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Minimizing impacts of land use change on ecosystem services using multi-criteria heuristic analysis

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ABSTRACT

Development of natural landscapes to support human activities impacts the capacity of the landscape to provide ecosystem services. Typically, several ecosystem services are impacted at a single development site and various footprint scenarios are possible, thus a multi-criteria analysis is needed. Restoration potential should also be considered for the area surrounding the permanent impact site. The primary objective of this research was to develop a heuristic approach to analyze multiple criteria (e.g. impacts to various ecosystem services) in a spatial configuration with many potential development sites. The approach was to: (1) quantify the magnitude of terrestrial ecosystem service (biodiversity, carbon sequestration, nutrient and sediment retention, and pollination) impacts associated with a suite of land use change scenarios using the InVEST model; (2) normalize results across categories of ecosystem services to allow cross-service comparison; (3) apply the multi-criteria heuristic algorithm to select sites with the least impact to ecosystem services, including a spatial criterion (separation between sites). As a case study, the multi-criteria impact minimization algorithm was applied to InVEST output to select 25 potential development sites out of 204 possible locations (selected by other criteria) within a 24,000 ha property. This study advanced a generally applicable spatial multi-criteria approach for 1) considering many land use footprint scenarios, 2) balancing impact decisions across a suite of ecosystem services, and 3) determining the restoration potential of ecosystem services after impacts.

1. Introduction

To increase the sustainability of human development around the world, it is important to consider the potential impacts that landscape modifications can have on ecosystem services. One approach is to consider the ecosystem service impacts of different sites, and seek to minimize the aggregate impacts. Ecosystem services can be enhanced by restoring degraded lands and protecting high value areas. Therefore, in planning new development, it is important to determine the baseline services (i.e. pre-project) and the potential changes from various footprint scenarios. Since there are commonly many services impacted simultaneously, it is important to use a multi-criteria analysis. In most cases there is a possibility of considering several development or restoration locations, requiring a spatial optimization algorithm to minimize impact (e.g. Bathrellos et al., 2012; Bathrellos et al. 2011). In some cases, there may be tens or hundreds of possible sites, requiring a robust analysis. Further, development may involve disturbances that are ancillary to the long-term site footprint, where restoration of services is possible; restoration potential should be considered when making land use decisions. The simultaneous consideration of multiple services and the prioritization of those services, multiple site options, and various restoration potentials for ancillary impacts is the complex challenge many land managers face.

One approach for determining the approximate magnitude of ecosystem services is the use of models such as InVEST (Integrated Valuation of Environmental Services and Tradeoffs), developed by the Natural Capital Project (Nelson et al., 2009). The InVEST model uses Geographic Information Systems (GIS) to account for the spatial nature of the underlying datasets, and performs a number of mechanistic calculations to estimate services such as carbon sequestration, biodiversity, nutrient and sediment retention, and pollination (Bagstad et al., 2013). The InVEST model may be useful for informing resource management strategies and quantitative ranking of scenarios that can aid decision making. However, the lack of monitoring data to calibrate the model and reliance on user-

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defined assumptions may limit the application of model outputs (De Groot et al., 2010; Wainger et al., 2010). For example, while model outputs are quantitative, they should be viewed as providing the direction of change (i.e. increasing or decreasing) and an overall sense of the magnitude of the change (De Groot et al., 2010). Further, InVEST does not optimize various land impact scenarios (i.e. tens or hundreds of footprints) to select the one scenario that reduces impacts across all ecosystem services simultaneously, nor does it consider restoration potential of impacts. Thus, there is a need to develop methods to process InVEST outputs for optimizing site management decisions that consider many ecosystem services, tens or hundreds of land use options, and the restoration of short-term impacts.

The general philosophy and conceptual model for InVEST was presented by Daily et al. (2009), providing examples of applications in different regions. Kareiva et al. (2011) discuss the use of InVEST in the context of the broader evaluation of ecosystem services with different approaches. Polasky et al. (2012) used InVEST to consider the value of biodiversity conservation. InVEST has been applied to evaluate different land use scenarios in the Willamete Valley (Oregon), the Amazon basin (Tallis and Polasky, 2009), Minnesota (Polasky et al., 2012), Argentina (Murdoch et al., 2010), China (Jing et al., 2011), and elsewhere. Here we advance methods for optimizing land use decisions when many smaller footprints are possible and across many ecosystem services simultaneously.

The primary objective of this research was to develop a heuristic approach to minimize multiple criteria (e.g. aggregate impacts to ecosystem services) in a spatial configuration with many potential development sites. A case-study useful for the analysis was consideration of the optimal location for shale gas wells, each one with an average 2 ha terrestrial footprint. Note that only the terrestrial footprints were considered; the impacts to ecosystem services associated with shale gas extraction, processing, or use were not considered in this study. An optimization algorithm was developed to process InVEST output.

2. Methods

The approach was to: (1) quantify the magnitude of terrestrial ecosystem services impacts associated with a suite of land use change scenarios using the InVEST model; (2) normalize results to compare across categories of ecosystem services; (3) apply the multi-criteria heuristic algorithm to select sites with the least impact to ecosystem services, including a spatial criterion (separation between sites). For this project, version 2.2.2 of the InVEST model was used, which was the most current version available at the time the project began. The InVEST modules considered were biodiversity, carbon sequestration, nutrient and sediment retention, and pollination, and the dataset used for implementing the model is presented in the Supporting information. To exemplify, a case study of shale gas well selection requiring a spatial multi-criteria optimization was applied. A general description of the site and its current land use are presented in the Supporting information. A total of 204 potential new well pad locations ("sites") were considered, representing 0.04% of the total site. The case study needed to choose approximately 25 well pads from the 204 options. An evaluation of the least impactful sites was conducted using InVEST output, processed using the "Greedy Heuristic" algorithm. For the purposes of this analysis, no impact from water supply lines or other shale gas activities were considered other than the terrestrial disturbance to the sites, its surrounding area and any proposed access roads.

Three alternative land use scenarios were developed for the purpose of investigating a range of plausible impacts associated with the sites considering the ecosystem services previously discussed. These impacts were evaluated relative to the current condition, prior to site impacts. All scenarios assumed that the impact of installing each site extends beyond the boundaries of the permanent site installation to the surrounding area. A 100 m buffer zone surrounding the permanently impacted areas (concrete well pads and new access roads) was assumed. It was also assumed that the area within these buffer zones is degraded during site and access road installation, causing them to negatively impact the capacity of the landscape to provide ecosystem services in a manner commensurate with that of the permanent well pads themselves.

Scenario 1. 100 m highly disturbed buffer zone. The buffer zone is considered to be bare soil, resulting in loss of vegetation and corresponding biodiversity and stored carbon, as well as decreased nutrient and sediment retention. This scenario can be thought of as "worst case" in terms of land use modifications because it effectively expands the proportion of the total study area disturbed from 0.04% to 6.2%. The dark grey areas in Fig. 1 represent all of the proposed sites and new access roads with the 100 m buffer areas surrounding them.

Scenario 2. 100 m early successional buffer zone. Under this scenario, it was assumed that after a few years, the land use within the 100 m buffer zone would convert to a transitional "Early Successional Stage" cover type, which would have an intermediate benefit on the various ecosystem services.

Scenario 3. 100 m restored buffer zone. In the third scenario, it was assumed that after 30–40 years, the vegetation returns to the original conditions in the buffer zones, as a result of active restoration. Hardwood trees have enough time to return to the original levels and rates of carbon sequestration, and biodiversity is mostly restored. This scenario effectively considers only the impact of the concrete well pads and their corresponding access roads.

To interpret the results for sediment and nutrient retention impacts, it is important to understand the process used by the InVEST model. A watershed or a number of subwatersheds need to be identified. Flow paths are calculated for water flowing after a precipitation event, accumulating water from the headwaters towards the outflow. Soil erosion due to rainfall and surface runoff were calculated using (Revised Universal Soil Loss Equation) RUSLE (Tetzlaff et al., 2011), which takes into account soil erodibility, rainfall erosivity, land cover (i.e. type of vegetation) and slope. The underlying soils, slope or rainfall amount do not change among scenarios, leaving only the change in land cover as the key variable. Different land covers can result in higher or lower retention of sediments (or nutrients), but it is important to consider the underlying soils and slope. The calculation was done for the entire subwatershed areas using the National Land Cover Dataset for the regions outside the study site. Since those areas are undisturbed, their effect on the sediment retention is not significant. The impact was determined per subwatershed, but was normalized on a per unit area basis to make a more meaningful comparison possible.

2.1. *"Greedy" site selection heuristic procedure*

The multi-criteria impact minimization algorithm is based on the "Greedy Best-First Search Heuristic" (Pearl, 1984; Ying and Cheng, 2010; Shu, 2010; Slotnick, 2011). First, the impacts to various ecosystems associated with each well site are normalized, allowing each well to be ranked relative to every other on the basis of aggregate impacts. Next, individual well sites are selected in an iterative process in which a distance based constraint is applied to avoid selecting well pads that are too close to one another. The selection process concludes when the desired number of least