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

Arturo A. Keller [a, *], Eric Fournier [a], Jessica Fox [b]

[a] Bren School of Environmental Science and Management, 3420 & 3418 Bren Hall, University of California, Santa Barbara, CA, 93106, USA
[b] Electric Power Research Institute, 3420 Hillview Avenue, Palo Alto, CA, 94304, USA

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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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* Corresponding author.
E-mail address: keller@bren.ucsb.edu (A.A. Keller).

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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

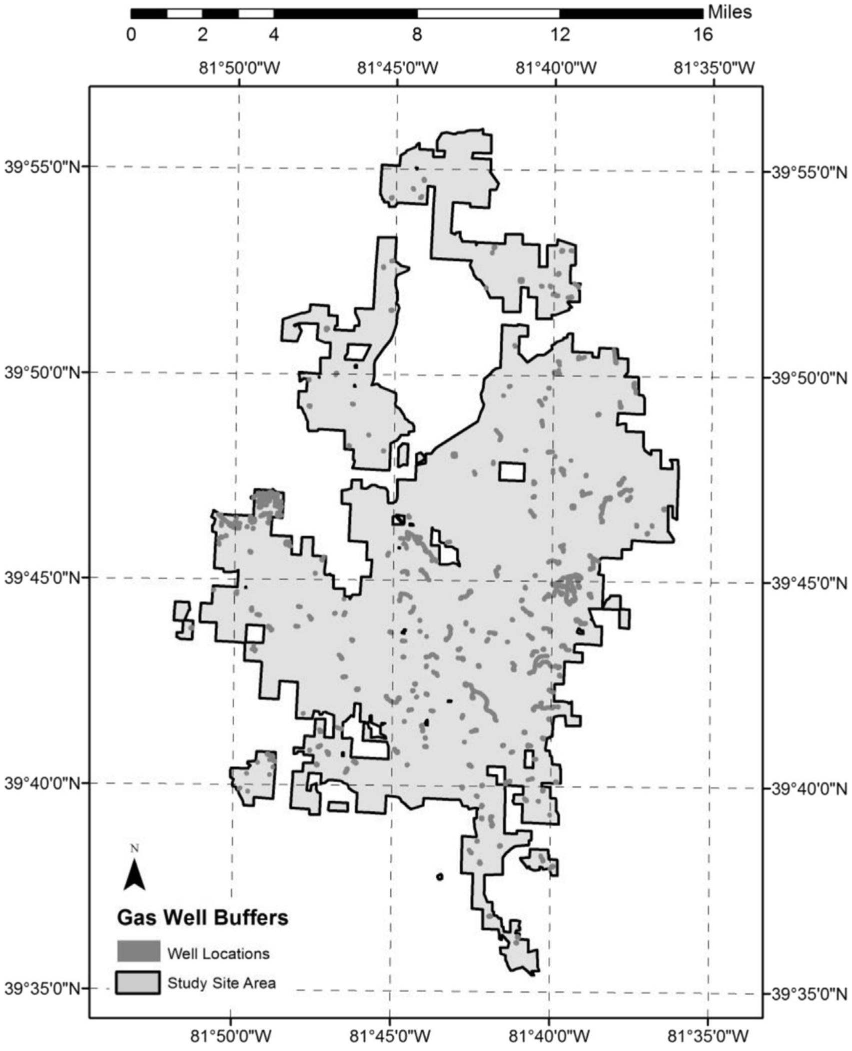

Fig. 1. Proposed well pads and access roads with 100 m buffer zones.

impactful sites has been chosen. The algorithm is presented in Fig. S18 and described below.

2.1.1. *Normalization*

An aggregate metric (Z-score) for the six ecosystem services was constructed by normalizing the scores by the range of scores for a given ecosystem service, adding the scores, and again normalizing by the range of aggregate scores so that the information is presented as a score from 0 to 1. Equal weights were given to the various ecosystem services, although one could incorporate a different weighting scheme.

2.1.2. *Spacing criterion*

To avoid placing two wells too near to each other, each site would need to be spaced at least 1.6 km (1 mile) away from other sites to maximize drilling coverage while at the same time minimizing well-to-well redundancy. Using MATLAB, a neighborhood analysis was performed using the following procedure to address this facility location problem (Church, 2002). To illustrate, in Fig. S19 a single (focal) site (colored in deep red) is surrounded by a uniform band of grid cells (colored in pale red) which are located 1.5–1.7 km apart. The focal well is the site being analyzed at a given time. Sites closer than this distance are excluded from being selected, since they would overlap too much with the focal site. In this way, any other sites (colored in green) which fall into this "Neighborhood Region" can be said to be "Neighbors" of the focal site, which will be evaluated to determine whether the focal site is a better site (lower aggregate Z score) relative to its "Neighbors." A Neighbors Matrix is then computed, which contains the viable neighbors for each site based on the spacing criterion.

2.1.3. *Impact minimization*

The Z-scores for all well pads are computed and ranked. The histogram is then sorted in descending order. Based on the desired number of sites to be developed (e.g. 25 in the case study) out of the total number of potential sites (e.g. 204 in this case), the sites with minimal ecosystem services impacts are then selected and mapped. The histogram in Fig. S20 shows the frequency with which each site appears as the least impactful neighbor in any of the neighborhoods that it is a part of. Sorting these sites with their respective frequency counts and iteratively selecting sites on the basis of a neighborhood exclusion rule approximates the "Best First Greedy Search Heuristic" which attempts to minimize impacts to aggregate ecosystem services while at the same time, ensuring the desired geographic distribution of sites.

Table 1
Estimated ecosystem services for baseline and disturbance scenarios.

	Baseline	Scenario 1	Scenario 2	Scenario 3
Biodiversity Quality Index (unit less)	100% (21,717)	62.1% (13,497)	90.9% (19,739)	95.3% (20,692)
Carbon Storage (metric tons C)	100% (819,339)	91.9% (753,030)	94.5% (774,376)	99.4% (814,440)
Sediment retention (millions of metric tons)	100% (94,722)	99.3% (94,101)	99.6% (94,321)	99.7% (94,452)
Crop pollination index (unit less)	100% (421,047)	85.7% (361,051)	88.1% (371,151)	99.2% (417,704)
Nitrogen retention (metric tons N)	100% (94,095)	90.8% (85,444)	94.7% (89,109)	95.5% (89,934)
Phosphorous retention (metric tons P)	100% (6444)	92.8% (5984)	92.9% (5991)	95.8% (6178)

3. Results

The potential impact of well sites on the different ecosystem services for the various scenarios differed significantly (Table 1). Baseline represents the current condition, in which all ecosystem services are normalized to 100%. The relative decrease in ecosystem service (in percent) as well as the aggregate score or decrease in storage or retention is also presented (Table 1). Biodiversity appears to be the ecosystem service most impacted initially by installing all the sites. However, the Biodiversity Quality Index as calculated by InVEST is rather sensitive to the “half saturation constant”, which influences the calculation based on the spatial extent of impact from a disturbed area. Since there is generally no data to calibrate the parameter value, the resulting Biodiversity Quality Index can be rather subjective. Even when normalized relative to the baseline, the Biodiversity Quality Index can vary substantially. In any case,

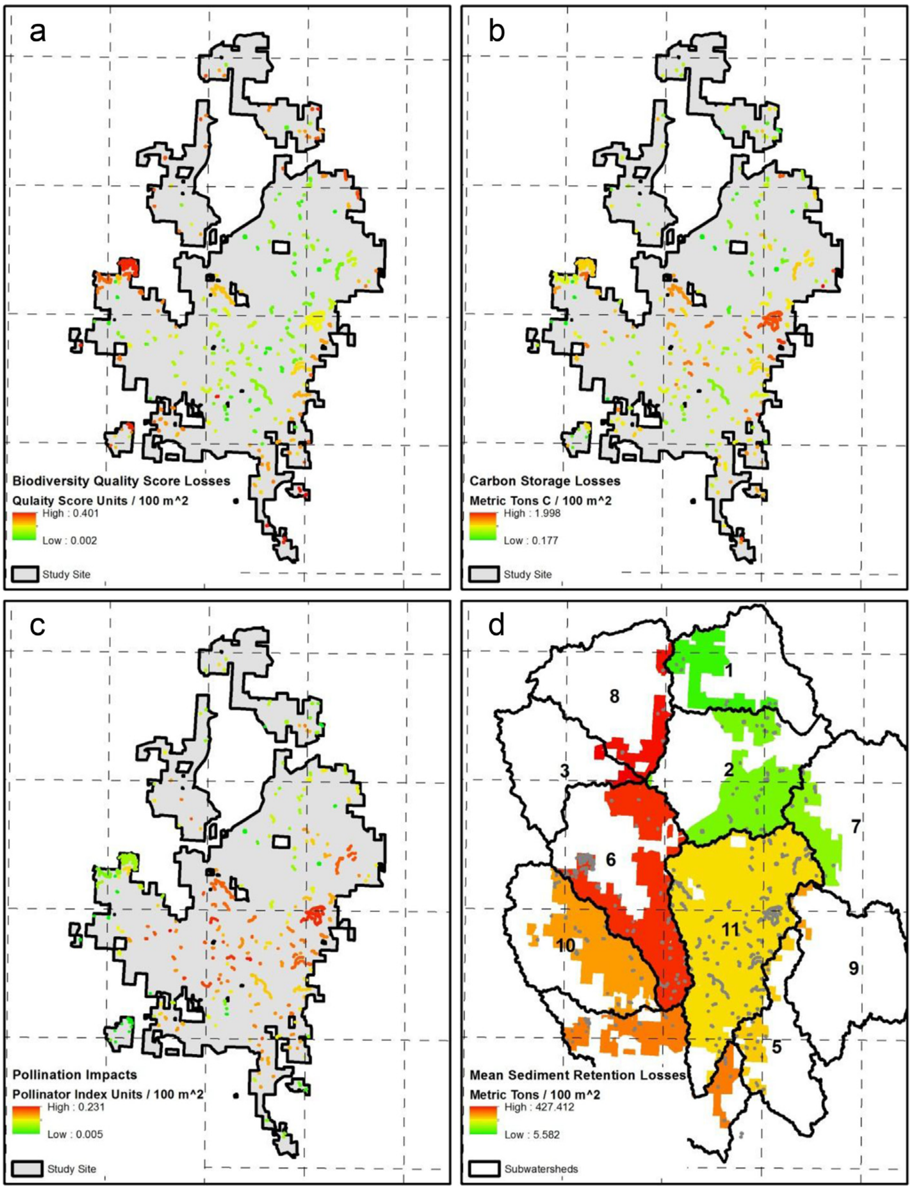

Fig. 2. Spatial distribution of impacts to ecosystem services under Scenario 1: a) biodiversity; b) carbon sequestration; c) pollination; and d) sediment retention.

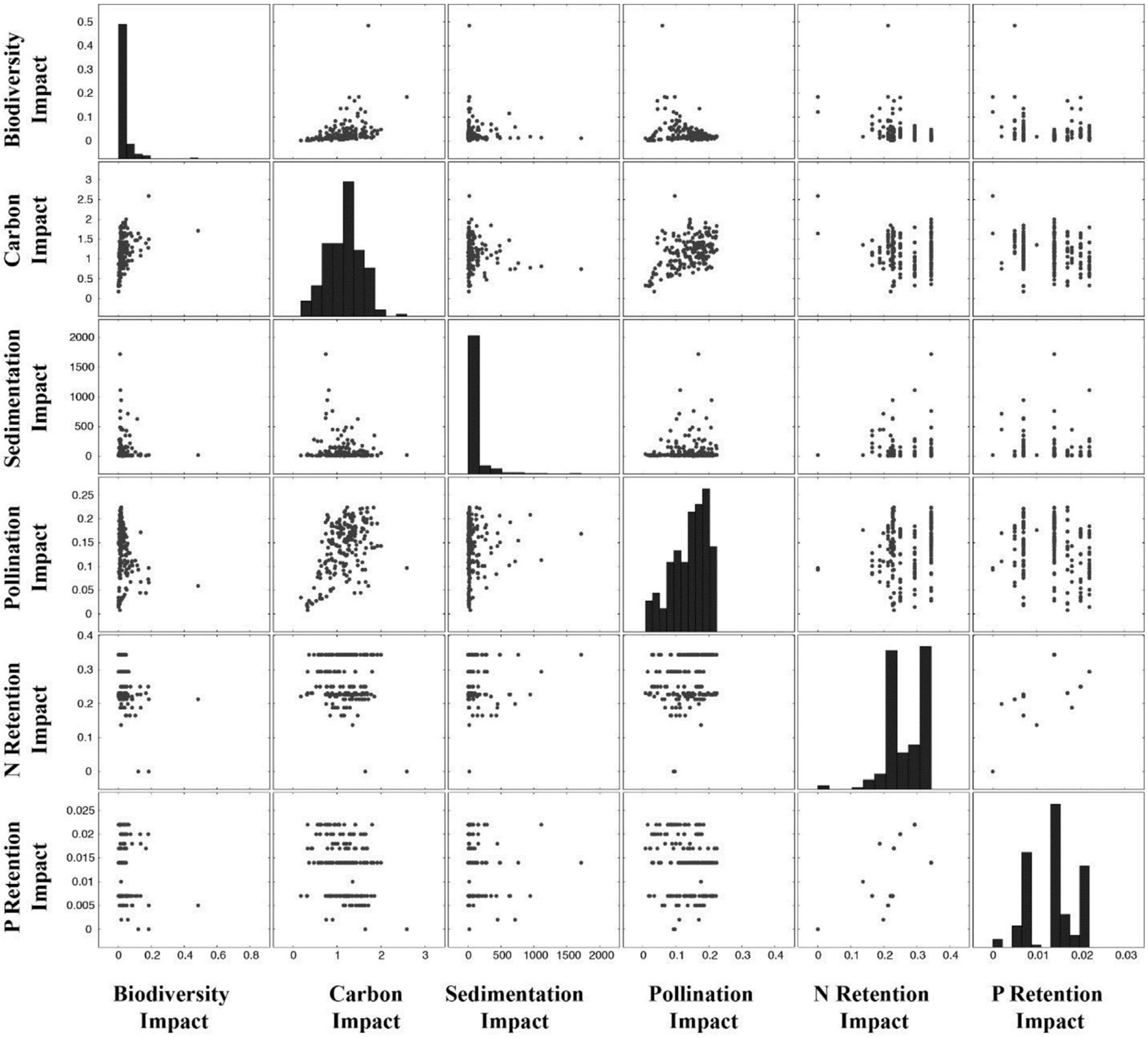

Fig. 3. Histograms and correlations for the ecosystem services studied.

the Biodiversity Quality Index decreases by around 38% immediately after site installation, but recovers to 91% after early successional vegetation, and to 95% after longer term tree growth. The crop pollination index is also significantly affected by initial well emplacement, since there is also a distance effect around the impacted area. It recovers to 99% in the long term. Carbon storage also returns almost to pre-disturbance levels after the trees grow back to maturity. Although there is a decrease in sediment

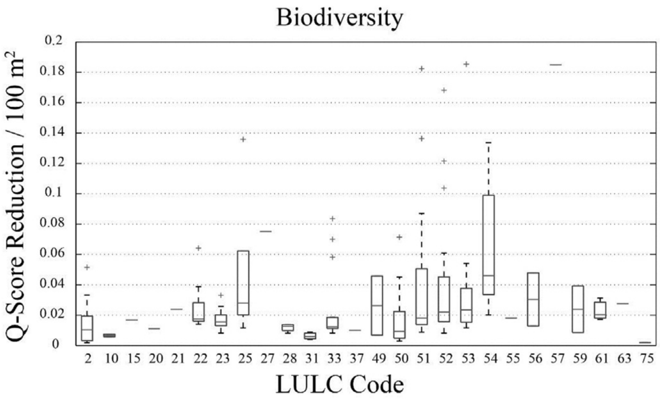

Fig. 4. Relationship between biodiversity quality score reduction and land use/land cover (LULC) codes. Table S1 contains a description of each code.

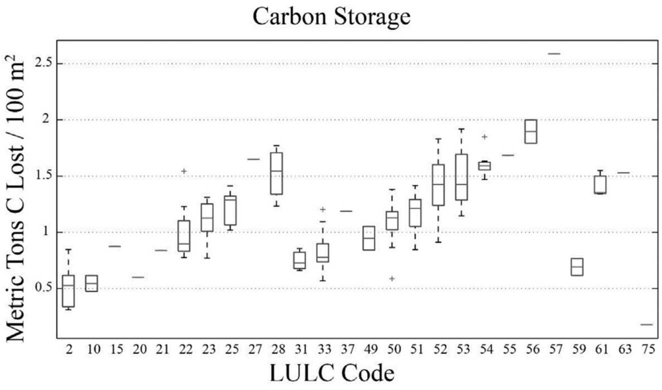

Fig. 5. Relationship between carbon storage loss and LULC codes.

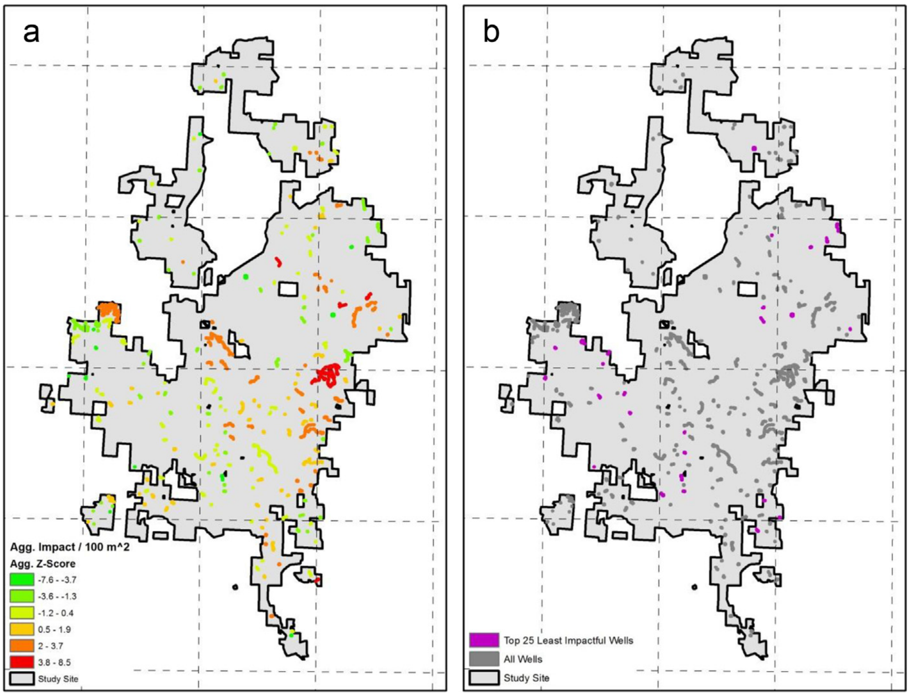

Fig. 6. Aggregate potential impact on ecosystem services for Scenario 1 considering a) all sites; and b) the 25 lowest impact sites (in magenta). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Ecosystem services impacts for 25 lower impact sites.

	Baseline	Scenario 1	Scenario 2	Scenario 3
Biodiversity Quality Index (unit less)	100% (21,717)	89.5% (19,437)	96.7% (20,992)	97.0% (21,049)
Carbon storage (metric tons C)	100% (819,339)	99.5% (815,209)	99.7% (817,120)	99.9% (819,092)
Sediment retention (millions of metric tons)	100% (94,722)	100% (94,781)	100% (94,739)	100% (94,723)
Crop pollination index (unit less)	100% (421,047)	92.9% (391,139)	94.3% (397,239)	99.7% (419,632)
Nitrogen retention (metric tons N)	100% (94,095)	99.4% (93,527)	99.8% (93,916)	99.9% (93,995)
Phosphorous retention (metric tons P)	100% (6444)	99.3% (6397)	99.6% (6416)	99.9% (6438)

retention, it is rather small. The impact is much greater for N and P retention, even after regrowth, since once the nutrients are lost, it will take a longer time to replenish them.

The spatial distribution of the impacts on the various ecosystem services is strongly dependent on the original land use (Fig. 2). For sediment and nutrient retention, the result is first calculated for the subwatersheds (as shown in Fig. 2) and then applied on a per unit area to the sites and their buffers. Additional maps for all ecosystem services are presented in the Supporting information. The particular land uses that are most affected with regards to biodiversity by the installation of the sites are different from those with the highest impact in terms of carbon sequestration, sediment and nutrient retention, and crop pollination.

Correlations were observed between different ecosystem services for the same land use (Fig. 3). Histograms were prepared and correlations for the six ecosystem services modeled. The diagonal presents the histograms for each ecosystem service, i.e. the distribution of the impact scores computed for all sites (Fig. 3). The height of each bar (y-axis) indicates the frequency with which each range of impacts was observed within the sample of proposed well sites (x-axis). While carbon storage impact has a rather broad distribution across the planned sites, biodiversity and sediment retention losses have a rather narrow distribution, indicating that impacts to biodiversity are fairly similar between the site options. Thus, carbon storage impacts are easier to minimize, but well selection to minimize biodiversity is more challenging because of the difficulty in discriminating impacts between sites. The off-diagonal elements of this plot matrix show the pairwise scatterplots for each combination of ecosystem service impact categories, in the corresponding units for each ecosystem service. These scatterplots provide a visual indication of the shape and direction of possible correlations between different combinations of impacts. For example, in column two - row four, the tight clustering of points and their positive right leaning skew suggests a significant positive correlation between pollination and carbon impacts. Significant “banding” in the scatterplots involving sediment and nutrient retention impacts are also indicated (Fig. 3). This banding effect occurs when there are large numbers of well sites sharing the same impact within a given impact category. We believe that one explanation for this result has to do with the relatively coarse granularity in terms of the spatial resolution for some of the key input data variables used to compute sediment and nutrient retention. The net result of this effect is that it can be difficult to establish meaningful correlations between nutrient retention and other impact categories. This type of information can be utilized to inform how to balance impacts to different ecosystem services at the same time.

The sensitivity of the biodiversity quality score to changes in each land use category was estimated (Fig. 4). There are a few land use types that appear to be particularly sensitive to change in terms of biodiversity impacts within the well zones, these include: 20–50 year old stands of red oak and yellow poplar (51–54) as well as mixed pine stands (25). The sensitivity of carbon storage to changes in each land use category was also estimated (Fig. 5). The trends seen in the sequences of land uses from 22 to 28 correspond to increasingly mature stands of mixed hardwoods; for land uses 50–54 they correspond to increasingly mature stands of red oak and yellow poplar (results for other ecosystem services are presented in the Supporting information).

4. Selection of lower impact site locations

The potential normalized impact (Z-score) to all ecosystem services from each of the possible 204 sites varies considerably (Fig. 6a), with some sites potentially having a much higher impact on ecosystem services. For example, there are clusters of wells that have a very high Z-score, relative to other wells. The high Z-score is not due to the clustering of sites, since all ecosystems service scores were normalized by the same area.

Although 204 sites were considered initially, the plan was to select only 25 sites. The question was how to select those locations with the least impact on ecosystem services. In addition, to avoid overlap and have a better geographical distribution, a 1.6 km radius spacing criterion was used to separate adjoining lower impact locations (Fig. 6b). The aggregate impact of these 25 sites was estimated for all ecosystem services evaluated (Table 2). This method can best be categorized as a heuristic, but it will not guarantee an optimal result. Nevertheless, it demonstrates the use of multi-criteria analysis to select the lowest impact sites spaced out as desired.

5. Conclusions

A spatial multi-criteria optimization algorithm was developed to suggest sites with the least impact to ecosystem services, which were estimated using InVEST. This approach can be used to support decision making for more sustainable development around the world. The algorithm can also serve to evaluate the potential recovery of ecosystem services after construction.

As an example, a case study was used to evaluate the impact of 204 possible 2 ha impact sites on the ecosystem services of a 24,000 ha undeveloped site. Three scenarios were considered relative to current conditions, as follows: (1) conditions during and immediately after installation of the sites; (2) conditions after a few years of early successional vegetation growth in the disturbed areas surrounding the sites; and (3) conditions after thirty years of regrowth. Restoration potential from short-term impacts was considered when comparing footprint options. The InVEST model results indicate significantly different responses across the various ecosystem services in the study area due to the installation of the sites. The difference in ecosystem service response is due to the combined effect of land use, topography, soils and other factors which are, for the most part, spatially variable. The analysis served to better understand the correlation between impacts to ecosystem services, as well as their sensitivity. A model that takes into consideration these spatial differences, such as InVEST, is useful for making decisions for selecting lower impact sites. However, InVEST does not provide a multi-criteria selection approach.

A Best First Greedy Search Heuristic algorithm was developed, incorporating a “spacing criterion” to specify site-to-site proximity. The multiple criteria were normalized to compare across ecosystem services, which can use equal weights, as was done for the case study, or assigning differential weights. Then an analysis of the neighbors of each site was done to select the least impacted site from each neighborhood, considering the spacing criterion. Finally, using an iterative ranking process the desired number of least impacted sites is selected from the total number of potential sites, to minimize the aggregate impact.

Consideration of impacts to ecosystem services during land management decisions is becoming increasingly common. Current models that can accommodate complex, real-life land manager considerations and easily optimize decisions are lacking. This study advanced a generally applicable, spatial, multi-criteria approach for 1) considering many land use footprint scenarios, 2) minimizing aggregate impacts across a suite of ecosystem services, and 3) determining the restoration potential of ecosystem services. Future application of this approach could include preferences for particular services, customization of footprints and buffer zones, and changes to the sizes of the neighborhoods.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.03.017.

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