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The effect of spatial interdependencies on prioritization and payments for environmental services

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ABSTRACT

Empirical studies and on-the-ground policies assessing optimal selection of projects in the context of payments for environmental services programs rarely consider spatial proximity of one project to other projects. This occurs despite evidence from theoretical and ecological studies that benefits are often spatially interdependent. This paper develops a flexible construct of "spatial synergy benefits" using the principles of Newtonian gravity similar to efforts in other application areas. This approach is novel to the literature on environmental preservation and, as a systematic method, can account for a wide variety of spatial interdependencies. The empirical setting for the application is farm and forest preservation in Delaware, with a quadratic knapsack algorithm used to select the optimal set of parcels. Application results show that the specific level of the spatial synergy benefit measure does not significantly alter the number of parcels and acreage preserved, but that the composition of the optimal set changes as agglomeration preferences increase. These changes in the optimal targeted set indicate a potential bias in past research on PES selection. Policy makers informed by methods that do not explicitly account for spatial agglomeration preferences often make incorrect investment choices from a cost-effectiveness perspective.

1. Introduction

Public investment in payments for environmental services (PES), such as those provided by land preservation, increasingly draws public funds from across the globe. Valuable amenity streams are often external to markets and are hence typically undersupplied by profit-maximizing management decisions (Gardner, 1977). Because of the difficulty of quantifying and valuing site-specific environmental service provision, PES programs often target observable activities associated with service provision rather than the services themselves (Kroeger and Casey, 2007). Examples include payments for conservation easements (PACE) on agricultural or undeveloped land, agricultural best management practices, and other land conservation activities. A large literature has developed to improve PES selection (i.e., how to optimally target or select environmental service investments). Among the central aspects of these decisions is spatial targeting, and a growing literature investigates these aspects of PES decisions. As noted by Bergstrom and Ready (2009), Bateman (2009), and Duke et al. (2014), incorporating spatial complexities into PES selection is an area in need of continuing research and innovation. Observations from this literature often parallel those in work devoted to the targeting of conservation activity, with both the PES and conservation targeting literature emphasizing the relevance of spatial considerations for optimal decisions (e.g., Ando et al., 1998; Knight et al., 2009; Pfaff and Sanchez-Azofeifa, 2004; Polasky et al., 2008). The specific focus of this paper is to evaluate a new spatial targeting approach for PES that optimizes over benefits subject to agglomeration effects. The application area involves land preservation, a longstanding and common example of PES.

Optimal targeting requires benefit and cost measures. Revealed and stated preference valuation are common tools used in PES selection studies because nonmarket valuation is required to estimate many of the benefits and some of the costs associated with individual PES projects. Stated preference techniques (or survey-based valuation techniques) are used when amenities have significant nonuse components and policies to enhance amenity provision trigger marginal changes in amenity supply. Studies of marginal and nonmarginal changes in environmental

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quality and ecosystem service supply show that spatial considerations frequently affect willingness to pay (WTP) (Bateman et al., 2006; Campbell et al., 2009; Hanley et al., 2003; Johnston and Ramachandran, 2014; Jørgensen et al., 2013; Johnston et al., 2002a; Schaafsma et al., 2012).[1] For example, in the marginal case, a substantial literature has emerged to evaluate continuous and noncontinuous spatial patterns in nonmarket WTP for numerous types of environmental commodities and services. This literature frequently shows statistically significant and policy-relevant impacts of spatial factors. In the nonmarginal case, the sorting literature has shown that consumers adjust their locational preferences and willingness to pay in response to large changes in environmental amenities (Sieg et al., 2004) and that different welfare estimates can result from spending a budget for procuring a public good in different locations (Walsh, 2007).

The present model and application assess spatial synergies using data from an application of marginal land preservation decisions, with benefit and cost data derived from stated and revealed preference studies. In agricultural land preservation programs, parcel prioritization necessitates locating specific parcels in space and determining that parcel *i* is more valuable preserved in its current state than parcel *j*. Studies that value average parcels at an average spatial location are likely inadequate, because parcel *i* and parcel *j* have parcel-specific spatial attributes that influence their benefit to society in often predictable ways. For example, as soon as any one specific parcel of land *i* is targeted for potential preservation, the fact that targeted parcel *i* has a distance to another parcel *j* creates a potential interaction that can influence the benefits of preserving both parcels. This interaction can be positive or negative, and implies that the benefits of jointly preserving *i* and *j* may exceed (benefit synergy) or be exceeded by (cost synergy) the summation of the independent benefits of preserving *i* and *j*. Furthermore, the interaction raises the possibility that the joint benefits of preserving *i* and *j* are less than the joint benefits of preserving *i* and *k*. Spatial synergies introduce considerable complications to optimal selection. If the synergies exist but are ignored, then project selection will suffer from a systematic bias. This bias occurs because spatial independence is (incorrectly) assumed, when a spatially interdependent process determines benefits or costs. This bias will reduce the net benefits and/or cost-effectiveness of independent optimal selection strategies (excepting the remote possibility that the interdependent and independent optimal selection sets overlap by chance because of a fortuitous benefit and cost ordering that matched distance synergies).

Numerous approaches have been used to investigate spatial aspects of PES and other environmental programs. The spatial nature of benefits[2] and the implications for cost-effective parcel selection has been assessed using stated preference data in the context of targeting location-specific single parcels (Breffle et al., 1998; Duke et al., 2012), benefit aggregation and transfer (Campbell et al., 2009 Hynes et al., 2010), distance decay of benefits (Hanley et al., 2003; Bateman et al., 2006), spatial availability of substitutes (Jørgensen et al., 2013), heterogeneity of pre-intervention environmental quality (Tait et al., 2012), and the potential for part-whole bias (Hanley et al., 2003; Brouwer et al., 2010). There also are studies examining optimal targeting in spatially explicit contexts, focusing on the probability of conversion and correlated land costs (Newburn et al., 2006, 2005; Stoms et al., 2011) and econometric simulations (Lewis et al., 2009). An examination of spatial land preservation in practice found little contiguous-block formation and that an optimization method would protect different lands (Stoms et al., 2009). Davis et al. (2006) examined prioritization and clustering in a spatially explicit biodiversity conservation study in California. There are also many studies that use revealed preference data to estimate the capitalized effect of quasi-use values for locational-specific amenity provision from land uses and preservation (Bolitzer and Netusil, 2000; Geoghegan, 2002; Geoghegan et al., 2003; Neumann et al., 2009; Borchers and Duke, 2012).

The most relevant works in this literature for the present analysis are those that employ spatial stated preference benefit estimates. Campbell et al. (2009), for example, highlight a potential improvement for benefit transfer by accounting for spatial autocorrelation of WTP estimates of households for rural landscape improvements. Similarly, Hynes et al. (2010) use synthetic estimates of WTP for small-area populations from a combination of survey and demographic data to improve benefit aggregation across space. The Hanley et al. (2003) examination of distance decay functions demonstrates the spatial extent for use and nonuse values in water quality improvements. This result implies that defining the extent of the geographic area where benefits accrue is an important consideration for optimal PES selection. Both Hanley et al. (2003) and Brouwer et al. (2010) find WTP for water quality improvements differ across the same river basins, with households willing to pay more for improvements in their own sub-basin than the river basin as a whole (i.e., part-whole bias). Taken together, the literature suggests that a household's utility for preservation or environmental improvement often depends on the household's relative proximity to the PES intervention.[3] Although these results are not universal (cf. Rolfe and Windle, 2012) and the specific influence of spatial relationships on economic value varies across different types of resources (Bateman et al., 2006; Hanley et al., 2003), the literature finds broad similarities in the types of spatial patterns found across different types of environmental service values (Schaafsma et al., 2012).

While demonstrating the important role of spatial factors for preservation value, the vast majority of this literature emphasizes the effect of distance between a potential beneficiary and an environmental improvement, the variable provision of environmental services that may occur over geographical areas,[4] or potential differences in preferences over these areas. Less attention is given to agglomeration effects or to the fact that the spatial proximity of multiple environmental improvements (e.g., parcels chosen for preservation) may influence the benefit of each individual improvement. For example, the combined net benefit of two parcels preserved in close proximity may be greater (or perhaps smaller) than otherwise identical parcels preserved at a greater distance, simply due to the proximity effect.

[1] Willingness to pay, or WTP, is a commonly used measure of economic value in benefit-cost analysis. It is defined conceptually as the maximum amount of money (or another good) that a person or group would voluntarily sacrifice in exchange for a specified quantity of a good or service. Marginal changes refer to incremental or very small changes in a variable from a baseline, for which effects on broader markets or conditions (e.g., prices for other goods and services) are generally assumed to be trivial. Nonmarginal changes refer to larger changes in a variable, which may lead to non-trivial effects on broader markets or conditions.

[2] This paper abstracts from spatial cost dynamics, where coordination strategies and incentives to induce agglomeration have received the bulk to the research attention. Experimental (Parkhurst et al., 2002; Parkhurst and Shogren, 2007; Banerjee et al., 2012, 2013; Fooks et al., forthcoming), and empirical (Drechsler et al., 2010) research has focused on the development of payment schemes (i.e., agglomeration bonuses) to incentivize landowners to overcome cooperation difficulties and spatially coordinate preservation decisions.

[3] This is a common but not universal finding. Other evaluations fail to find statistically significant distance decay in values, particularly for cases involving WTP motivated largely by nonuse values (e.g., Johnston and Ramachandran, 2014; Rolfe and Windle, 2012).

[4] For example, flood attenuation benefits of a riparian buffer are often greater for buffers located upstream, compared to similar buffers located downstream. This is because larger areas are affected by the upstream services compared to downstream ones, ceteris paribus.

This paper complements existing spatially explicit PES research by examining a project's proximity to other projects, specifically evaluating potential agglomeration effects. That is, the model isolates the potential biases if an otherwise optimal PES project selection study overlooks preferences for spatial agglomeration. Spatial agglomeration, or the joint preservation of contiguous and proximate projects or parcels, is an interaction concept recognized across disciplines[5] as a mechanism to achieve higher social benefits than preservation in isolation. When agglomeration effects are present, relaxing the implicit assumption of spatial independence may enable project managers to increase net benefits that are achievable (e.g., with a fixed program budget). Indeed, many theoretical and experimental economic studies analyze the agglomeration phenomenon and policy solutions (see for instance Parkhurst and Shogren, 2007; Parkhurst et al., 2002; Fooks et al., forthcoming).

Despite the demonstrated importance of this type of spatial interdependence, it is often overlooked in applied PES research, likely because little evidence exists on how to measure it. Welfare analysis based on economic valuation studies that overlook such interdependencies might, in fact, produce the wrong answer—not because of a lack of information, but due to the fact that the information used might lead to misguided policy when applied in a spatial context unrecognized by the original valuation analysis. The problem is difficult to overcome. For example, most valuation studies addressing WTP for land conservation evaluate values for individual, independent, and marginal changes in conservation. This follows common approaches in benefit-cost analysis (BCA), in which each evaluation focuses on a particular proposal in isolation, without consideration of other proposals that might be enacted. This well-known "independent valuation" problem leads to biased estimates of value when multiple proposals are enacted (Hoehn and Randall, 1989). Although each study correctly evaluates the marginal value of each program *in isolation*, it incorrectly evaluates the marginal value of each program *when combined with other programs*.

The solution to this problem, as discussed by Hoehn and Randall (1989) and illustrated by Johnston et al. (2002b), is to evaluate combinations of programs simultaneously rather than each program in isolation. However, this solution may be impractical as a means to account for many types of spatial interdependencies, because it requires accurate estimates of the ways that WTP for one program varies with spatial relationships (e.g., proximity) to other programs. These relationships can be difficult to estimate. For example, recent evidence suggests that respondents may misunderstand even simple spatial relationships communicated in stated preference surveys used to estimate values for land conservation, and that this misunderstanding can lead to biased WTP estimates (Holland and Johnston, 2014). Other evaluations of spatial patterns in WTP have revealed anomalies and complexities that confound simple explanations (e.g., Rolfe and Windle, 2012). Due to challenges such as these, dependable empirical estimates of spatial interdependencies in values are often unavailable from primary studies, suggesting the need for frameworks that can accommodate these relationships ex post. Viewed from this perspective, the results of the present analysis demonstrate the benefits of incorporating spatial preferences into PES targeting and the costs of ignoring them. We also demonstrate a means to evaluate the potential impact of spatial synergies on optimal PES targeting, using information from primary studies that did not estimate these synergies as part of the original study design.

Information such as this is directly relevant to program design. Programs seeking to conserve and enhance terrestrial and aquatic ecosystem services through PES or other approaches increasingly consider spatial synergies and conflicts. For example, marine spatial planning is increasingly used to account for spatial synergies and conflicts between multiple uses of coastal and marine resources, such as recreational and commercial fishing, production of wind energy, aquaculture operations, sand mining and other activities (Holland et al., 2010). There are few examples in the context of land conservation; however, Bucholtz et al. (2010) studied Oregon's contiguity-promoting bonus scheme in the Conservation Reserve Enhancement Program, finding it had not provided additional contiguity when compared to a control. Programs such as these increasingly require some way to account for spatial interdependencies in value, although (as noted above) the empirical information required to evaluate these interdependencies is typically unavailable.

The paper overcomes the lack of measures of interdependence by developing a flexible construct of "spatial synergy benefits" or SS benefits, using the principles of Newtonian gravity. This construct is used in other applications (such as international trade) but is novel to the literature on environmental preservation and provides a systematic method to account for a wide variety of possible spatial interdependencies. The empirical setting for the application of this approach is farm and forest preservation in Sussex County, Delaware. Preferences for spatial agglomeration in this setting arise from concept of critical mass for agriculture (Lynch, 2006), as a means to use easements to achieve growth management objectives (Stoms et al., 2009), or from large open spaces contributing to scenic views. One anticipates nonnegative SS benefits because preserving clustered farms: (1) reduces the negative land-use externalities arising from adjacent agriculture and residents, such as odors; (2) enhances positive pecuniary externalities when agricultural land use has a large enough scale to support viable input and output markets; (3) preserves larger open space for scenic views; and (4) provides growth-management protection, preventing patchwork land uses and, if large enough, leapfrog sprawl. Rural areas of Sussex County have been under intense development pressure from suburban sprawl in recent decades and preferences for agglomeration are likely in order to maintain the rural character and economic viability of the agricultural communities. Welfare-theoretic benefits and costs are estimated from a choice experiment and hedonic model, respectively, following the methodology outlined in Duke et al. (2014). A quadratic knapsack algorithm (Gallo et al., 1980; Pisinger, 2007) is used to select the optimal set of parcels given a budget constraint.

The application results show that parcel numbers and acreage preserved are not significantly altered by the specific level of the SS benefit measure, but the composition of the optimal set changes considerably as agglomeration preferences increase. The significant changes indicate the possibility of systematic bias in research on optimal PES project selection. Hence, policy makers informed by methods that do not explicitly account for spatial agglomeration preferences might make cost-ineffective investment choices. For example, the results show that, when spatial proximity benefits are high, otherwise low-quality projects should be selected simply due to their proximity.

2. Methods and data

This section develops an analytic approach for incorporating spatial synergies into optimal PES policy with a generalized, synergy parameter that allows spatial preferences to vary substantively. This flexibility allows for a set of hypotheses that assess both the impact on optimal selection of different spatial preferences and

[5] Examples include conservation of biodiversity (Margules and Pressey, 2000), production of landscape amenities (Ahern, 1991), and forestry management (Swallow and Wear, 1993; Albers, 1996).

measure the systematic bias of ignoring real-world spatial synergies. Among the advantages of this approach is that it is not tied to a single, quantitative measure of agglomeration benefit, but analyzes the effect of a wide range of agglomeration effects within a single framework.

Let there exist a SS benefit construct, which assumes economies of agglomeration in PES project selection produce a measurable benefit—even if it is nil. Specifically, SS benefits measure the joint value of (or enhancement to) environmental service flows from two or more project investments solely arising from the fact that the projects are spatially proximate. In other words, SS benefits are those in excess of the public good benefit of the independent investments, a value termed "project WTP" and abbreviated PWTP. If the projects are independent of space, then SS benefits are 0 and the parameter used to measure synergy in this paper is nil (i.e., $\alpha = 0$). In some settings, SS benefits might be negative, but this paper focuses on nonnegative synergies because the application setting involves public goods that are enhanced when proximately located. Although many studies suggest that synergies in agri-environmental policy, land conservation, and ecology are likely positive, no research was found about their magnitude in the setting of land preservation. Thus, for purposes of this paper, the analysis proceeds with SS benefits varying over the broadest possible range: from independent to highly dependent project selection.

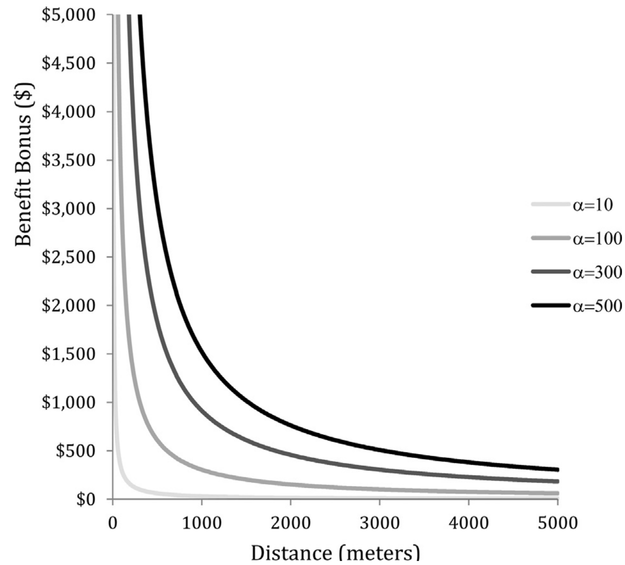

Fig. 1. Benefit bonus vs. distance with varying α for two average parcels.

2.1. A Gravity model of spatial synergy

SS benefits are quantified, following efforts in other fields, using principles of Newtonian gravity and spatial interaction. The gravity equation assumes the relationship between two objects is proportional to their size (mass) and inversely proportional to distance between the objects (Rodrigue et al., 2009). Gravity models have explained diverse phenomena, such as the flow of goods across regional and national borders (Anderson, 1979; Anderson and van Wincoop, 2003) and interurban transportation (Quandt, 1965).

The land parcels used in this PES application are preserved with a conservation easement. The size of parcels (acres) and the distance (meters) between their respective parcel edges are used to estimate the spatial interactions. The gravity equation specifies the interaction between parcels i and j as:

$$G_{ij} = \frac{[1\,(\text{Preserve}_i) A_i] \times \left[1\,\left(\text{Preserve}_j\right) A_j\right]}{D_{ij}^{\beta}} \qquad (1)$$

where G_{ij} is the gravity of parcels i and j, 1(Preserve) is a binary indicator denoting whether the parcel is selected for preservation, A is acreage, D_{ij} is the distance between parcels i and j, and β is a parameter representing the gravitational friction caused by distance. Intuitively, this *parcel-specific gravity* measures the degree to which the social benefits of these two parcels are related as determined by their size and distance.[6]

A frictionless gravity model (i.e., $\beta = 1$) simplifies the analysis by focusing on spatial preferences. This assumption is common in the international trade literature (i.e., Anderson and van Wincoop, 2003), and it also is intuitively appealing for this empirical setting because it allows for parcels to be nearby but not necessarily contiguous to receive benefit synergies. However, the value of the bonus drops dramatically as distance between parcels increases. For a larger β, the friction of distance would quickly minimize the potential for spatial benefit bonuses and a smaller β could allow bonuses to accumulate for simultaneous preservation of parcels not considered spatially relevant.

This parcel-specific gravity is then scaled by α, the agglomeration preference parameter, to calculate joint preservation benefit: $SS_{ij} = \alpha G_{ij}$, where SS_{ij} is the spatial synergy benefit if parcels i and j are jointly preserved. The preference parameter allows for the possibility that there may be different agglomeration preferences in different settings and locations. The gravity-augmented total benefit for parcel i thus is PWTP plus the increment to SS benefit from being included in the selected set. For the two-parcel case, adding parcel i increases total preservation benefit by: $TB_{ij} = NB_{i;\alpha=0} + NB_{j;\alpha=0} + SS_{ij}$, where TB_{ij} is the total benefit of preserving parcel i and j and $NB_{i;\alpha=0}$ is the net independent benefit (i.e., PWTP minus its predicted easement cost) of preserving parcel i or j. In the optimization program, each SS_{ij} is not double-counted, meaning it reflects the addition to total benefits of adding parcel j given that parcel i was already selected.

An advantage of this approach is that it allows analysis of a wide array of spatial influences and preferences on optimal selection. For example, varying α changes the bonus structure, implicitly changes the spatial preference, and potentially induces changes in the optimal selected set. Fig. 1 demonstrates how SS benefits change with distance for two parcels of equal size (55 acres, from the data described below) where agglomeration preferences are represented by the set $\alpha \in \{0, 10, 100, 300, 500\}$.

2.2. Application data

To assess the potential impact of SS benefits in an actual policy setting, the paper applies the gravity model to an existing application of parcel prioritization. Data reported in Duke et al. (2014) show welfare-theoretic, empirical estimates of parcel preservation benefits and costs in Sussex County, Delaware, USA. These measures reflect the external benefits (measuring the PWTP) from a

[6] Parcel size is likely to measure accurately the synergy benefits among preserved large-acre crop and animal agricultural parcels because the synergy benefits (associated with, for instance, critical mass, scenic vistas, and growth management) probably highly correlate to acreage. In other words, it is the precisely the quantity of acreage in the specified land use that delivers the extra protection or benefit. Furthermore, the area in the application reported in this paper is under significant and widespread development threat, so a marginal preservation intervention is unlikely to reach diminishing marginal returns. In some other settings, this simple gravity approach may need modification. For instance, even a marginal intervention to preserve habitat may have significant thresholds or nonlinearities, which will make a simple acreage-based synergy not as helpful.

Table 1
Summary of hypotheses and results.

Hypothesis and number	Description	Application outcome
1: Clustering	As α and SS benefits increase, the optimal set of parcels under a limited budget will form clusters	Support
2: Linear responsiveness	The average cluster acreage changes directly and linearly with changes in α	Mixed support (linear or increasing at a decreasing rate above $\alpha = 300$)
3: Declining aggregate WTP	The total aggregate PWTP varies inversely to α	Support
4: Relative rate of decline in aggregate WTP	The total aggregate PWTP will decrease in α at a lower rate than the Total SS benefits	Support
5: Negative net benefit parcels	As α increases, some parcels will be selected where the PWTP is less than preservation cost	Support
6: Negative WTP parcels	As α increases, some parcels will be selected where the individual PWTP is less than 0	Support

stated preference choice experiment[7] and hedonic easement costs[8] applied to 5315 parcels that are highly eligible for preservation in the County.[9] Results from Duke et al. (2014) show optimal selection without spatial preference; that is, $\alpha = 0$. This study reexamines the prioritization results with the gravity model and various levels α to estimate how SS benefits affect optimal selection.

2.3. Optimization method with spatial synergies

Spatial interaction effects increase the complexity of the optimization problem. The solution uses a branch and bound algorithm, which solves an optimization problem similar to the quadratic knapsack problem (Pisinger 2007), evaluating all possible combination of parcel bundles with added SS benefits. The method identifies the parcel set that maximizes net benefits subject to a budget constraint as follows:

$$\text{Max}_{\sigma}\text{TB} = \sigma'\Psi_{\alpha}\sigma \;\; s.t. \;\; \sigma'C \le b\sigma \in \left\{0, 1\right\} \quad (2)$$

where TB is total benefits, σ is a vector of binary decision variables indicating selection, Ψ_{α} is a spatial benefit matrix with capitalized aggregate WTP for each parcel on the diagonal. Spatial synergy benefits from joint preservation populate the lower triangle of the matrix, with zeros on the upper triangle to avoid double counting. C is the vector of easement costs for all parcels, and b is the budget constraint. Parcel costs are assumed to be independent of each other and of benefits so that the analysis can focus on synergies on the benefit side.[10]

The optimization algorithm was applied to 5315 parcels with a $30 million conservation budget. This budget approximates average spending on land preservation in Sussex County over a five year time period (Messer and Allen, 2010). The budget is small enough that the policy constitutes a marginal land market intervention. Specifically, this budget level leads to only 111–123 of the eligible set of 5315 parcels being selected.

The algorithm was executed in Python programming language and supported with Gurobi Optimizer 4.0. Each model required approximately 24 h to load the elements of the optimization (i.e., spatial benefit matrix, cost vector). After the set-up time, the algorithm produced a solution in less than 1 s for α, s for $\alpha = 10$, in 70 h for $\alpha = 100$, and approximately 94 h for both $\alpha = 300$ and $\alpha = 500$.

2.4. Hypotheses

Duke et al. (2014) offers a comparison of optimal section, comparing this to the results of suboptimal selection techniques, such as benefit and cost targeting. This paper shows that – in the same setting and data as described here – optimization can generate hundreds of millions of dollars in additional net benefits: Benefit targeting is 46% cost effective, while cost targeting is 71%. However, the results in Duke et al. (2014) are only valid when spatial synergies do not exist ($\alpha = 0$). This paper extends the Duke et al. (2014) analysis by exploring how selection changes when synergies are positive.

With true α unknown, the spectrum of preferences includes: no preference ($\alpha = 0$), very weak ($\alpha = 10$), weak ($\alpha = 100$), strong ($\alpha = 300$), and very strong ($\alpha = 500$). Although α is a continuous variable, this paper cannot test every value because of the time-consuming, iterative optimization process. Six hypotheses – all posed only in relation to the application data – are collected in Table 1. An initial hypothesis is: As α and SS benefits increase, the optimal set of parcels under a limited budget will form clusters. A cluster is a group of contiguous parcels. A single parcel preserved in isolation is considered its own cluster. Therefore, hypothesis 1 suggests that accounting for SS benefits significantly impacts the preservation landscape by altering the optimal selected-parcel set, and the selected set will tend to form clusters as agglomeration benefits increase. The first hypothesis will not be supported if the spatial preference (represented by α) is small relative to the PWTP. Thus, actual parcel data produces a measure of how responsive the optimal parcel set is to changes in α.

A corollary to this hypothesis is that increasing agglomeration preferences leads to the optimal selection of an increasing number of parcels that would *not* be selected if spatial preferences were

[7] Parcel benefits are the WTP of Delaware residents for amenities generated when a given parcel changes from unpreserved to preserved. This WTP is derived from state and community level choice experiments conducted in 2005 and 2006 in Delaware and Connecticut (Johnston and Duke, 2007, 2008, 2009a,b, 2010; Duke and Johnston, 2010), with specific coefficient estimates directly from Duke and Johnston (2010) utilized to calculate per-acre WTP. This valuation research is ideally suited for this application as it represents the most comprehensive data on WTP for farmland preservation in Delaware. The reader is referred to Duke and Johnston (2010) and Johnston and Duke (2007) for the specific details of the choice experiment survey, model specifications, and WTP estimation. The benefits of each parcel in the application are calculated using the same approach and data as in Duke et al. (2014).

[8] Easement costs are predicted using a hedonic pricing model (HPM). The data set contains data for parcels in Sussex County applying to the Delaware Agricultural Lands Preservation Foundation program from 1995 to 2003. The HPM specification that minimized average prediction error via k-fold cross validation was selected as the final model. The coefficient estimates are the same as in Duke et al. (2014). These coefficients are matched with parcel characteristics of the 5315 parcels to measure preservation cost. Further model specifications and potential limitations are described in Duke et al. (2014).

[9] For further details on the study area and the GIS data and processes used to determine the eligible set, the reader is referred to Duke et al. (2014).

[10] In reality, parcel costs may be correlated with proximity, though the sign of the correlation is unknown. For instance, an easement on one parcel may raise the value of a neighboring property in a residential use because the undeveloped views will be protected. But easements could also raise the agricultural value of the property (and decrease the easement cost) by increasing the likelihood that farming persists in the region and that agricultural nuisance actions will not be brought against the owner. Babcock et al. (1997) examine the mathematics of project selection with correlated benefits and costs.

Table 2
Comparison of selection with spatial interdependence bonuses at varying levels of a spatial synergy (α) given a budget of $30 million.

	α = 0	α = 10	α = 100	α = 300	α = 500
Parcels preserved	118	116	111	115	123
Acres preserved	16,710	16,685	16,165	16,204	16,630
Total aggregate PWTP	$842,215,415	$841,891,625	$782,432,221	$505,144,291	$362,465,098
Number of parcel clusters[a]	82	76	45	25	22
Average cluster acreage	204	220	359	648	756
Number of negative PWTP parcels selected	0	0	2	24	43
Total spatial synergy (SS) benefits	$0	$7,139,380	$180,685,000	$987,957,904	$1,827,015,502
Total benefits[b]	$842,215,415	$849,030,905	$963,117,221	$1,493,102,195	$2,189,480,600
Total cost	$29,999,682	$29,999,240	$29,999,149	$29,999,280	$29,986,987
Total net benefits (NB)[c]	$812,216,051	$819,032,425	$933,118,923	$1,463,103,635	$2,159,506,626
% Increase in potential NB	0%	0.008%	14.886%	83.831%	165.878%

[a] A cluster is defined as group of contiguous parcels. A single parcel preserved in isolation is considered its own cluster.
[b] Total benefits = Total aggregate WTP + Total SS benefits, where total SS benefits ($SS_{ij} = \alpha G_{ij}$) and G_{ij} is determined by Eq. (1).
[c] Total net benefits = (total benefits – total cost) + budget remainder.

ignored. Hence, observing these selection patterns can provide insight into the extent to which nonspatial targeting leads to suboptimal selection. This also highlights the importance of considering combined "packages" of PES investments, rather than individual investments in isolation; this extends prior evaluations of non-spatial policy package effects by (Cummings et al., 1994; Hoehn, 1991; Hoehn and Randall, 1989; Hoehn and Loomis, 1993; Johnston et al., 2002b). Additional aspects of this problem are explored formally in hypotheses 3–6 below.

A second, more speculative but related, hypothesis is: The average cluster acreage changes directly and linearly with changes in α. There are various clustering measures, but the metric chosen here is average contiguous or "cluster" acreage. The mathematics of optimization, α, and the application data do not suggest that the relationship between cluster size and α is direct and linear; however, linearity provides a benchmark measure of the rate of responsiveness of clusters to α. In this exploratory work, it will be useful to know, if the relationship is nonlinear, whether cluster size declines or accelerates in α.

The solution algorithm (specified below) motivates questions about (A) whether some parcels are valued more for their spatial proximity than for their PWTP and (B) the resulting magnitude of the trade-offs between SS benefits and PWTP. Hypotheses 3–6 explore these questions. The third hypothesis is that the total aggregate PWTP varies inversely to α. One expects an inverse relationship because the algorithm gives weight to α, which is independent of total aggregate PWTP. Although unsurprising, the application also tests how fast this rate changes with α; the fourth hypothesis it that the aggregate PWTP will decrease in α at a lower rate than the Total SS benefits. In effect, this tests the tradeoff between benefits foregone and benefits gained in selecting with spatial synergies.

The analysis also examines two hypotheses about the relative value of selected parcels. The fifth hypothesis is that as α increases, some parcels will be selected where the PWTP is less than preservation cost. The related, sixth hypothesis is that as α increases, some parcels will be selected where the individual PWTP is less than 0.[11] The sixth hypothesis assumes the fifth. These test whether parcels that would otherwise be ignored in any standard optimization might warrant preservation when spatial synergies are considered. In other words, a negative-net-benefit parcel (hypothesis 5) or a disamenity parcel (hypothesis 6) might be selected solely to trigger enhanced proximity.

[11] The existence of negative WTP is a controversial topic in environmental economics but conditions exist where the expression of negative WTP is legitimate (see Bohara et al., 2001).

3. Optimization results and discussion

Table 2 presents the optimization results. Fig. 2 shows the spatial configuration of preservation at each level of spatial preference. The baseline of spatially independent optimization (α = 0) preserves 118 parcels totaling 16,710 acres, with net benefits of approximately $812 million. Relaxing the spatial-independence assumption does not alter substantively the acreage preserved, and the number of parcels preserved varies by no more than 10%. However, the assumed value of α does significantly alter the composition of the optimal set. These changes accelerate as α increases. For instance, weak preferences for agglomeration (α = 10) slightly alter the optimal set by adding two new parcels and removing four parcels selected under in the baseline. In contrast, very strong agglomeration preferences (α = 500) produce dramatically different results, having only 21 percent of parcels selected in common with the baseline. This change in the optimal set offers evidence to support hypothesis 1 (increased clustering with increased α)—a result that is visually apparent in Fig. 2. Furthermore, there is evidence to support hypothesis 2, i.e., that this increase in clustering is approximately linear with α. As agglomeration preferences become stronger, optimization produces increased clustering in the optimal set. Under the baseline of spatially independent optimization (α = 0), the average contiguous area of preserved land is 204 acres. This average contiguous area increases to 756 acres with very strong preferences for agglomeration. Fig. 3 shows how α varies with average cluster acreage, a relationship with a correlation of 0.98. Because the number of observations is low, it is not clear that this relationship is linear. Although a linear regression shows that average contiguous area equals 227.8 + 1.15α with high statistical significance (t-values for the intercept and α are 6.73 and 9.01, respectively), Fig. 3 shows that the cluster acreage may be rising less quickly as spatial preference increases above α = 300. The results also show that the number of optimal clusters declines as α increases (see Fig. 3). The correlation between these variables is −0.90.

In sum, the first two hypotheses show that spatial synergies can affect optimal selection and that there is the potential to create substantial clustering if a selection process is adjusted to account for SS benefits. The optimal number of clusters will tend to shrink as SS benefits increase. The results indicate that significant, desirable clustering is likely foregone by existing policies that claim to value contiguous habitat or critical mass of preserved land but do not systematically select based on spatial preferences

The inclusion of the SS benefits increases the potential for net benefits given the $30 million budget constraint. To be clear, the SS benefits are hypothetical in the sense that they are derived from the α parameter, which is a measure used for sensitivity analysis rather than a welfare-theoretic value like the benefit and cost

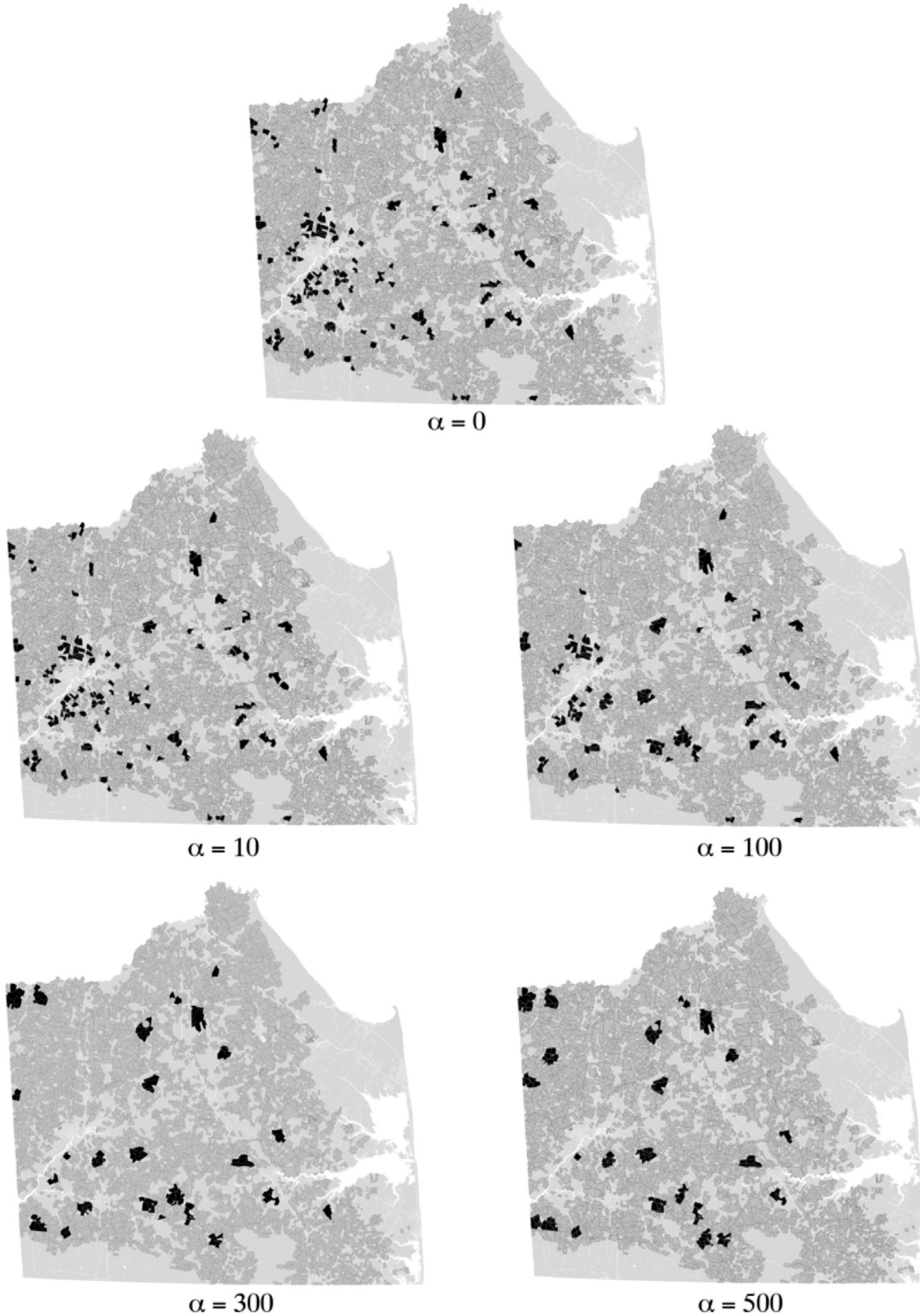

Fig. 2. Selection results at varying levels of a spatial synergy (α) given a $30 million budget.
Note: Sussex County, Delaware, outline is light gray, eligible parcels are dark gray and selected parcels are black.

data on the parcels. Optimization yields potential increases in a range of 0.008% ($\alpha = 10$) to 165% ($\alpha = 500$) relative to the baseline of spatially independent optimization ($\alpha = 0$). These magnitudes are substantial at high agglomeration preference, indicating the potential for substantial efficiency losses if policy selects projects without considering agglomeration preference when in fact it exists.

Table 2 also provides evidence to support hypothesis 3: That the aggregate PWTP decreases as spatial preference increases. This matches expectations because as α increases, the optimization algorithm is increasingly assigning preference based on SS benefits, not individual PWTP. However, the results also illustrate the relative rate at which this total PWTP declines with increasing values of α. Fig. 4 graphs the data from Table 2, showing that the rate at which total aggregate PWTP decreases in α is lower than the rate at which total SS benefits increase (support for hypothesis 4). This suggests that, at least in this application and the assumed gravity model, the benefits of accounting for spatial synergies outweighs the opportunity cost of doing so, over a significant spectrum of synergy parameters. Optimization research that treats parcel selection as spatially independent, when in fact it is spatially relevant, is systematically cost-ineffective. Greater omitted spatial preferences will increase efficiency losses. Although support for hypothesis 4 is the principal policy finding of the analysis, several qualifications of hypothesis 4 are warranted. Because the true value of α

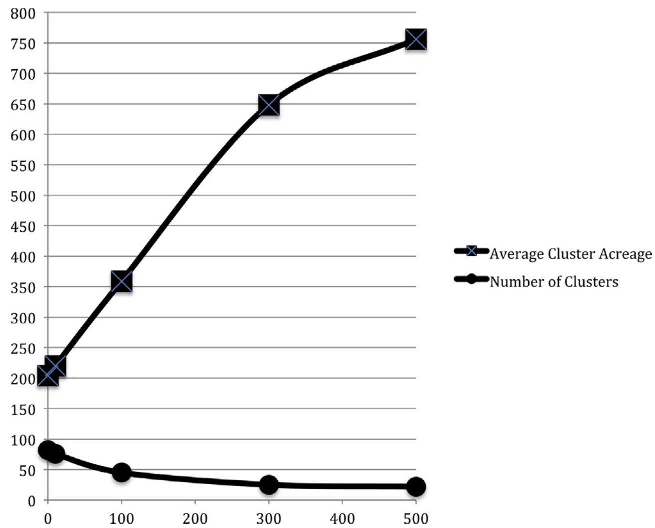

Fig. 3. Average cluster acreage and cluster number by spatial synergy parameter (α).
Note: Spatial synergy parameter is on horizontal axis. Curvature added.
Source: Original data from QKP algorithm results calculated in Python and Excel.

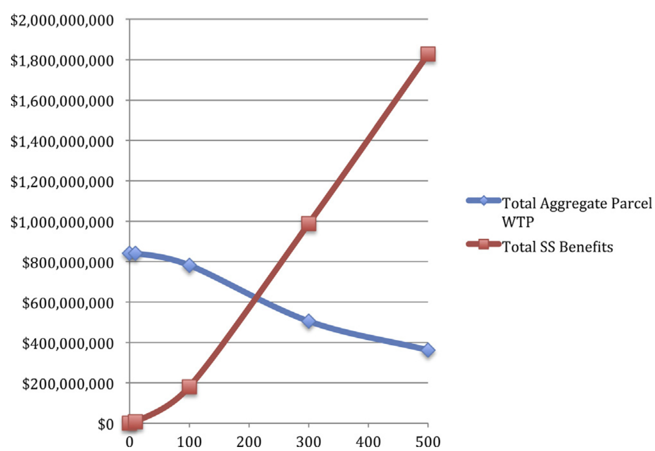

Fig. 4. Spatial synergy (α) impact on total aggregate PWTP and SS benefits (with smoothing).

is unknown, these results cannot be interpreted as an exact solution, but rather a guidance tool for policy makers to incorporate spatial interdependence into prioritization strategies informed by stated preference techniques. This motivates further research into the condition of indifference, i.e., if there are data or values of α for which the decrease in PWTP would just offset the increases in SS benefits.

Beyond the analysis of the aggregate results, a surprising and policy-relevant result is the increased selection of parcels with negative individual net benefits or even negative benefits within the optimal preservation set, as α increases. Table 2 presents evidence for hypothesis 6 (which automatically supports hypothesis 5). When $\alpha = 0$ and $\alpha = 10$, no negative PWTP parcels are selected. However, when spatial preference increases to $\alpha = 100$, two negative PWTP parcels are selected. At the two highest preference levels ($\alpha = 300$ and $\alpha = 500$), 24 and 43 negative PWTP parcels are selected, representing 21% and 35% of the selected parcels. Clearly, at high preferences levels, the SS benefit begins to overtake the PWTP in relative importance, and otherwise low-quality parcels will populate a significant minority of the optimal set. The reason this issue arises is because survey respondents indicated a disutility for the preservation of parcels classified with a disamenity, which in this application was apparently low risk of development. These negative values are likely a reaction to using public funds to preserve non-specific parcels somewhere in the state that are not likely to be developed in the near future (Duke and Johnston, 2010). Planners cannot overlook these low-development-risk parcels, if they believe agglomeration has an important effect on net social benefits. That said, the result of negative-WTP arising in our model is driven by the estimated parameters in our benefit model. In many other PES and land preservation cases, researchers will likely find that all quantity measures (acres) provide positive benefits. The intuition in our model implies that these other optimization settings – if they lack the complications of development pressure – will likely find their project set to be consistently positive. As such, our results imply that the spatial-synergistic optimization will select some surprising very-low benefit parcels (rather than negative-WTP parcels found here).

Extending this result, one sees that maximizing net social benefits may not require payments for environmental services in some locales. Other policy instruments, such as preservation districts or zoning, may lead to substantial welfare gains in settings with strong agglomeration preferences when used in combination with PES. Recognition of this impact can also reduce the potential welfare-deflating effects of adverse selection, as policy makers could avoid making payments for easements to landowners that likely do not have the outside option for development (for an analysis of this point, see Arnold et al., 2013). This also suggests that planners may be challenged in implementing these policies because they must explain why disfavored or disamenity parcels were selected over favored parcels. Taxpayers will likely not understand why agencies are securing projects that (at least independently) have low environmental-service values.

4. Conclusions and policy implications

This article presents a new and novel approach to conceptualize and measure the impact of spatial agglomeration preferences on the cost effectiveness of PES policies, such as land preservation. Welfare-theoretic benefit and cost measures for a set of eligible parcels in a U.S. county provide data to investigate the effect of relaxing the common assumption in optimization studies of spatial independence.

The spectrum of hypothetical SS benefits demonstrates that using valuation methods to prioritize selection without consideration of the systematic impact of spatial location is likely to produce cost-ineffective policy outcomes. While the true nature of the spatial interactions of agricultural land is unknown, a gravity model can provide a systematic foundation to address spatial interdependencies. The sensitivity analyses conducted here demonstrates the extent to which optimization adjusts the welfare-maximizing selections according to the relative importance of spatial interactions. An advantage of the proposed approach is its generalizability; the proposed approach can be adapted easily to different magnitudes of spatial synergies, thereby accounting for different types of empirical relationships observed in the literature. Hence, while the specific empirical findings of the illustrated model are specific to our case study, the general framework is broadly applicable.

Despite these insights, the analysis contains limitations in guiding future optimal selection research. As suggested above, the analysis will not apply in settings of nonmarginal intervention in the land market and when the spatial synergy process contains nonlinearities or thresholds. This approach also cannot provide specific planning guidance without knowing the spatial synergy parameter. If known with precision, the optimal selection program needs to be run once—depending on computing speed and whether another applied setting has more potential projects, this process might take several days. If the planner knows only a range of synergy parameters, then multiple optimizations and further analysis will slow selection. However, given the potential increase in environmental benefits from using this approach, our recommendation is that the cost of the extra computation time should be incurred give the large positive environmental return. An obvious future applied research project would examine a setting where the synergies could be estimated with the help of natural scientists. This may require an additional estimate of the β parameter of gravitational friction or even a modified version of the gravitational process that accounts for nonlinearities and/or thresholds.

From a policy perspective, the results of this study present cautionary evidence to policy makers and planners running PES programs. Spatially naïve welfare analysis might, in fact, provide information that leads to misguided policy in spatially complex preservation environments. Although it may seem counter-intuitive, the selection of seemingly undesirable or negative-WTP PES projects – projects that would potentially draw negative press and official investigations – can occur in an optimal strategy if the spatial benefits from joint preservation of contiguous parcels are large. This implies that the structure of many PES programs may need to be reconsidered at a fundamental level. A new program may explicitly quantify and argue in favor of these SS benefits, or planners could shift to potentially use cost-saving hybrid strategies. For instance, in land preservation, agencies could use preservation districts in areas of low development risk, within an optimal selection strategy set if there are strong preferences for agglomeration.

Observations such as this are common in fields such as conservation ecology. For example, when conserving parcels based on their anticipated value to species populations, it may be optimal to preserve habitat corridors that – while of low habitat value themselves – provide opportunities for organisms to move between more highly valued habitat patches. This can lead to the optimal preservation of parcels with lower individual habitat value (Johnston et al., 2014). Yet similar insights are commonly ignored when prioritizing PES based on economic benefits and costs. As a result, seemingly "optimal" PES investments may, in fact, lead to lower net social benefits.

The approach developed herein provides one possible avenue to quantify the spatial complexities involved in PES decisions such as land preservation. Future efforts could attempt to determine more refined values for the unknown parameters (α and β) that could improve the robustness of the results. Additionally, research integrating the idea of spatial synergy benefits modeled as gravity with the advances in the agglomeration bonus payments literature could generate an incentive structure to further improve preservation policies. A clear limitation of this analysis is that the application involves a single conservation intervention; in reality, many conservation programs make investments over time. Dynamic optimization with path dependencies would be required to inform efficient intertemporal choice. This research is a step forward in attempting to assess spatial interactions in a preservation setting, but work remains to further enhance the economic applications that ultimately influence real world policy changes.

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