey and Kytzia, 2007; Getzner, 2000; Gliick and Kuen, 1911; Glos et al., 2006; Golo et al., 2005; Hackl and Pruckner, 2007; Jaggin, 1999; Tangerini and Soguel, 2004). The majority of these studies have used contingent valuation methods to value a single ecosystem service (e.g. scenic beauty, avalanche protection, recreation). Only two of the studies (Golo et al., 2005; Gret-Regamey and Kytzia, 2007) attempted to value multiple ecosystem services, including carbon sequestration. All of these studies focused on just one discrete geographical location e.g. Davos Switzerland. Grêt-Regamey et al. (2012) point out that there is scope and potential benefits to policy makers in broadening valuation frameworks (beyond this narrow focus) to support planning processes, particularly when considering the most appropriate location for a new development. Gret-Regamey and Kytzia (2007) go further and advocate the benefits that ecological economic valuation can contribute to regional planning and development. At the global level, no such studies exist for how LULUC might impact C stores in MGS ecosystems.

What is known, however, is that MGS are among the world's most vulnerable ecosystems, with climate change, overgrazing, tourism, wildfires and intensive cropping posing a growing threat to the C pools contained within these ecosystems (Korner et al., 2005; Ward et al., 2015). Putting aside the direct impacts of climate change, the expansion and intensification of cropping and grazing are considered by many experts to be the most significant anthropogenic stressors facing MGS ecosystems today (Korner et al., 2005; Ward et al., 2015). These land use types dominate the economic makeup of many mountain countries around the world, yet the extent to which these activities influence MGS ecosystems, the C stored within and the rates of CO_2 sequestered, has not been quantified or analysed at a global scale.

Here we present the results from the first global model to estimate the impact of LULUC on C stored and CO_2 exchanged by MGS ecosystems. This model considers MGS ecoregions in 48 mountain countries (98% of the MGS land area identified by Ward et al., 2014) for the years 2000 to 2015. We then go one step further and offer the first estimate of the economic value of this C, using Social Cost of Carbon (SCC) as a proxy for the avoided damage to society (as used in similar studies e.g. Pendleton et al., 2012). Though there are considerable uncertainties, the best available global-scale and national-scale biophysical and socioeconomic spatial data was used to provide the first global estimate of CO_2 emissions from MGS, and the associated ecological economic value. Withstanding the morale and intrinsic issues arising from putting a price on what many consider priceless values (McCauley, 2006), in estimating this value we aim to make policy-makers, researchers and potential carbon market participants aware of the value of C stored in MGS ecosystems, through making “the values of nature visible and accountable for in economic decision making” (Akerman and Peltola, 2012, p.1; Costanza et al., 2014; Ackerman and Heinzerling, 2004; Ward et al., 2015). Ultimately, we hope that policy-makers will use this estimate to make more informed and equitable decisions when considering the absolute and relative benefits of these important ecosystems from a climate policy perspective in the same way that has been done in the past by other researchers e.g. Costanza et al., 2014.

2. Materials & Methods

The method for this study consists of three stages. First, we used the spatial data outputs from Ward et al. (2014) as the basis for Geographical Information Systems (GIS) analysis in *Esri ArcGIS*. We overlayed additional datasets and ran a number of calculations to determine a set of spatially-resolved input parameters critical to stage 2 (Supplementary Table 1). Second, using these input parameters, a performance model was developed in *AnyLogic* to estimate the monthly impact of LULUC on Net Primary Productivity (NPP), soil erosion and MGS C stocks and CO_2 exchange dynamics between 1 January 2000 and 31 December 2015. Finally, using *Microsoft Excel*, we undertook an economic assessment by applying a range of SCC values to absolute C stocks for 31 December 2015 and to annual net CO_2 exchanges over the simulation timeframe as per the outputs from our *AnyLogic* model. This assessment takes into account changes in biomass and soil C over 15 years under current land use regimes (*Scenario 1 - Business as usual*) versus a hypothetical scenario where the natural environment experiences minimal anthropogenic disturbance i.e. it is conserved or managed more sustainably *(Scenario 2 – Minimal disturbance)*. Below we detail the GIS procedure. We also describe the model based on Overview-Design-Details (ODD) protocols for Individual Based Models (IBMs) as established by Grimm et al. (2006). Though our model is not exclusively an IBM (there are no direct interactions between individual ecoregions) it does share many of the same characteristics that such IBMs exhibit. For example, the characteristics of each ecoregion are tracked through time (Reynolds, 1997). The model also shares the same purpose of many IBMs which is to provide an insight into how local actions translate into global consequences. Therefore, in the absence of a better framework, the ODD protocols were judged to be fit for this purpose.

2.1. Model Purpose

The purpose of the model is to use the best available input data to gain a global-scale insight into how MGS C stocks might change over time under present day LULUC practices (*Scenario 1 - Business-as-usual*) versus an alternative scenario where natural MGS ecosystems experience minimum disturbance from human activities (*Scenario 2 - Minimal Disturbance*). In other words, we wanted to know how much additional CO_2 intact and pristine MGS ecosystems could potentially uptake if not degraded by anthropogenic influences (as is currently the case). Understanding the difference in absolute C stocks between these two scenarios, at the end of the model run, serves to infer important information about annual CO_2 exchanges in MGS globally. Specifically, where and how much additional CO_2 could theoretically be stored worldwide by MGS if these ecosystems were not degraded by unsustainable land use practices.

The output data is then used to make an economic assessment of the value of this C using a range of SCC scenarios as metric for avoided economic damage to society. Our objectives here were to: understand the economic value of *existing* C stocks; and, the potential *additional* annual economic value that could be realised if MGS were managed more sustainably.

2.2. Input Parameters, Variables and Scales

The model consists of three hierarchical levels: ecoregion (individual), country (group) and global (simulation). Ecoregions are considered individuals and are initially characterised by a number of input parameters, the data of which was derived from the biogeographically-derived outputs of the study by Ward et al. (2014).

Considering the limitations of available computer processing power, MGS surface area was divided into 20,798 land area vectors (of varying area) based primarily on ecoregion boundary. Important input parameters for each of these ecoregions include: proportion of land use for each ecoregion; mean soil bulk density; mean organic content; mean climatic factors important to determining NPP (rainfall, temperature and snow coverage); crop harvest frequency (CHF); and, factors critical to determining soil loss using the *Universal Soil Loss Equation* (USLE) e.g. mean rainfall erosivity, mean soil structure and mean land cover protection factor. The model input parameters are detailed in Supplementary Table 1, and utilise the data outputs from a recently published biogeographically-focused study (Ward et al., 2014) to define the extent of MGS ecosystems and associated carbon stocks (above and below-ground biomass and soil carbon to one metre depth) for the year 2000. The input parameters drive the variables of the model, through a series of monthly time steps as described below. These dynamic variables influence and change each ecoregion's input parameters, incorporating any feed-back that may be present in the system (Supplementary