Grassland Easement Acquisition: Conversion Hazard Rate, Additionality, and Spatial Spillover

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Abstract: This study investigates the roles of additionality of environmental benefits and spatial spillover effect of grassland conversion in determining the optimal grassland easement acquisitions. The preliminary results indicate that when conversion hazard rate is large then considering additionality and spatial spillover does not secure much additional environmental benefit than does ignoring additionality or spatial spillover. The study further explores the performance of three environmental benefit targeting strategies as well as three heuristic optimization algorithms in terms of securing environmental benefits via easement acquisition.

Keywords: additionality, conversion hazard, heuristic algorithms, grassland easement, spatial spillover

JEL Classifications: Q15, Q24, Q28

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Introduction

Grasslands provide critical ecosystem services (White et al. 2000). However, due to agricultural production and climate change, they are enduring degradation and acreage reduction (Bardgett et al. 2021). This is particularly the case for grasslands in the U.S. Prairie Pothole Region (PPR), where the pressure of grassland-to-cropland conversion has been imposed by the expansion of row crop production in the western Corn Belt (Wright and Wimberly 2013; Lark et al. 2015; Wimberly et al. 2017). As a result, significant investments have been directed at grassland conservation in the PPR. As a major effort among these investments, the U.S. Fish and Wildlife Service (USFWS) has made a plan to protect 10 million acres of grassland in this region, mainly through permanent grassland easements that pay landowners in a lump-sum in exchange of keeping the land under grass permanently (USFWS 2011).

Several issues exist pertaining to grassland easement acquisition. First, due to the relatively high cropping returns and land values in the past 15 years (Davis 2021), the average easement payment increased significantly (Walker et al. 2013; Claassen et al. 2017). Therefore, to ensure easement program efficiency, easement acquisition should be more carefully evaluated. Second, since easements prevent grassland conversions that may occur in the future, reliably accounting for future possible conversion incentives as well as the dynamic and stochastic nature of landowners' conversion decisions is key to understand the benefits and costs of alternative approaches. In practice, however, current approach in easement acquisition typically specifies the easement value as a fraction of market value of land (Walker et al. 2013). It does not consider the uncertainty of land-use returns and the possible land-use outcomes resulting from this uncertainty. Because this uncertainty is critical to determining the additionality of environmental benefits from easement acquisition (i.e., the difference in environmental benefits provided by a grassland tract with and without easement acquisition), ignoring this uncertainty results in additionality not being considered in easement acquisition (Claassen et al. 2017).

Furthermore, current ease acquisition practice does not explicitly account for the spatial spillover effect of land-use change, i.e., the effect that converting one tract of grassland may increase the conversion probability for neighboring grassland tracts, and that placing a grassland tract under easement may reduce a neighboring grassland tract's conversion probability. However, studies have shown that the spatial spillover effect can be an important factor that influences grassland conversion (e.g., Costello and Polasky 2004; Arora et al. 2021).

This paper is an attempt to fill the gaps described above by developing an internally consistent conceptual framework that integrates conversion risk, acquisition costs, environmental benefits, and spatial spillover effect into the decision rule for easement acquisition. Our intent is to a) provide easement managers with a more structured and data-driven framework to assist in acquisition decisions; b) highlight the importance of acquisition targeting strategy in determining the environmental benefits generated by the easement program; and c) explore heuristic land selection algorithms that are straightforward to implement for easement managers.

We first develop a theoretical framework on a representative easement manager's acquisition problem by using a stochastic dynamic programming approach. Because explicitly solving a general stochastic dynamic programming problem is challenging, we employ a simple example in which only four hypothetical tracts of grassland are considered to illustrate the difference in acquisition outcomes between various acquisition targeting strategies. We then expand this hypothetical example into a larger numerical example that is based on real-world data for six grassland tracts located in Ransom county, North Dakota. Acquisition targeting strategies considered in the examples are: 1) one that views environmental benefits from eased grassland as benefits secured by easement acquisition and does not consider spatial spillover effect, termed "basic targeting"; 2) one that considers conversion hazard rate when quantify secured environmental benefits but ignores the spatial spillover effect, termed "additionality targeting"; and 3) one that considers both conversion hazard rate and the spatial spillover effect, termed "additionality with spatial spillover targeting."

Due to the complexity of the optimal solutions under these targeting strategies, we also explore the performance of three heuristic algorithms to solve the easement manager's stochastic dynamic programming problem. These three heuristic algorithms are: 1) one that selects land tract with the largest environmental benefit available in the decision period without considering the tract's conversion probability, termed "naïve myopic algorithm"; 2) one that selects land tract with the largest product of environmental benefit and conversion probability in the decision period, termed "informed myopic algorithm"; and 3) one that is similar to aforementioned 2) but with spatial spillover effect incorporated in the conversion probability, termed "spatially informed myopic algorithm". A common feature of these three heuristic algorithms is that under them the easement manager only seeks to maximize the *current-period* environmental benefits without considering the dynamic nature of the optimization problem.

We find that in the optimal solution "additionality with spatial spillover targeting" outperforms "additionality targeting", which outperforms "basic targeting" in terms of securing environmental benefits. However, this order may not hold under heuristic algorithms. Particularly, under "naïve myopic algorithm" and "informed myopic algorithm" the three targeting strategies generate the same additionality of environmental benefits. Under "spatially informed myopic algorithm", however, "basic targeting" outperforms the other two targeting strategies.

The remainder of the article proceeds as follows. The next section summarizes relevant literature, followed by a section that presents a conceptual framework under which a representative easement manager maximizes environmental benefits obtained from easement acquisition under a budget constraint in an infinite temporal horizon. Then we illustrate the efficiency of different acquisition targeting strategies based on a four-tract example and a six-tract example. The last section concludes.

Literature Review

Easement acquisition strategies are essentially conservation targeting strategies, aiming to determine which land tracts to conserve and in what sequential order. There is a large literature on conservation targeting in which cost-benefit analysis has been documented as a preferred means to enhance conservation efficiency (e.g., Arrow et al. 1996; Babcock et al. 1996, 1997; Wu, Zilberman, and Babcock, 2001; Murdoch et al. 2010; Ando and Mallory 2012; Miao et al. 2016). Furthermore, the literature has shown that the benefit-cost analysis should consider not only the conservation costs and environmental benefits but also land conversion hazards due to the dynamic and stochastic nature of land-use changes (Ando et al. 1998; Costello and Polasky 2004; Newburn et al. 2006; Wilson et al. 2006; Walker et al. 2013).

Land conversion hazards are critical because it is essential to quantify the additionality of an easement acquisition, defined as the difference between environmental benefits offered by a land tract with and without easement acquisition (i.e., the additional environmental benefits secured solely due to easement acquisition). Intuitively, everything else equal, easing a grassland tract with a larger conversion hazard generates larger additionality than does easing a tract with a smaller conversion hazard. In an extreme case, easing a land tract with zero conversion hazard will generate no additionality. Even with its importance to conservation efficiency, additionality was not explicitly considered in easement acquisition practices (Walker et al. 2013). Claassen et al. (2017) find that only about 0.28% of the grasslands protected under easement in the PPR would have been converted per year had there been no easement protection, indicating low additionality of existing easement programs. Based on a real option framework, Miao, Hennessey, and Feng (2021) examine the relationship between conversion hazard and the minimum easement payment that a landowner is willing to accept. They find that when the option value of not easing or converting the grassland land is considered, then the minimum easement payment is not always increasing in conversion hazard rate. However, they do not consider the spatial spillover effect of grassland conversion.

Although spatial spillover effect of ecological benefits have been widely discussed in the conservation literature (e.g., Saunders, Hobbs, and Margules 1991; Margules and Pressey 2000; Williams, Revelle, and Levin 2005; Parkhurst and Shogren 2007; Banerjee 2018), the spatial spillover effect of land conversion decisions on the conversion of neighboring grassland tracts has not attracted much attention in the literature. Lawley and Yang (2015) find that easement on one grassland tract increases the likelihood that its neighboring grassland tracts being eased. Arora et al.'s (2021) findings corroborate the conclusion in Lawley and Yang (2015) and also show that grassland-to-cropland conversion of one parcel will prompt such conversion on neighboring grasslands. They argue that this spatial spillover effect of conversion and conservation should be taken into consideration when targeting grassland tracts for easement. Panchalingam et al. (2019) state that because the land value of a tract of land is likely influenced by the land-use status of surrounding land tracts, conservation agencies should consider this influence to enhance the conservation efficiency.

The present study contributes to the literature by explicitly modeling the impact of considering additionality in environmental benefits and spatial spillover effect in land conversion under a dynamic stochastic framework. We also compare the efficiency of a few heuristic algorithms with the efficiency of optimal acquisition algorithm.

Theoretical Framework

We first develop a theoretical framework that describes the optimal easement acquisition strategy. This model pertains to one easement manager and *K* landowners in an infinite time framework. At the beginning of the temporal framework (i.e., $t = 0$), each landowner possesses a tract of grassland. Land quality across these *K* tracts of grasslands differs. To simplify the exposition and to focus on easement manager's optimal acquisition problem, we assume that a grassland tract $i \in \{1, ..., K\}$ is converted to cropland with probability p_{it} at the beginning of period *t* unless it is eased. We further define $q_{it} \equiv 1 - p_{it}$ as the probability of tract *i* remaining as grassland during period *t*. This probability is determined by the joint distribution of returns from grassland and cropland, which are in turn determined by the land-use status of neighboring tracts. Note that we assume that the conversion occurs at the very beginning of a period. If land is not converted at the beginning of a period then it will remain under grass till the end of the period.

We further assume that a grassland tract *i* generates grassland return π_{it}^{g} and environmental benefits, b_{it}, in period *t*. If converted to cropland, then cropping return π_{it}^{c} can be generated in period *t* whereas the environmental benefits, without loss of generality, vanish to zero.[1] Let N_t

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[1] We acknowledge that this is a strong assumption because cropland can still provide some environmental benefits (Phalan et al. 2011). However, what matters for the modeling purpose is the difference in environmental benefits between grassland and cropland. Relaxing this

denote the number of tracts of grassland available to be eased at the beginning of period *t*; clearly, $N_t \leq K$ for any $t \geq 0$.

Benefits and costs of easing grassland tracts

If a tract of grassland is protected by grassland easement, then it will be under grass production permanently. Therefore, in period *t*, the aggregate present value of environmental benefits from a grassland tract *i* under easement is:

$$V_{i,t}^{\mathrm{e}} = \sum_{s=t}^{+\infty} \beta^{s-t} b_{i,s}, \tag{1}$$

where $\beta \in [0,1]$ is a discount factor. If easement is unavailable, then the aggregate present value of expected environmental benefits from tract *i* is:

$$V_{i,t}^{\mathrm{ne}} = \sum_{s=t}^{+\infty} [\beta^{s-t} (\prod_{\tau=t}^{s} q_{i,\tau}) b_{i,s}]. \tag{2}$$

Therefore, the difference in benefits between with and without easement for tract *i* is

$$\Delta V_{i,t} = V_{i,t}^{\mathrm{e}} - V_{i,t}^{\mathrm{ne}} = \sum_{s=t}^{+\infty} [\beta^{s-t} (1 - \prod_{\tau=t}^{s} q_{i,\tau}) b_{i,s}]. \tag{3}$$

Here $\Delta V_{i,t}$ measures the additionality of easement acquisition on environmental benefits. In other words, it excludes the environmental benefit generated by the grassland tract when it remains unconverted yet (i.e., $V_{i,t}^{\mathrm{ne}}$). It is readily checked that if $q_{i,t} = 1 \ \forall t,$ then $\Delta V_{i,t} = 0.$ Intuitively, if with certainty that a tract of grassland will not be converted in any period, then easing this tract of land will not generate any additional environmental benefits (i.e., zero additionality).

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assumption by replacing zero environmental benefit with a positive benefit smaller than b_{it} will not affect the insight that the analysis seeks to convey.

For simplicity, we assume that the easement manager will only offer the difference between the expected returns from the status quo and those from placing the grassland under a grassland easement. Specifically,

$$\begin{aligned} C_{i,t} &= C_{i,t}(\pi_i^c, \pi_i^g, p_i, \theta_i; \beta) \\ &= \sum_{s=t}^{+\infty}[\beta^{s-t}(1-\prod_{\tau=t}^{s} q_{i,\tau})(\pi_{i,s}^c - \pi_{i,s}^g)] - \theta_i \sum_{s=t}^{+\infty}[\beta^{s-t}(\prod_{\tau=t}^{s-1} q_{i,\tau}) p_{i,s}], \end{aligned} \qquad (4)$$

where $\prod_{\tau=t}^{t-1} q_{i,\tau}$ is defined to be equal to 1; i.e., we examine land that has stayed in grass up to the present day and investigate how easement payments can be designed to cost-effectively protect such land. The parameter θ_i is the one-time conversion costs from grassland to cropland.[2] The first term in the second line of equation (4) is the potential returns from cropping foregone were the land to be eased and the second term is the expected one-time conversion cost. Obviously, the lower the potential benefits from conversion or the higher the conversion cost, the lower the easement cost.

Easement agency's decision problem

We consider a decision framework with an infinite temporal horizon. The object of the easement manager is to maximize the expected present value of environmental benefits over the entire temporal horizon under her budget constraint. Figure 1 depicts the decision timeline of the easement manager. At the beginning of each period, the easement manager makes the acquisition decision for that period based on the information about available grassland tracts, their benefits and costs, as well as their conversion probability. The easement manager has a fixed budget inflow in each period, m_t, and aims to maximize the expected aggregate environmental benefits protected by grassland easements (i.e., the additionality). Following Costello & Polasky (2004),

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[2] Item A in the Supporting Information (SI) displays details to obtain this equation.

we assume that the agency cannot borrow, but they can defer expenditures to the next period, earning interest at rate *r*. Fund carried over from previous periods to period *t* is denoted by M_t. Hence, the total acquisition fund in period *t* is $M_t + m_t$. Define $\Omega_t \equiv \{1, ..., N_t\}$ as the set of all grassland tracts available to be eased in period *t*, where $N_t \leq K$ and further define $\mathscr{P}(\Omega_t)$ as the set of all subsets of set Ω_t. Let $h_t \in \mathscr{P}(\Omega_t)$ be the subset of tracts acquired by the agency in period *t*. The agency's maximization problem in period *t* can then be written in a Bellman equation as follows:

$$\begin{aligned} &\mathscr{B}_t(\Omega_t) = \max\nolimits_{h_t \in \mathscr{P}(\Omega_t)} \left\{ \sum\nolimits_{k \in h_t} \Delta V_{k,t} + \beta \sum\nolimits_{\Omega_{t+1} \in \mathscr{P}(\Omega_t)} \Gamma(\Omega_{t+1} \mid \Omega_t, h_t) \mathscr{B}_{t+1}(\Omega_{t+1}) \right\}, \\ &\text{s.t.} \quad \sum\nolimits_{k \in h_t} C_{k,t} \leq M_t + m_t, \quad M_{t+1} = (M_t + m_t - \sum\nolimits_{k \in h_t} C_{k,t})(1 + r). \end{aligned} \tag{5}$$

where $\mathscr{B}_t(\Omega_t)$ is the maximized expected environmental benefits over period *t* and onward secured via grassland easement under the budget and land availability constraints; $\beta \in [0,1]$ is the discount factor; $\Gamma(\Omega_{t+1} \mid \Omega_t, h_t)$ is the probability that a specific Ω_{t+1} is realized in period $t+1$, given land tracts available in period *t*, Ω_t, and land tracts acquired in period *t*, h_t; and finally, $C_{k,t}$ is the lump sum cost of easing grassland tract *k* in period *t*. The spatial spillover effect is incorporated in the state transition probability function $\Gamma(\Omega_{t+1} \mid \Omega_t, h_t)$.

Solving Model (5) is challenging, particularly because one must consider the conversion probability of one grassland tract is determined by the conversion or easement status of its neighboring tracts. In what follows we therefore first use a four-tract example to illustrate how the outcome of easement acquisition may differ under various targeting scenarios and optimization algorithms.

Targeting strategies and heuristics

Since one purpose of the study is to explore the performance of various environmental benefit targeting strategies and heuristic acquisition algorithms, in this subsection we outline the three targeting strategies and three heuristic algorithms to be considered in the remaining part of this paper.

We consider three targeting strategies: 1) one that views environmental benefits from eased grassland as benefits secured by easement acquisition and does not consider spatial spillover effect, termed "basic targeting"; in other words, neither additionality nor spatial spillover is considered in this "basic targeting" strategy. 2) one that considers environmental benefit additionality when quantifying secured environmental benefits but ignores the spatial spillover effect, termed "additionality targeting"; and 3) one that considers both environmental benefit additionality and the spatial spillover effect, termed "additionality with spatial spillover targeting". Optimization problem (5) represents the "additionality with spatial spillover targeting." Define $\Lambda(\Omega_{t+1} | \Omega_t, h_t)$ as the state transition probability function that ignores the spatial spillover effect of land-use change. Then the "additionality targeting" can be represented by problem (5) after replacing $\Gamma(\Omega_{t+1} | \Omega_t, h_t)$ with $\Lambda(\Omega_{t+1} | \Omega_t, h_t)$ in the objective function. Furthermore, "basic targeting" can be represented by problem (5) after replacing $\Gamma(\Omega_{t+1} | \Omega_t, h_t)$ with $\Lambda(\Omega_{t+1} | \Omega_t, h_t)$ and replacing $\Delta V_{k,t}$ with $V_{i,t}^{\mathrm{e}}$ in the objective function.

In additional to the optimal solutions to the three targeting strategies, we further consider solutions from three heuristic algorithms. These three algorithms are: 1) "naïve myopic algorithm" that selects land tract with the largest targeting environmental benefit available in the decision period without considering the tract's conversion probability; 2) "informed myopic algorithm" that selects land tract with the largest product of targeting environmental benefit and conversion probability in the decision period, without considering the spatial spillover effect of conversion; and 3) “spatially informed myopic algorithm” that is similar to “informed myopic algorithm” but with spatial spillover incorporated in the conversion probability.

Numerical Examples

In this section we provide two numerical examples to illustrate the performance of the aforementioned targeting strategies and heuristic algorithms. The first example is highly simplified and hypothetical with the purpose of demonstrating the underlying mechanisms of each targeting strategy and heuristic algorithm. The second example, however, is based on actual data for six grassland tracts in Ransom County, North Dakota. This county is chosen because it is located in the Prairie Pothole Region and the edge of western corn belt, where grassland tracts are facing large conversion pressure (Arora et al. 2021).

Four-tract example

Assuming that at the beginning of period one there are four grassland tracts, namely A, B, C, and D, available to be eased. The geographical configuration of these four tracts is shown in Figure 2. Specifically, tracts A, B, and C are neighbors, with tract B located between tracts A and C but closer to tract A than to tract C. However, tract D is not a neighbor of any tract. Spatial spillover effect exists only among the neighbors (i.e., tracts A, B, and C). As a result, tract D does not create or receive any spatial spillover effect. The environmental benefits and conversion probability of each tract under various targeting scenarios are presented in Table 1. For instance, without considering spatial spillover effect of neighboring tracts’ land-use status, the easement manager would believe that the conversion probability of Tract A is 0.3. However, the actual conversion probability of Tract A is influenced by the land-use status of neighboring land tracts, which is specified in Table 1 (see the row of “Conversion probability (spatial spillover considered)”). For example, when both tracts B and C remain unconverted (denoted by (B^1, C^1)), then the conversion probability of tract A is 0.3; when both Tract B and Tract C have been converted to cropland, denoted by (B^0, C^0), however, then the conversion probability of Tract A becomes 0.7. To reflect the fact that Tract B is closer to Tract A than Tract C is and hence Tract B may have larger spatial spillover effect on Tract A, we set that, if only Tract B (respectively, C) is converted in a previous period then the conversion probability of Tract A in the current period becomes 0.6 (respectively, 0.4). For simplicity, we assume that conversion is contemporaneously uncorrelated among tracts and is only affected by previous period land-use status of neighboring tracts.

Our objective is to investigate how outcomes differ under different targeting mechanisms. First, let us consider the baseline scenario under which the easement manager *i*) views all the environmental benefits generated by an eased tract as the environmental benefits secured by the easement acquisition (i.e., $V_{i,t}^{e}$ described in equation (1)), and *ii*) ignores spatial spillover effect of any grassland-to-cropland conversion. Under this scenario, the easement manager believes that the conversion probabilities for tracts A, B, C, and D are 0.3, 0.6, 0.5, and 0.8, respectively (see Table 1), regardless of the conversion status of neighboring tracts. Furthermore, if tract A is eased then the manager will view the environmental benefits obtained from the easement acquisition is 13.9583. For tracts B, C, and D, the corresponding numbers are 8.2667, 4.200, and 7.0875, respectively. For simplicity, we assume that the easement acquisition cost across all the four tracts is the same and the easement manager has the budget to acquire exactly one tract in each period.

The entire decision tree of the decision problem under the baseline scenario is illustrated in Figures 3, SI-1, SI-2, and SI-3.[3] Figure 3 presents a sub-branch of the entire decision tree wherein tract A is chosen in period one. The number "19.4912" at the right lower corner of the top box "If chooses A in period 1" is the expected aggregate environmental benefits that the easement manager believes that she would obtain if she chooses tract A in period one. We term the believed environmental benefits as *subjective* environmental benefits, which may differ from the *actual* environmental benefits under a period-one choice because the easement manager's belief in the conversion probability may differ from the actual conversion probability whenever the spatial spillover effect of conversion is ignored. Table 1 presents expected subjective environmental benefits for each period-one choice under each targeting scenario.

In the decision trees, the numbers along the segments are *subjective* probabilities of the states at the bottom of the segments occurring. When spatial spillover effect is not considered, then the subjective probabilities may differ from the actual probabilities. For instance, in Figure 3 the number "0.06" along the very top right segment indicates that probability of state $\left(B^0C^1D^1\right)'$ occurring is 0.06, which is calculated by using $0.6\times(1-0.5)\times(1-0.8).$ Here superscript "0" in $\left(B^0C^1D^1\right)'$ indicates that the corresponding tract is under cropping (i.e., converted) and "1" indicates that the corresponding tract is under grass (i.e., not converted). Given the status $\left(B^0C^1D^1\right)'$ (i.e., tract B unavailable and tracts C and D available for easement) in period two, the easement manager has two options in period two: to ease tract C or to ease tract D. If the

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[3] Because the entire decision tree of this four-tract example cannot fit in one page, we present the branch of the decision tree associated with each possible choice (i.e., tract A, B, C, and D) in period one in an individual figure (i.e., Figures 3, SI-1, SI-2, and SI-3) respectively.

easement manager acquires tract D, then she believes that, due to her being unaware of spatial spillover effect, the probability that tract C will be converted is 0.5, even though the actual conversion probability of tract C is 0.6 in this case.

In Figure 3, the number at the lower right corner of state $\left(B^0C^1D^1\right)'$, 8.63, is the maximized expected environmental benefits under the state, excluding the benefits from tracts chosen before this state occurs (Tract A in this case). Specifically, 8.63 is obtained from

$$\max\{\beta\times 4.2+\beta^2\times 0.2\times 7.0875,\ \beta\times 7.0875+\beta^2\times 0.5\times 4.2\},$$

where β is the discount factor and is set to be equal to 0.95 throughout the example. Backward induction is applied to identify the optimal choice in period *t*. By analyzing the expected environmental benefit under each possible choice in period one, we find that the optimal choice in period one under the baseline scenario is tract A.

Under the second scenario, the easement manager considers additionality when determining the environmental benefit secured by easement acquisition; but she still ignores the spatial spillover effect. By following the similar approach in the baseline scenario except replacing $V_{i,t}^{e}$ with $\Delta V_{i,t}$, we find that under this scenario the optimal choice in period one is tract D. The decision tree under this scenario is presented by Figures SI-4 to SI-7. Table 1 also presents the expected *subjective* environmental benefits if a tract is chosen in period one under this targeting scenario.

Under the third scenario, the easement manager considers both additionality and spatial spillover effect. Note that because tract D is not a neighbor of any other grassland tracts, its conversion status does not have any spatial spillover effect. Under this scenario, the optimal choice in period one becomes tract B.[4] This is intuitive because the conversion of tract B would increase the conversion probability of tracts A and C whereas the conversion of tract D would not have such a spatial spillover effect. Therefore, when spatial spillover effect is considered, tract B should be protected with higher priority than tract D (see Table 1 for the expected environmental benefits under each period-one choice). The decision trees under this targeting scenario are presented in Figures SI-8 to SI-11.

Outcomes of Various Heuristics

So far, we have considered the optimal choice under three different targeting scenarios. Because in many cases identifying the optimal solution for a dynamic stochastic programming problem is challenging, it is meaningful to explore performance of some heuristic algorithms. In this subsection we consider three of them as we explained earlier. Continuing with Example 1, the naïve myopic algorithm will always rank the four tracts, from high to low acquisition priority, as A, B, D, and C (0.6979 > 0.4133 > 0.3544 > 0.2100 in Table 1), whereas the informed myopic algorithm will always rank the four tracts as D, B, A, and C (0.8×0.3544 > 0.6×0.4133 > 0.3×0.6979 > 0.5×0.21 in Table 1), regardless of the conversion status of neighboring tracts. For the spatially informed myopic algorithm, period-one choice is always tract D because at the beginning of period one none of the tracts have been converted yet and the conversion

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[4] For simplicity, we assume that the environmental benefits additionality is not affected by spatial spillover effect. That is, under the additionality with spatial spillover targeting scenario, we assume that the spatial spillover effect only affects the easement manager's belief about the availability of a grassland tract in a future period. We acknowledge that this is a strong assumption and that the example can be improved by relaxing the assumption. However, we believe that, if we consider the impact of fragmentation, then the additionality might not be affected very much by the spatial spillover effect. For instance, if some neighboring tracts of a grassland tract are converted, then the conversion risk of the tract in question will increase and the environmental benefits per period may decrease due to fragmentation. Therefore, the overall benefit of easing the tract (i.e., $\Delta V_{i,t}$) may not change much.

probabilities are 0.3, 0.6, 0.5, and 0.8 for tracts A, B, C, and D, respectively. However, in later periods, this algorithm takes the spatial spillover effect into consideration when calculating the product of conversion probability and environmental benefits. For instance, at the beginning of period two, if the realized state is $\left(A^1B^1C^0\right)'$ (i.e., only tracts A and B are available for easement acquisition), then the easement manager will ease tract A instead of B because when tract C is the only tract that is converted then the conversion probabilities of tracts A and B are 0.4 and 0.65, respectively, and 0.4×0.6979 > 0.65×0.4133.

Table 2 presents period-one choice under each targeting strategy and each heuristic algorithm. The corresponding expected *actual* environmental benefits additionality are also included in the table. From Table 2 we can see that in the optimal solution, the first period choice under the basic targeting, the additionality targeting, and the additionality with spatial spillover targeting is tract A, D, and B, respectively. The maximized environmental benefit additionality under the three targeting strategies is 17.8231, 17.9832, and 18.0966, respectively. Clearly, among the three targeting strategies, the basic targeting strategy achieves the smallest environmental benefit additionality whereas the additionality with spatial spillover targeting achieves the highest.

Under the naïve myopic algorithm, the easement manager will always choose grassland tract A in the first period. Then in the later periods, she will follow the order “B, D, and C” to ease available land tracts. The expected actual environmental benefit additionality achieved by the naïve myopic algorithm is 17.7911. Under the informed myopic and spatially informed myopic algorithms, however, the easement manager will choose grassland tract D in the first period. The expected actual environmental benefit additionalities under these two algorithms are 17.9832 and 17.9879, respectively (see Table 2). As expected, the naïve myopic algorithm generates the lowest environmental benefit additionality; the informed myopic algorithm performs better than the naïve myopic algorithm but worse than the spatially informed myopic algorithm. In Example 1, the informed myopic algorithm secures the same amount of environmental benefit additionality as the optimal algorithm does under the additionality targeting scenario. Moreover, the spatially informed myopic algorithm outperforms the optimal algorithm under basic targeting and additionality targeting in terms of securing environmental additionality (17.9879 vs. 17.8231 and 17.9832 in Table 2). This indicates that if a targeting strategy does not consider spatial spillover effect, then an optimal algorithm under such a targeting strategy may perform worse than a heuristic algorithm that considers spatial spillover effect in terms of securing environmental benefit additionality, which underscores the importance of the consideration of spatial spillover effect.

A Numerical Example Based on Data for Grassland Tracts in North Dakota

We now consider another example that is based on actual data for six grassland tracts located in Ransom County, North Dakota (see Figure 4). Grasslands in this county are facing increasing pressure of conversion to cropland as they are located on the edge of western corn belt (Arora et al. 2021). These selected six grassland tracts are identified as permanent grassland based on land-use history reflected in the USDA Cropland Data Layer (CDL). In this example, we will examine the environmental outcomes of easement acquisition under the three targeting strategies and three heuristic algorithms. We first predict the conversion probability of each grassland tract based on a grassland conversion hazard rate model developed by Arora et al. (2021). We then assign environmental benefits to the six grassland tracts by using duck pair data obtained from U.S. Fish and Wildlife Service (USFWS). Finally, we will apply the Markov Decision Processes (MDP) Toolbox developed by Chadès et al. (2014) to solve the optimization problems for each targeting strategies. Easement acquisition results under the aforementioned heuristic algorithms will be studied as well.

Conversion probability estimation

Based on the data for 447 grassland tracts in North Dakota, Arora et al. (2021) estimate a grassland conversion hazard rate model (see their equation (9) and related discussion for details). We utilize their estimation results to predict conversion probabilities of the six grassland tracts considered in this example. Because the six tracts are included in the 447 grassland tracts studied by Arora et al. (2021), our prediction is in-sample prediction. Even though the six tracts are currently under grass, we utilize the model in Arora et al. (2021) to predict the conversion probabilities of these grassland tracts under counterfactual scenarios where some or all neighboring tracts are assumed to be converted. The point estimate results of the conversion probabilities are presented in Table 3, which also includes some environmental characteristics of the six tracts.

We find that the conversion probability of a grassland tract is significantly affected by the conversion status of its neighboring tracts. For instance, the conversion probability of tract a is ten times larger when its neighboring tracts (i.e., tracts b, c, and d) are all converted than when none of the neighboring tracts are converted. The more neighboring tracts are converted, the larger the conversion probability of the grassland tract in question. We also find that, overall, the conversion probabilities of the six grassland tracts are extremely small, which is caused by their relatively higher land slope, lower land quality, and further distance to highway. However, the conversion probabilities vary considerably among the six grassland tracts, with Tract *a* having the lowest conversion probability (around 5E-8) while Tract *d* having the highest (around 0.01).

Environmental benefits

We use the number of duck pairs as a measurement of environmental benefits of the six grassland tracts (Table 3). Tract c has the highest duck pair density, 6.87 pairs/acre, whereas Tract f has the lowest, 3.59 pairs/are. In terms size, Tract c is the largest (14.23 acres) and Tract e is the smallest (5.12 acres). In the simulations we assume that the duck pair density of a tract does not change over time.

Results

Based on the environmental benefit data and conversion probability discussed above, we solve the easement manager's optimization problem under each of the targeting scenarios using the MDPtoolbox in Matlab. We find that whenever additionality is not considered, then the optimal choice in period one is Tract c. However, whenever additionality is considered, then the optimal choice in period one is Tract d. Even though in this example whether or not the spatial spillover effect is considered does not affect period-one decision, considering spatial spillover effect influence the aggregated environmental benefits of easement acquisition.

Concluding Remarks

This study creates a framework for land conversion trade-offs that integrates conversion risk, acquisition costs, environmental benefits, and spatial spillover into an internally consistent decision rule for easement acquisition. We find that under "spatially informed myopic algorithm", "basic targeting" may outperform the other two targeting strategies. This result highlights the importance the selection of targeting strategy and heuristic algorithm. The study provides easement managers with useful insights to better understand economic determinants of conversion choices and to think through whether easement dollars are effectively spent.

References

Ando, A., J. Camm, S. Polasky, A. Solow. 1998. "Species distributions, land values, and efficient conservation." *Science* 279(5359):2126-2128.

Ando, Amy W., and Mindy L. Mallory. 2012. “Optimal Portfolio Design to Reduce Climate-Related Conservation Uncertainty in the Prairie Pothole Region.” Proceedings of the National Academy of Sciences of the United States of America 109 (17):6484–89.

Arora, G., Feng, H., Hennessy, D.A., Loesch, C., Kvas, S. 2021. The impact of production network economies on spatially-contiguous conservation - Theoretical model with evidence from the U.S. Prairie Pothole Region. Journal of Environmental Economics and Management 107:102442. DOI: https://doi.org/10.1016/j.jeem.2021.102442

Arrow, Kenneth J., Maureen L. Cropper, George C. Eads, Robert W. Hahn, Lester B. Lave, Roger G. Noll, Paul R. Portney, Milton Russell, Richard Schmalensee, V. Kerrry Smith, and Robert N. Stavins. 1996. “Is There a Role for Benefit-Cost Analysis in Environmental, Health, and Safety Regulation?” Science 272 (5259): 221–22.

Babcock, Bruce A., P. G. Lakshminarayan, JunJie Wu, and David Zilberman. 1996. “The Economics of a Public Fund for Environmental Amenities: A Study of CRP Contracts.” American Journal of Agricultural Economics 78 (4): 961–71.

———. 1997. “Targeting Tools for the Purchase of Environmental Amenities.” Land Economics 73 (3): 325–39.

Banerjee, S. 2018. Improving Spatial Coordination Rates under the Agglomeration Bonus Scheme: A Laboratory Experiment with a Pecuniary and a Non-Pecuniary Mechanism (NUDGE). American Journal of Agricultural Economics 100(1):172-197.

Bardgett, R.D., J.M. Bullock, S. Lavorel, and P. Manning et al. 2021. Combatting global grassland degradation. Nature Reviews Earth & Environment 2, 720–735. doi: https://doi.org/10.1038/s43017-021-00207-2

Chadès, I., Chapron G., Cros MJ., Garcia F., Sabbadin R. 2014. MDPtoolbox: a multi-platform toolbox to solve stochastic dynamic programming problems. *Ecography* 37:916-920.

Claassen, R., J. Savage, C. Loesch, V. Breneman, R. Williams, B. Mulvaney, and T. Fairbanks. 2017. Additionality in Grassland Easements to Provide Migratory Bird Habitat in the Northern Plains. *Journal of Agricultural and Resource Economics* 42(3):291-309.

Costello C, S Polasky. 2004. “Dynamic Reserve Site Selection.” *Resource and Energy Economics* 26(2):157-174.

Davis, J.B. 2021. South Dakota Agricultural Land Market Trends, 1991-2021: Results from the 2021 South Dakota State University Extension South Dakota Farm Real Estate Survey. South Dakota State University. Available at: https://extension.sdstate.edu/south-dakota-agricultural-land-market-trends (accessed December 10, 2021).

Lark, T.J., J.M. Salmon, and H.K. Gibbs. 2015. Cropland expansion outpaces agricultural and biofuel policies in the United States. Environmental Research Letters 10(4) (2015), Article 044003.

Lawley, C. and W. Yang. 2015. Spatial interactions in habitat conservation: Evidence from prairie pothole easements. Journal of Environmental Economics and Management 71:(71-89).

Margules, C.R. and R. Pressey. 2000. Systematic Conservation Planning. Nature 405: 243-253.

Miao, Ruiqing, Hongli Feng, David A. Hennessy, and Xiaodong Du. 2016. “Assessing Cost-effectiveness of the Conservation Reserve Program and Its Interaction with Crop Insurance Subsidies”. Land Economics 92(4):593-617.

Miao, Ruiqing, David A. Hennessy, and Hongli Feng. 2021. “Grassland Easement Evaluation and Acquisition: An Integrated Framework.” Working paper. Department of Agricultural Economics and Rural Sociology, Auburn University.

Murdoch, William, Jai Ranganathan, Stephen Polasky, and James Regetz. 2010. “Using Return on Investment to Maximize Conservation Effectiveness in Argentine Grasslands.” Proceedings of the National Academy of Sciences of the United States of America 107 (49): 20855–62.

National Fish and Wildlife Foundation (NFWF). 2016. National Fish and Wildlife Foundation Business Plan for the Northern Great Plains. Available at http://www.nfwf.org/greatplains/Documents/ngp_busplan_w.appendix.pdf (last accessed, January 13, 2019).

Newburn, D.A., P. Berck, A.M. Merenlender. 2006. “Habitat and Open Space at Risk of Land-Use Conversion: Targeting Strategies for Land Conservation.” *American Journal of Agricultural Economics* 88(1):28-42.

Panchalingam, T. C.J. Ritten, J.F. Shogren, M.D. Ehmke, C.T. Bastian, G.M. Parkhurst. 2019. Adding realism to the Agglomeration Bonus: How endogenous land returns affect habitat fragmentation. Ecological Economics 164:1-10. doi: https://doi.org/10.1016/j.ecolecon.2019.106371

Parkhurst, G.M. and J.F. Shogren. 2007. Spatial incentives to coordinate contiguous habitat. Ecological Economics 64(2):344-355.

Phalan, B., M. Onial, A. Balmford, and R.E. Green. 2011. Reconciling Food Production and Biodiversity Conservation: Land Sharing and Land Sparing Compared. Science 333(6047):1289-1291. doi: 10.1126/science.1208742

Rashford, B.S., A.M. Scott, L.S. Smutko, and A. Nagler. 2019. “Assessing Economic and Biological Tradeoffs to Target Conservation Easements in Western Rangelands.” Western Economics Forum 17(1):9-23.

Saunders, D.A., R.J. Hobbs, and C.R. Margules. 1991. Biological consequences of ecosystem fragmentation: a review. Conservation Biology 5(1):18-32.

U.S. Fish and Wildlife Service (USFWS). 2011. Land Protection Plan—Dakota Grassland Conservation Area. Lakewood, Colorado: U.S. Department of the Interior, Fish and Wildlife Service, Mountain–Prairie Region. 169 p.

Walker, J., J.J. Rotella, C.R. Loesch, R.W. Renner, J.K. Ringelman, M.S. Lindberg, R. Dell, K.E. Doherty. 2013. “An Integrated Strategy for Grassland Easement Acquisition in the Prairie Pothole Region, USA.” *Journal of Fish and Wildlife Management* 4(2):267-279.

Williams, J.C., C.S. ReVelle, and S.A. Levin. 2005. Spatial attributes and reserve design models: A review. Environ Model Assess 10, 163–181 (2005). https://doi.org/10.1007/s10666-005-9007-5

Wilson, K.A., M.F. McBride, M. Bode, H.P. Possingham. 2006. “Prioritizing global conservation efforts.” *Nature* 440:337-340.

Wimberly, M.C., L. Janssen, D.A. Hennessy, M. Luri, N.M. Chowdhury, and H. Feng. Cropland expansion and grassland loss in the eastern Dakotas: new insights from a farm-level survey. Land Use Policy, 63:160-173. doi: https://doi.org/10.1016/j.landusepol.2017.01.026

White, Robin P., Siobhan Murray, Mark Rohweder. 2000. *Pilot Analysis of Global Ecosystems: Grassland Ecosystems*. World Resources Institute, Washington, D.C.

Wright, C.K. and M.C. Wimberly. 2013. Recent land use change in the Western Corn Belt threatens grasslands and wetlands. Proceedings of National Academy of Sciences of the United States of America 110 (10), pp. 4134-4139

Wu, JunJie, David Zilberman, and Bruce A. Babcock. 2001. “Environmental and Distributional Impacts of Conservation Targeting Strategies.” Journal of Environmental Economics and Management 41 (3): 333–50.

Table 1. Example 1 (the Four-tract Example): Specifications and Results

	Tract A	**Tract B**	**Tract C**	**Tract D**
Environmental benefit per period when unconverted (b_i)	0.6979	0.4133	0.2100	0.3544
Total environmental benefit if eased (i.e., $V_{i,t}^e$ in eqn. (1)):	13.9583	8.2667	4.200	7.0875
Conversion probability (spatial spillover effect ignored):	0.3	0.6	0.5	0.8
Total environmental benefit secured by easement (i.e., additionality, $\Delta V_{i,t}$ in eqn. (3)):	12.5	8	4	7
Neighbor of:	Tracts B and C	Tracts A and C	Tracts A and B	None
Conversion probability (spatial spillover considered)[a]:	$\begin{cases} 0.3 & \text{if } (B^1, C^1) \\ 0.4 & \text{if } (B^1, C^0) \\ 0.6 & \text{if } (B^0, C^1) \\ 0.7 & \text{if } (B^0, C^0) \end{cases}$	$\begin{cases} 0.6 & \text{if } (A^1, C^1) \\ 0.65 & \text{if } (A^1, C^0) \\ 0.7 & \text{if } (A^0, C^1) \\ 0.8 & \text{if } (A^0, C^0) \end{cases}$	$\begin{cases} 0.5 & \text{if } (A^1, B^1) \\ 0.6 & \text{if } (A^1, B^0) \\ 0.55 & \text{if } (A^0, B^1) \\ 0.65 & \text{if } (A^0, B^0) \end{cases}$	0.8
Expected subjective environmental benefits if choose corresponding tract (Basic targeting: additionality and spatial spillover ignored)[b]:	**19.4912**	19.4239	15.8976	19.3059
Expected subjective environmental benefits if choose corresponding tract (Additionality targeting: spatial spillover ignored)[b]:	17.8592	18.1810	14.7978	**18.2278**
Expected subjective environmental benefits if choose corresponding tract (Additionality with spatial spillover targeting: spatial spillover considered)[b]:	17.8231	**18.0966**	14.6638	17.9879

Notes: [a] Here the superscript 1 indicates that the tract is under grass and superscript 0 indicates that tract is not under grass (i.e., converted). For simplicity we assume that the conversion is contemporaneously uncorrelated among tracts and is only affected by the land-use status of neighboring tracts in the previous period. Therefore, for instance, "0.3 if (B^1, C^1)" in the column of Tract A should be interpreted as follows: if both tracts B and C are under grass in period t then the conversion probability of tract A in period $t+1$ is 0.3. [b] The underlined and bold numbers are the largest among the four in the same row. The discount factor, β, is assumed to be 0.95 in this example.

Table 2. Expected environmental benefit additionality under various environmental benefit targeting and optimization algorithms in Example 1

	Basic targeting	Additionality targeting	Additionality with spatial spillover targeting
Land tract choice in period one	A	D	B
Expected environmental benefit additionality	17.8231	17.9832	18.0966

	Naïve myopic algorithm
Land tract choice in period one	A
Expected environmental benefit additionality	17.7911

	Informed myopic algorithm
Land tract choice in period one	D
Expected environmental benefit additionality	17.9832

	Spatially informed myopic algorithm
Land tract choice in period one	D
Expected environmental benefit additionality	17.9879

Notes: The numbers highlighted by the same color are identical. The basic targeting strategy maximizes the expected environmental benefits provided by land under easements. It ignores the additionality and spatial spillover effect. The additionality targeting maximizes environmental benefit additionality secured by easement acquisition. It ignores spatial spillover effect. The additionality with spatial spillover targeting maximizes environmental benefit additionality secured by easement acquisition while accounting for the spatial spillover effect of grassland tract conversion. Under the naïve myopic algorithm, the easement manager selects the tract with the largest targeted environmental benefits among the available grassland tracts in a period, regardless of the tract's conversion probability. Under the informed myopic algorithm, the easement manager selects the tract with the largest product of targeted environmental benefit and conversion probability among the available grassland tracts in a period. However, spatial spillover effect of conversion is ignored. Under the spatially informed myopic algorithm, the easement manager selects the tract with the largest product of targeted environmental benefit and conversion probability among the available grassland tracts in a period, considering the spatial spillover effect.

Table 3. Characteristics of the Six Grassland Tracts in Example 2

	Tract a	**Tract b**	**Tract c**	**Tract d**	**Tract e**	**Tract f**
Duck pairs per acre when unconverted	6.58	6.57	6.87	6.45	4.00	3.59
Tract size (acres)	5.78	8.45	14.23	8.67	5.12	6.45
Duck pairs on a tract (pairs)	38	56	98	56	20	23
Five-year conversion probability (spatial spillover effect ignored, point estimates):	9.55E-9	4.34E-6	2.82E-6	5.44E-3	3.98E-4	9.48E-7
Total environmental benefits if eased (i.e., $V_{i,t}^{e}$ in eqn. (1)):	761	1,111	1,957	1,118	409	463
Total environmental benefit secured by easement (i.e., additionality, $\Delta V_{i,t}$ in eqn. (3))[a]:	2.76E-5	1.83E-2	2.10E-2	2.27E1	6.18E-1	1.67E-3
Neighbor of:	Tracts b, c, d	Tracts a, c, d	Tracts a, b, d	Tracts a, b, c	Tract f	Tract e
Five-year Conversion probability (spatial spillover considered, point estimates)[b]:	$\begin{cases} 9.55\text{E}-9 \text{ if } (b^1,c^1,d^1) \\ 3.36\text{E}-8 \text{ if } (b^1,c^0,d^1) \\ 1.25\text{E}-8 \text{ if } (b^0,c^1,d^1) \\ 4.41\text{E}-8 \text{ if } (b^0,c^0,d^1) \\ 2.06\text{E}-8 \text{ if } (b^1,c^1,d^0) \\ 7.23\text{E}-8 \text{ if } (b^1,c^0,d^0) \\ 2.70\text{E}-8 \text{ if } (b^0,c^1,d^0) \\ 9.49\text{E}-8 \text{ if } (b^0,c^0,d^0) \end{cases}$	$\begin{cases} 4.34\text{E}-6 \text{ if } (a^1,c^1,d^1) \\ 1.41\text{E}-5 \text{ if } (a^1,c^0,d^1) \\ 5.48\text{E}-6 \text{ if } (a^0,c^1,d^1) \\ 1.78\text{E}-5 \text{ if } (a^0,c^0,d^1) \\ 5.11\text{E}-6 \text{ if } (a^1,c^1,d^0) \\ 1.66\text{E}-5 \text{ if } (a^1,c^0,d^0) \\ 6.45\text{E}-6 \text{ if } (a^0,c^1,d^0) \\ 2.10\text{E}-5 \text{ if } (a^0,c^0,d^0) \end{cases}$	$\begin{cases} 2.82\text{E}-6 \text{ if } (a^1,b^1,d^1) \\ 4.33\text{E}-6 \text{ if } (a^0,b^1,d^1) \\ 5.28\text{E}-6 \text{ if } (a^1,b^0,d^1) \\ 8.11\text{E}-6 \text{ if } (a^0,b^0,d^1) \\ 5.37\text{E}-6 \text{ if } (a^1,b^1,d^0) \\ 8.25\text{E}-6 \text{ if } (a^0,b^1,d^0) \\ 1.01\text{E}-5 \text{ if } (a^1,b^0,d^0) \\ 1.54\text{E}-5 \text{ if } (a^0,b^0,d^0) \end{cases}$	$\begin{cases} 5.44\text{E}-3 \text{ if } (a^1,b^1,c^1) \\ 6.84\text{E}-3 \text{ if } (a^1,b^0,c^1) \\ 8.62\text{E}-3 \text{ if } (a^0,b^1,c^1) \\ 1.08\text{E}-2 \text{ if } (a^0,b^0,c^1) \\ 1.64\text{E}-2 \text{ if } (a^1,b^1,c^0) \\ 2.01\text{E}-2 \text{ if } (a^1,b^0,c^0) \\ 2.45\text{E}-2 \text{ if } (a^0,b^1,c^0) \\ 2.94\text{E}-2 \text{ if } (a^0,b^0,c^0) \end{cases}$	$\begin{cases} 3.98\text{E}-4 \text{ if } (f^1) \\ 6.90\text{E}-4 \text{ if } (f^0) \end{cases}$	$\begin{cases} 9.48\text{E}-7 \text{ if } (e^1) \\ 1.34\text{E}-6 \text{ if } (e^0) \end{cases}$

Notes: [a] Calculated based on conversion probability without considering spatial spillover effect. [b] Here the superscript 1 indicates that the tract is under grass and superscript 0 indicates that tract is not under grass (i.e., converted). For simplicity we assume that the conversion is contemporaneously uncorrelated among tracts and is only affected by the land-use status of neighboring tracts in the previous period. For instance, "9.55E-9 if (b^1,c^1,d^1)" in the column of Tract a should be interpreted as follows: if tracts b, c, and d are under grass in period *t* then the conversion probability of tract A in period $t+1$ is 9.55E-9.

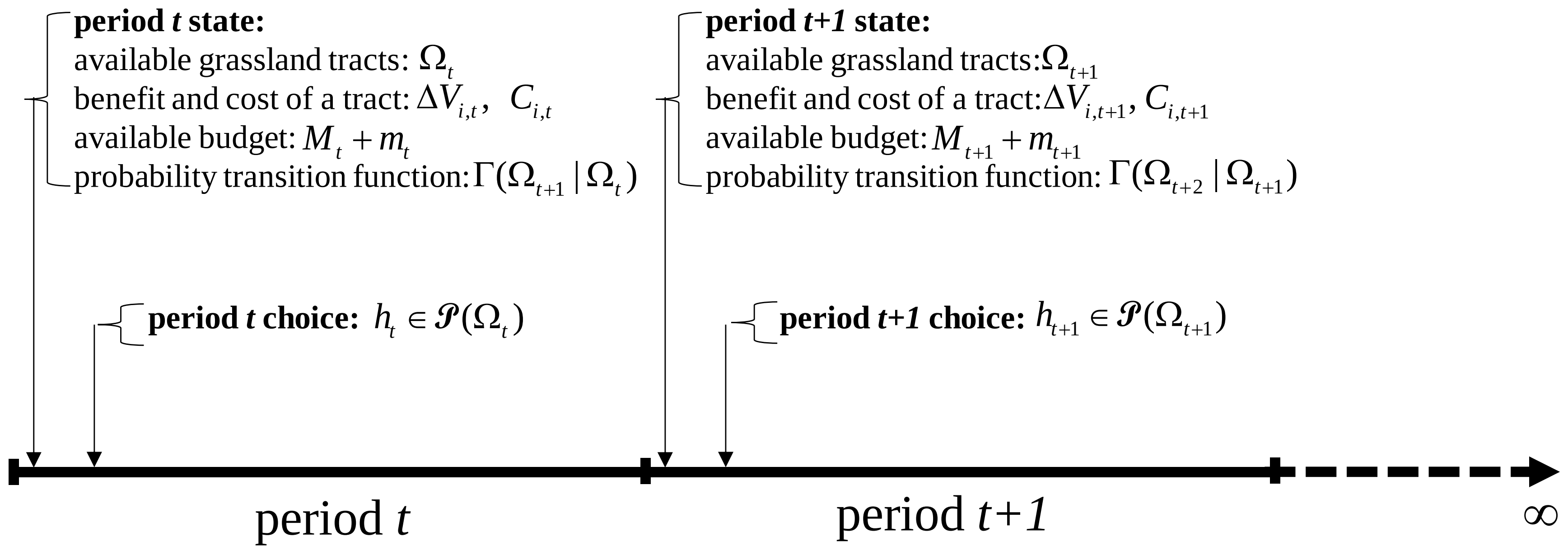

Figure 1. Timeline of the model

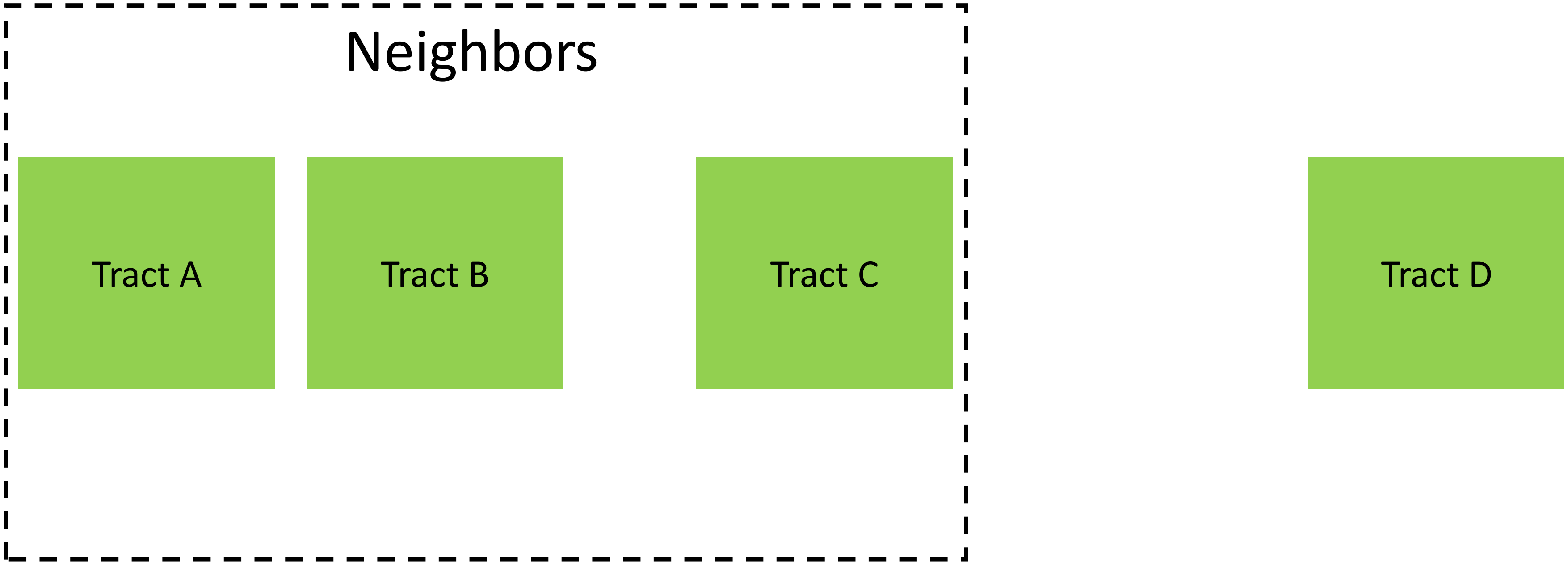

Figure 2. Location of grassland tracts in the four-tract example

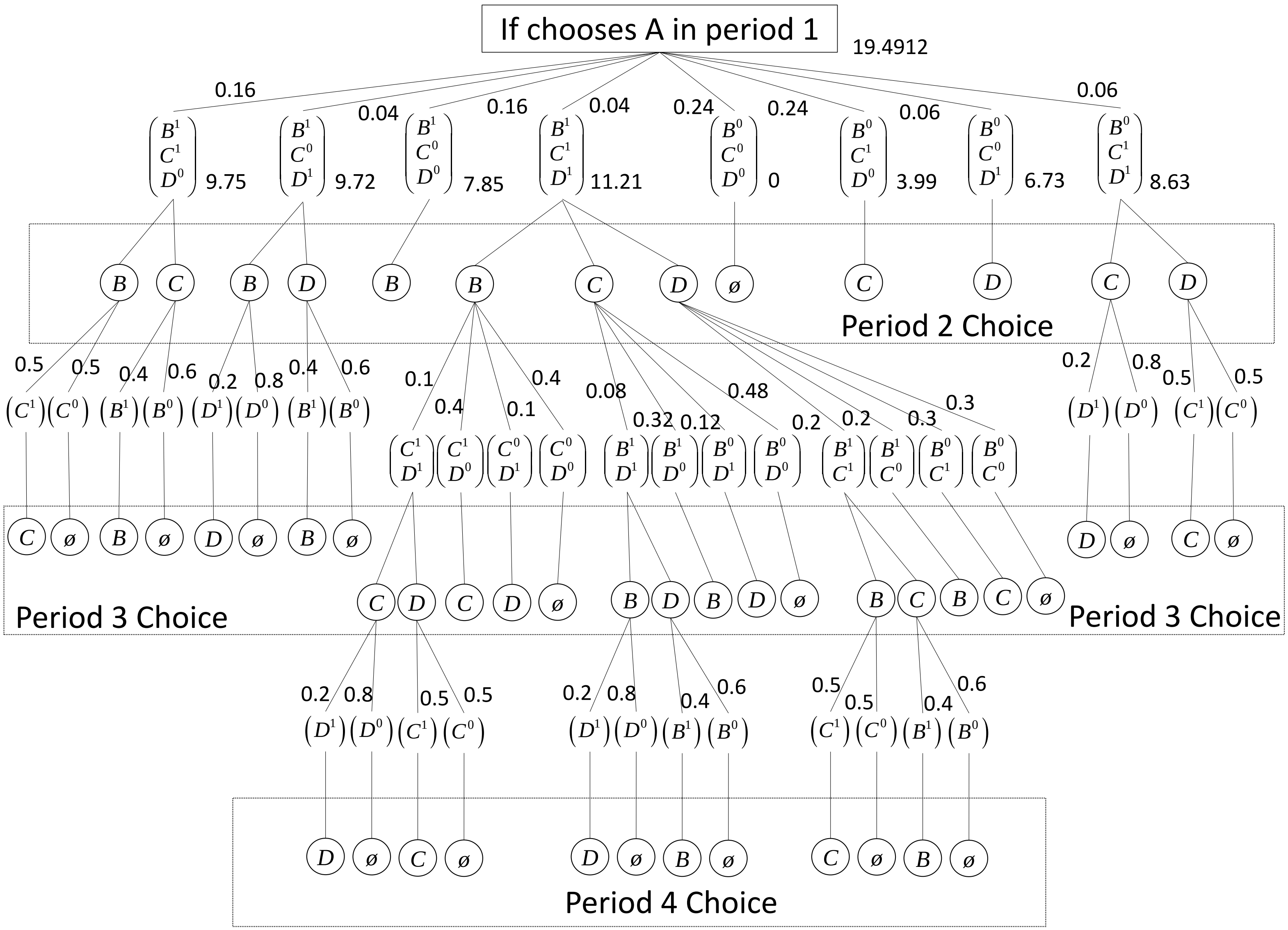

Figure 3. The decision tree when Tract A is chosen in period one (no additionality, no spatial spillover)

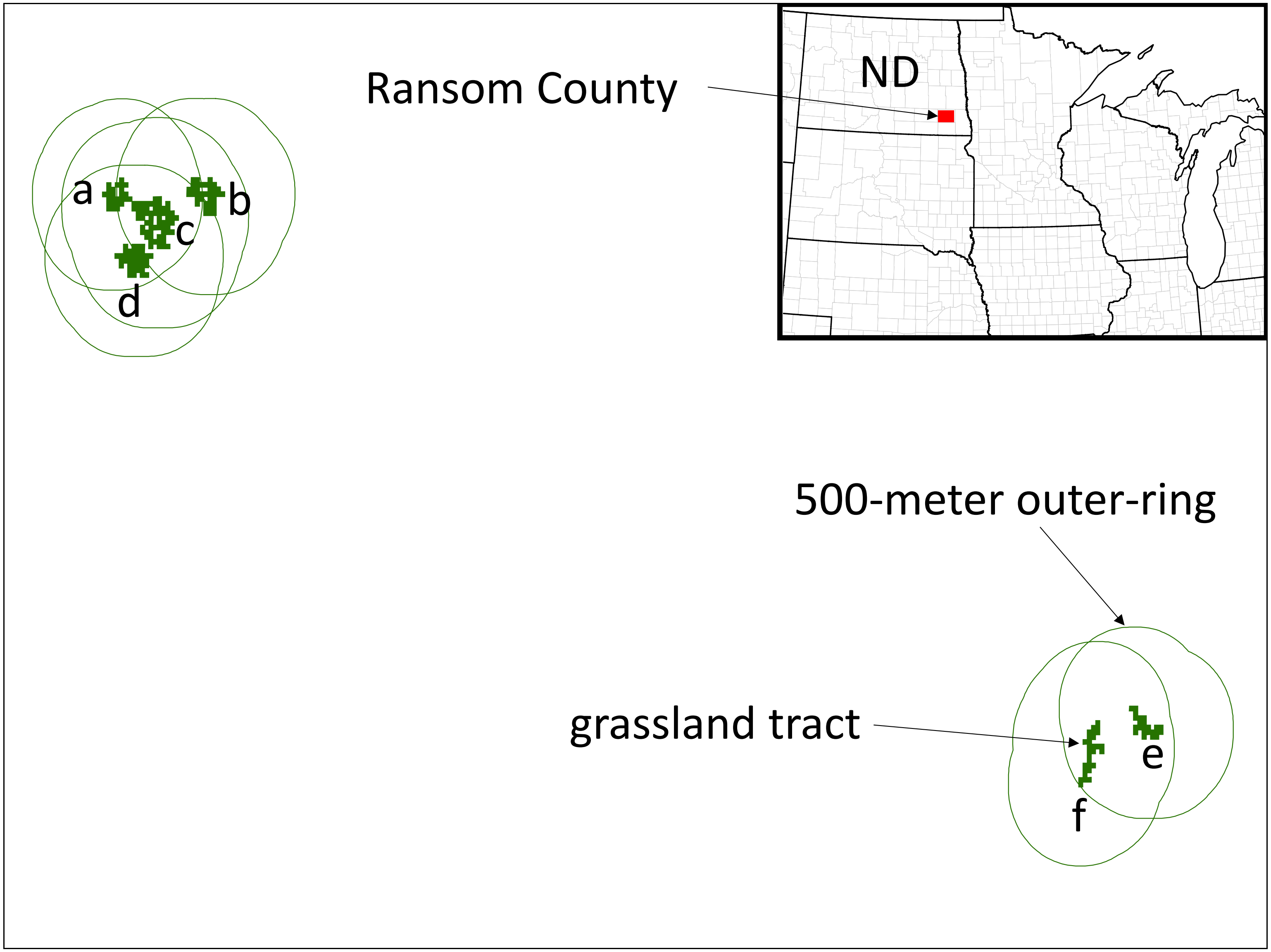

Figure 4. Six Grassland Tracts in Ransom County, North Dakota, and Their 500-meter Out-rings

Supporting Information for "Grassland Easement Acquisition: Conversion Hazard Rate, Additionality, and Spatial Spillover"

(to be available online only)

Item A. Deriving the easement cost

In this item we display detailed steps to obtain equation (4) in the main text.

$$\begin{aligned}
&C_{i,t} = C_{i,t}(\pi_i^c, \pi_i^g, p_i, \theta_i; \beta) \\
&= p_{i,t}[(\sum_{s=t}^{+\infty} \beta^{s-t} \pi_{i,s}^c) - \theta_i] + q_{i,t}\pi_{i,t}^g + \\
&\qquad q_{i,t}\beta\Big[p_{i,t+1}[(\sum_{s=t+1}^{+\infty} \beta^{s-(t+1)} \pi_{i,s}^c) - \theta_i] + q_{i,t+1}\pi_{i,t+1}^g + \\
&\qquad\qquad q_{i,t+1}\beta\Big[p_{i,t+2}[(\sum_{s=t+2}^{+\infty} \beta^{s-(t+2)} \pi_{i,s}^c) - \theta_i] + q_{i,t+2}\pi_{i,t+2}^g + \\
&\qquad\qquad\qquad \cdots]\Big] - \sum_{s=t}^{+\infty} \beta^{s-t} \pi_{i,s}^g \\
&= q_{i,t}\pi_{i,t}^g + \beta q_{i,t} q_{i,t+1} \pi_{i,t+1}^g + \beta^2 q_{i,t} q_{i,t+1} q_{i,t+2} \pi_{i,t+2}^g + \cdots + \\
&\quad p_{i,t} \sum_{s=t}^{+\infty} \beta^{s-t} \pi_{i,s}^c + \beta q_{i,t} p_{i,t+1} \sum_{s=t+1}^{+\infty} \beta^{s-(t+1)} \pi_{i,s}^c + \beta^2 q_{i,t} q_{i,t+1} p_{i,t+2} \sum_{s=t+2}^{+\infty} \beta^{s-(t+2)} \pi_{i,j}^c + \cdots - \\
&\quad (p_{i,t} + \beta q_{i,t} p_{i,t+1} + \beta^2 q_{i,t} q_{i,t+1} p_{i,t+2} + \cdots)\theta_i - \sum_{s=t}^{+\infty} \beta^{s-t} \pi_{i,s}^g \\
&= \sum_{s=t}^{+\infty} [\beta^{s-t} (\prod_{\tau=t}^{s} q_{i,\tau}) \pi_{i,s}^g] + \sum_{s=t}^{+\infty} [(\prod_{\tau=t}^{s-1} q_{i,\tau}) p_{i,s} \sum_{j=s}^{+\infty} \beta^{j-t} \pi_{i,s}^c] - \\
&\quad \theta_i \sum_{s=t}^{+\infty} [\beta^{s-t} (\prod_{\tau=t}^{s-1} q_{i,\tau}) p_{i,s}] - \sum_{s=t}^{+\infty} \beta^{s-t} \pi_{i,s}^g \\
&= \sum_{s=t}^{+\infty} [\beta^{s-t} (\prod_{\tau=t}^{s} q_{i,\tau}) \pi_{i,s}^g] + \sum_{s=t}^{+\infty} [(\prod_{\tau=t}^{s-1} q_{i,\tau}) p_{i,s} (\sum_{j=s}^{+\infty} \beta^{j-s} \pi_{i,s}^c - \beta^{s-t}\theta_i)] - \sum_{s=t}^{+\infty} \beta^{s-t} \pi_{i,s}^g \\
&= \sum_{s=t}^{+\infty} [\beta^{s-t} (1 - \prod_{\tau=t}^{s} q_{i,\tau})(\pi_{i,s}^c - \pi_{i,s}^g)] - \theta_i \sum_{s=t}^{+\infty} [\beta^{s-t} (\prod_{\tau=t}^{s-1} q_{i,\tau}) p_{i,s}],
\end{aligned}$$

where $\prod_{\tau=t}^{t-1} q_{i,\tau}$ is defined to be equal to 1.

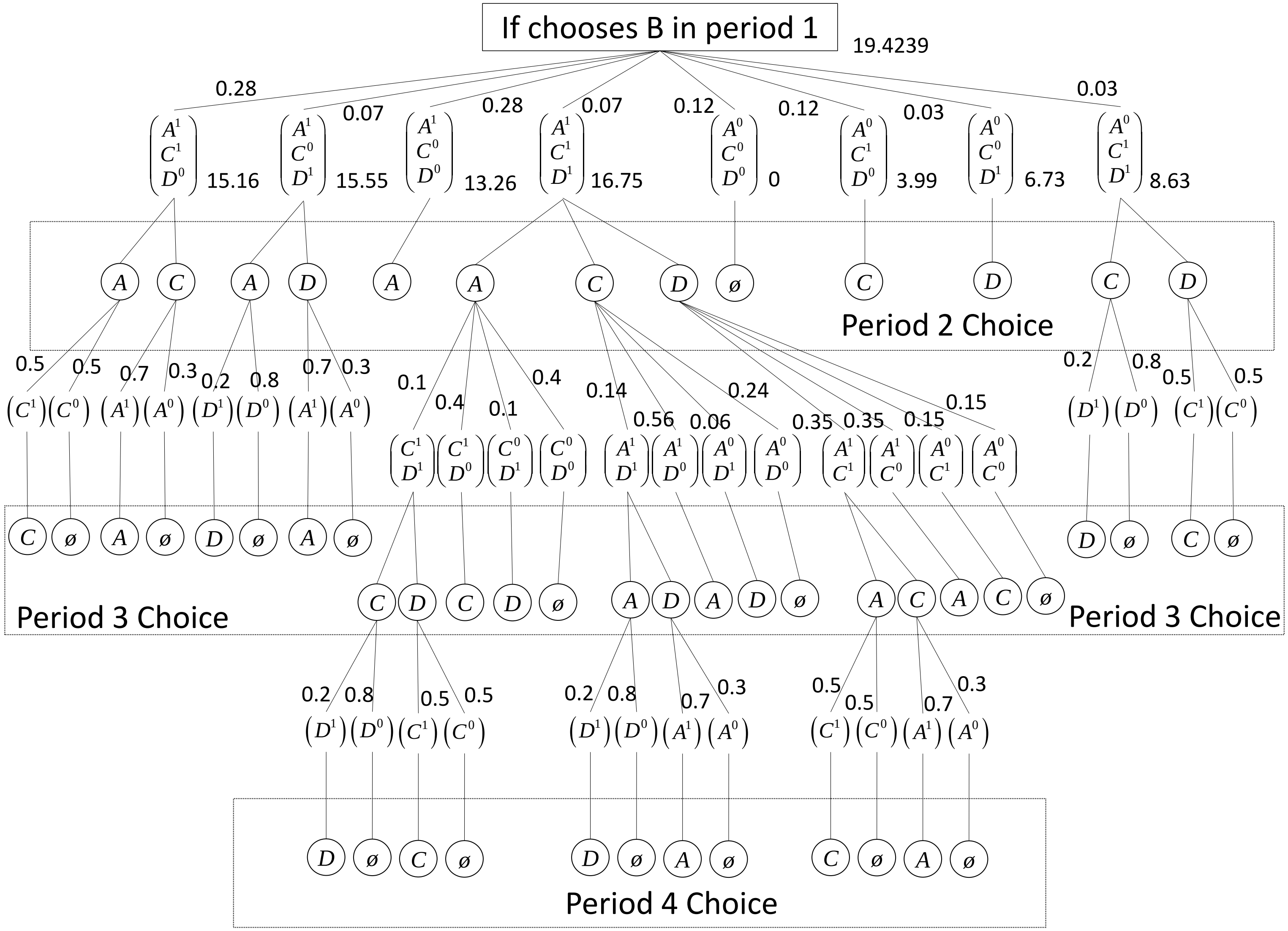

Figure SI-1. The decision tree when Tract B is chosen in period one (no additionality, no spatial spillover)

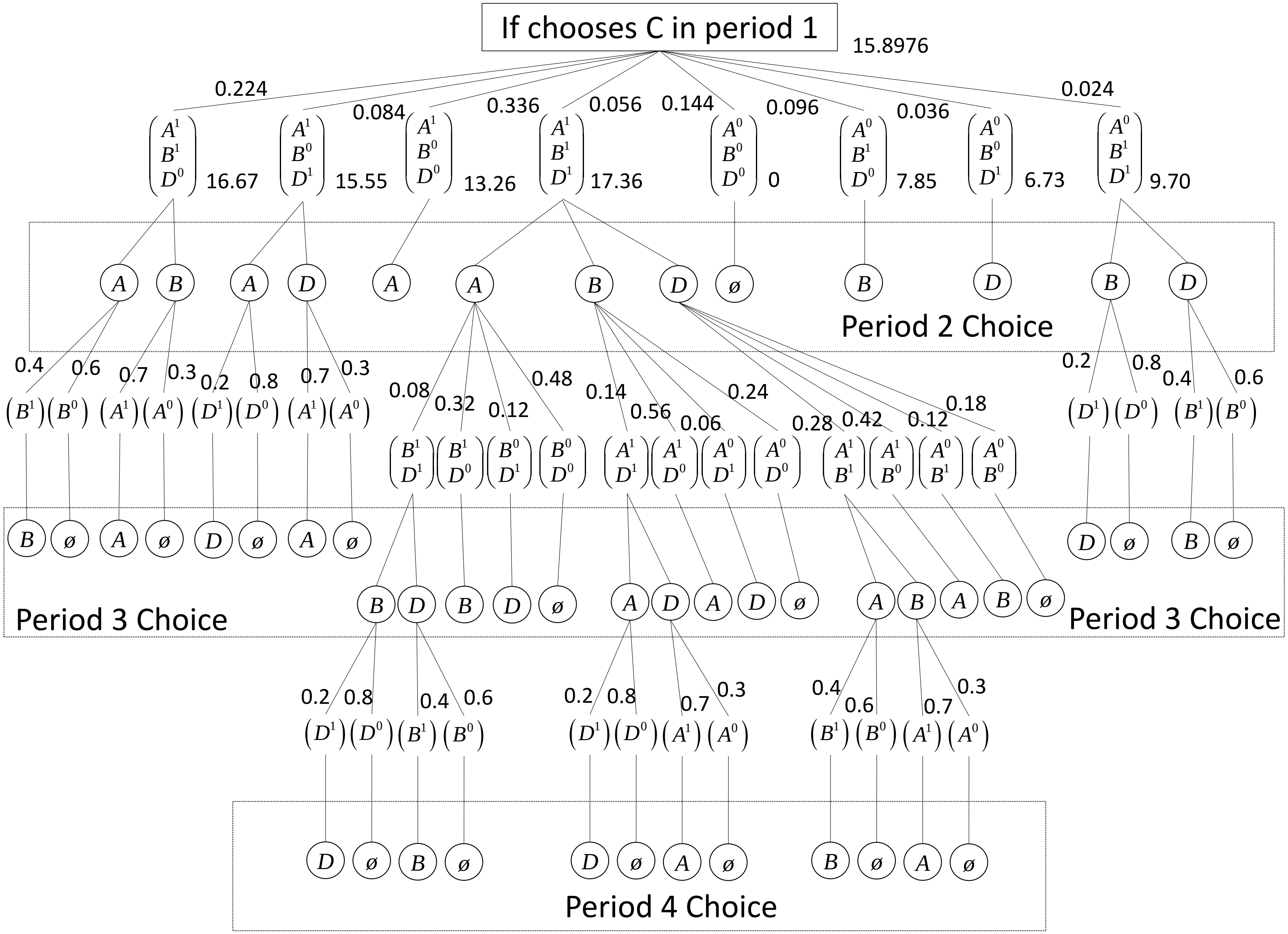

Figure SI-2. The decision tree when Tract C is chosen in period one (no additionality, no spatial spillover)

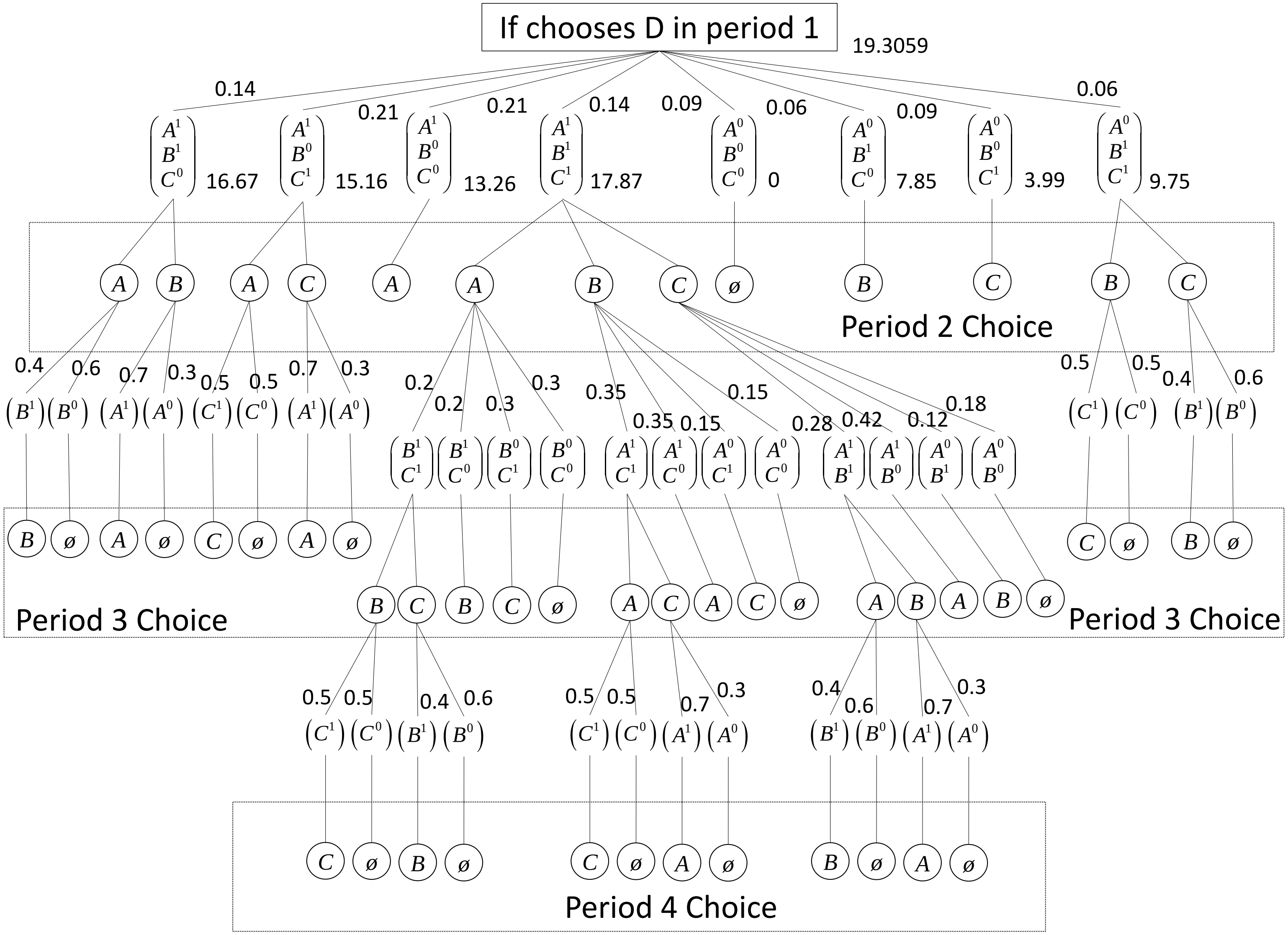

Figure SI-3. The decision tree when Tract D is chosen in period one (no additionality, no spatial spillover)

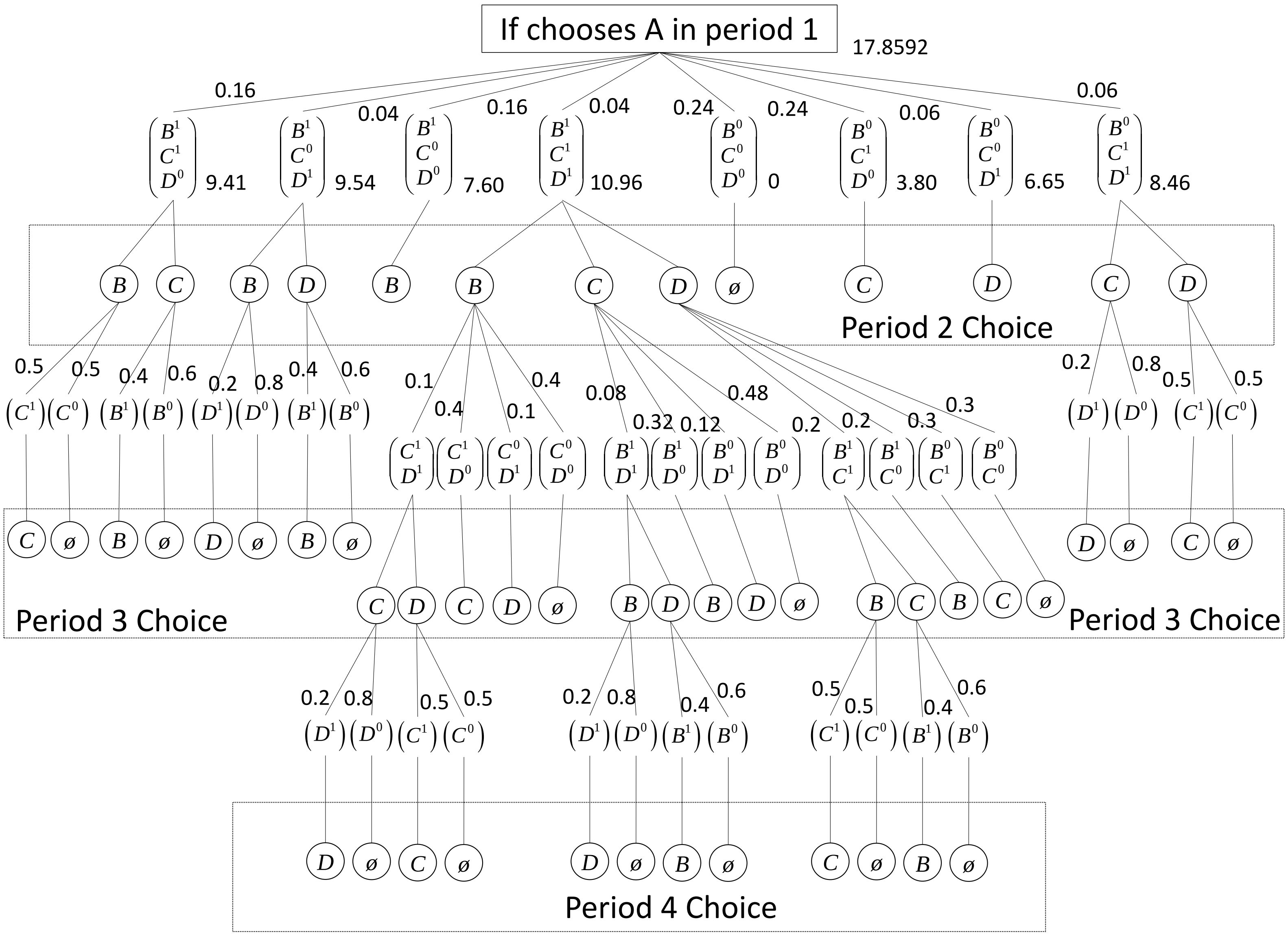

Figure SI-4. The decision tree when Tract A is chosen in period one (additionality, no spatial spillover)

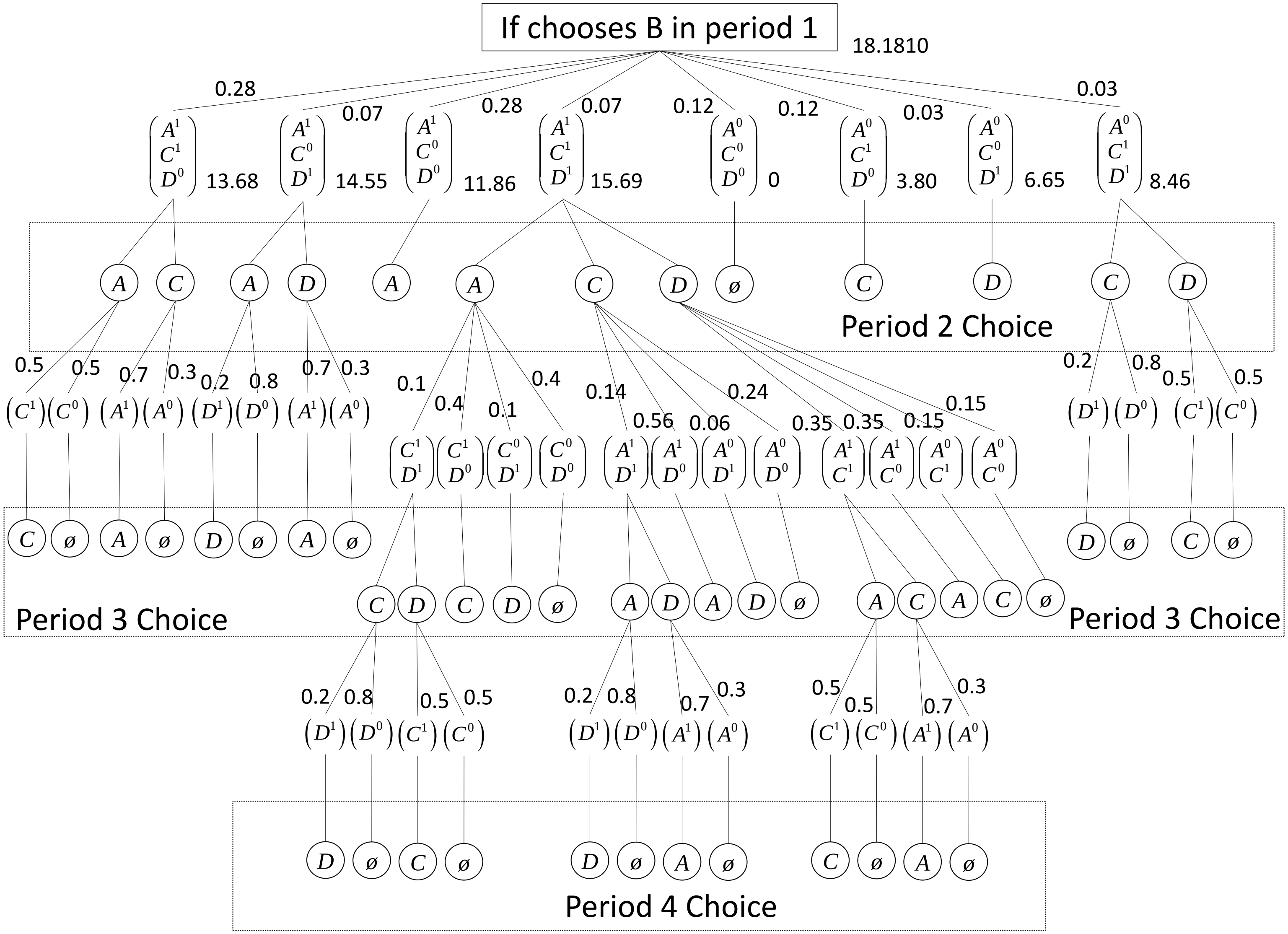

Figure SI-5. The decision tree when Tract B is chosen in period one (additionality, no spatial spillover)

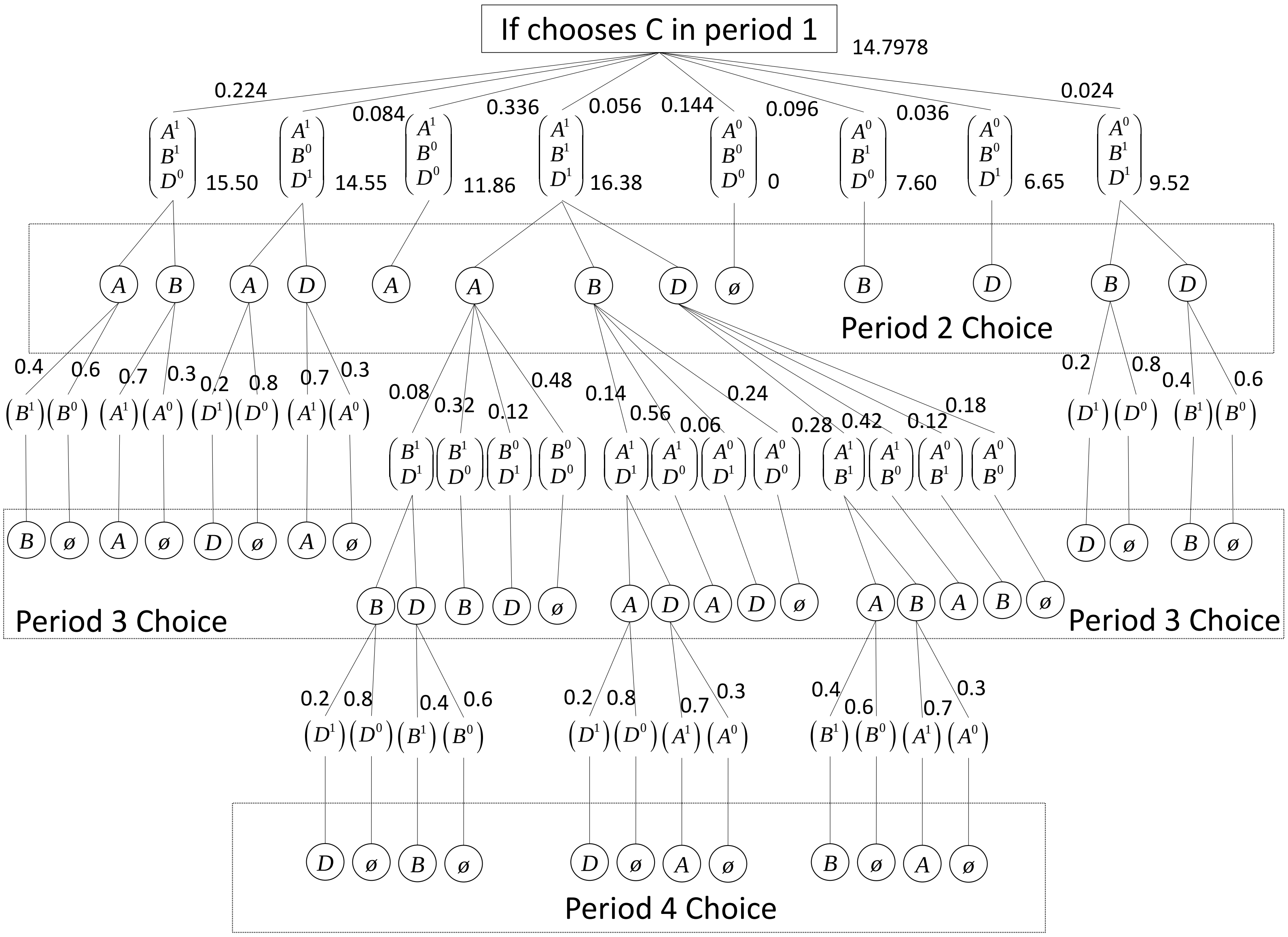

Figure SI-6. The decision tree when Tract C is chosen in period one (additionality, no spatial spillover)

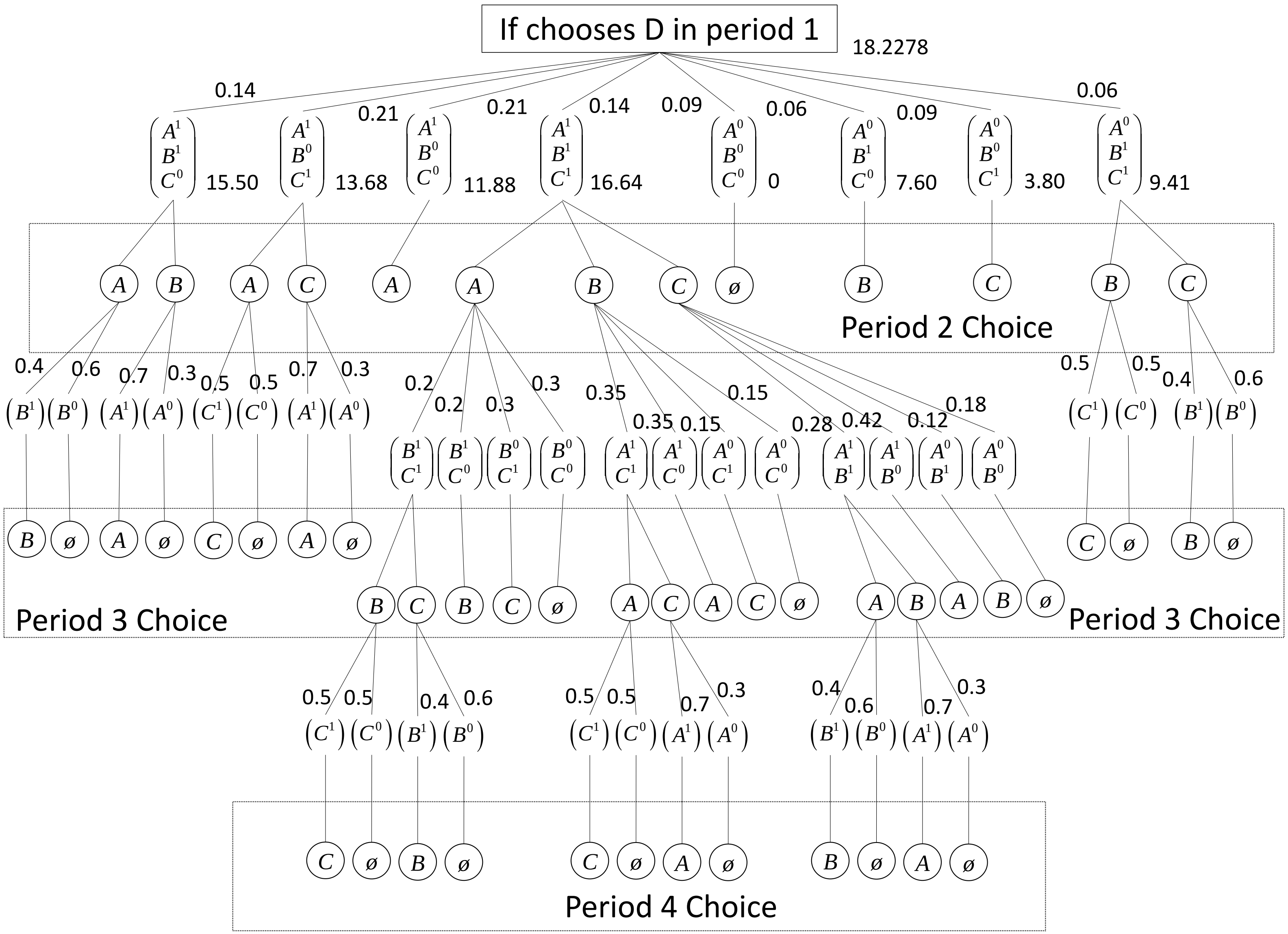

Figure SI-7. The decision tree when Tract D is chosen in period one (additionality, no spatial spillover)

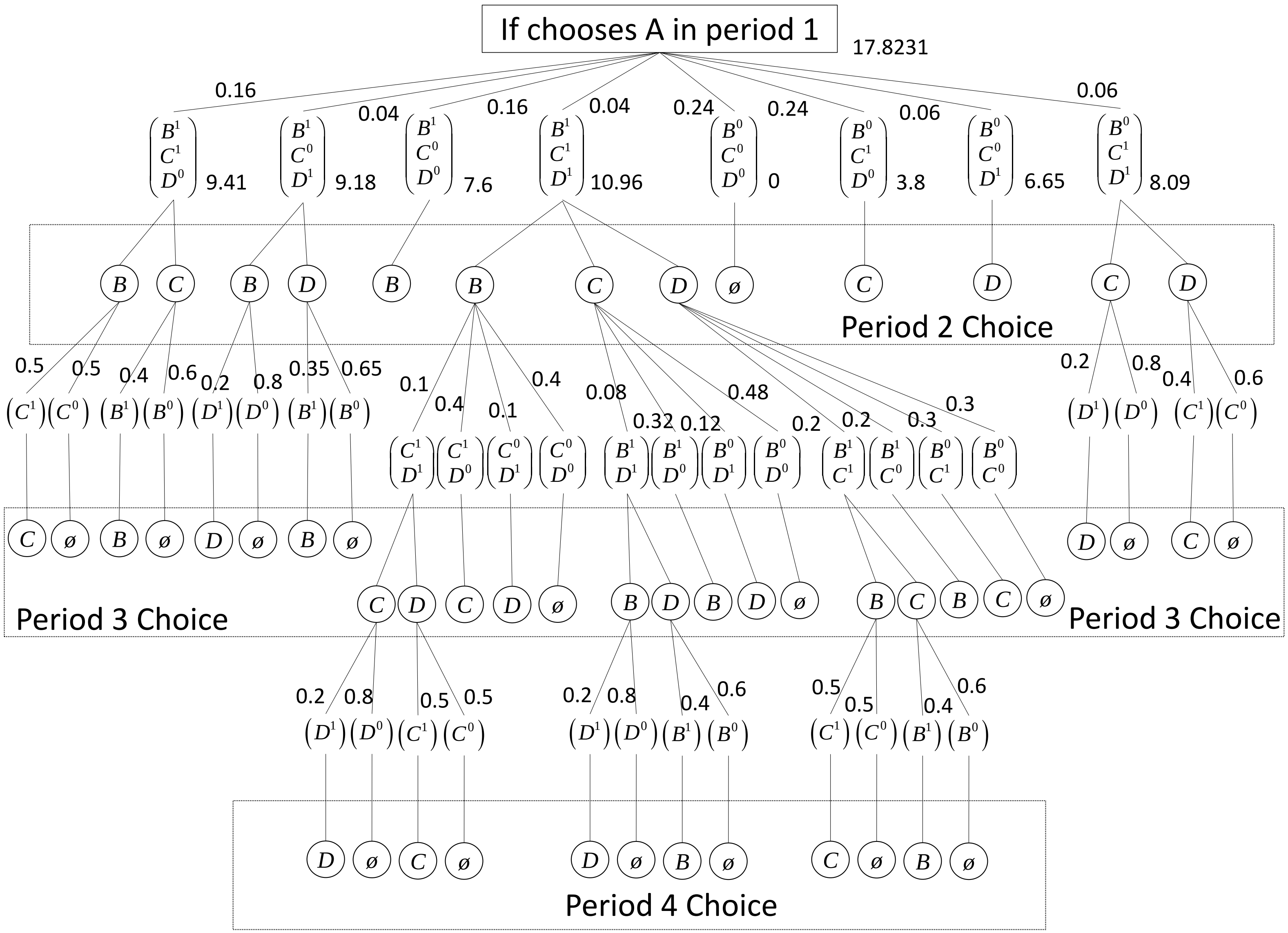

Figure SI-8. The decision tree when Tract A is chosen in period one (additionality and spatial spillover)

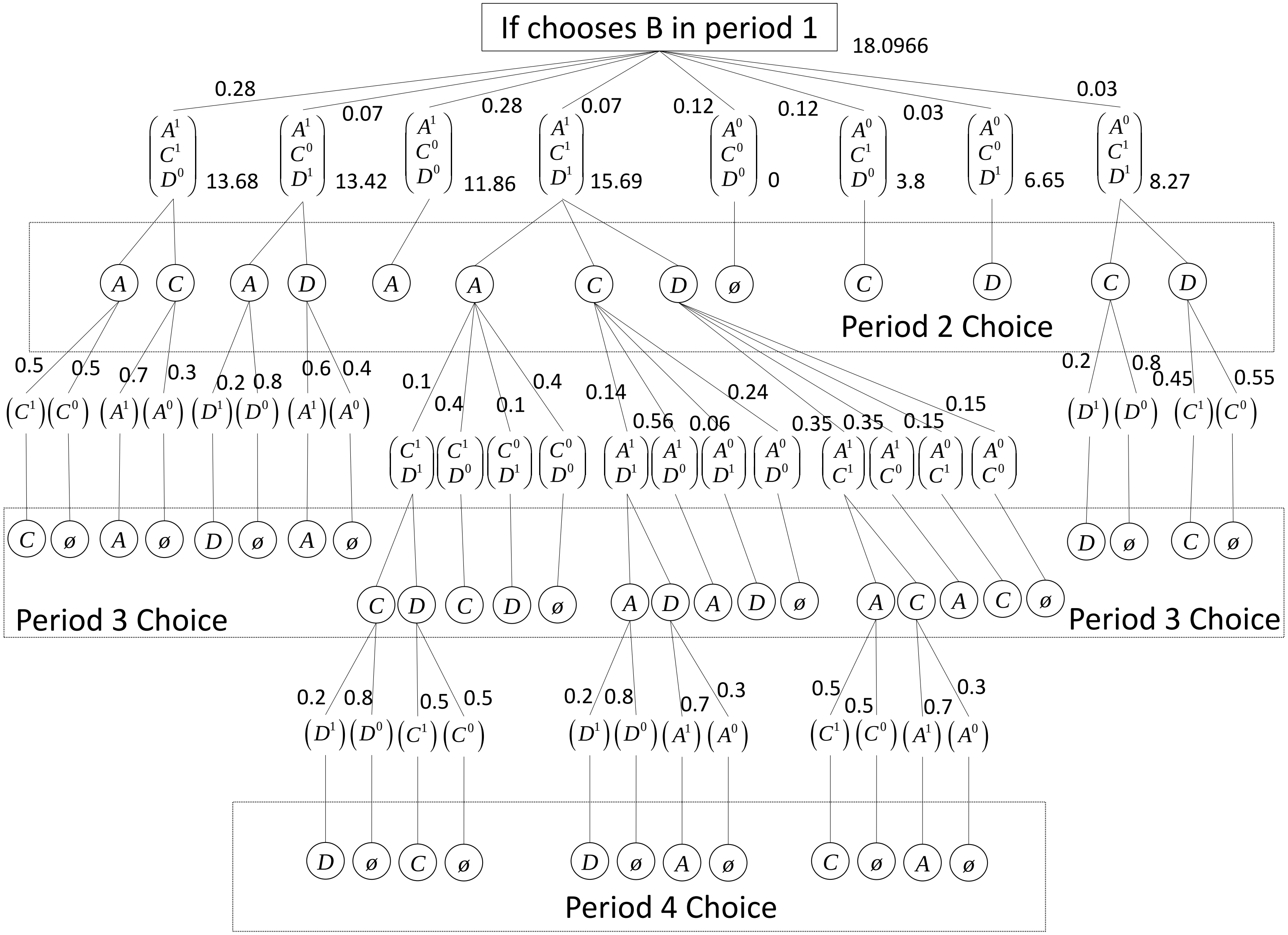

Figure SI-9. The decision tree when Tract B is chosen in period one (additionality and spatial spillover)

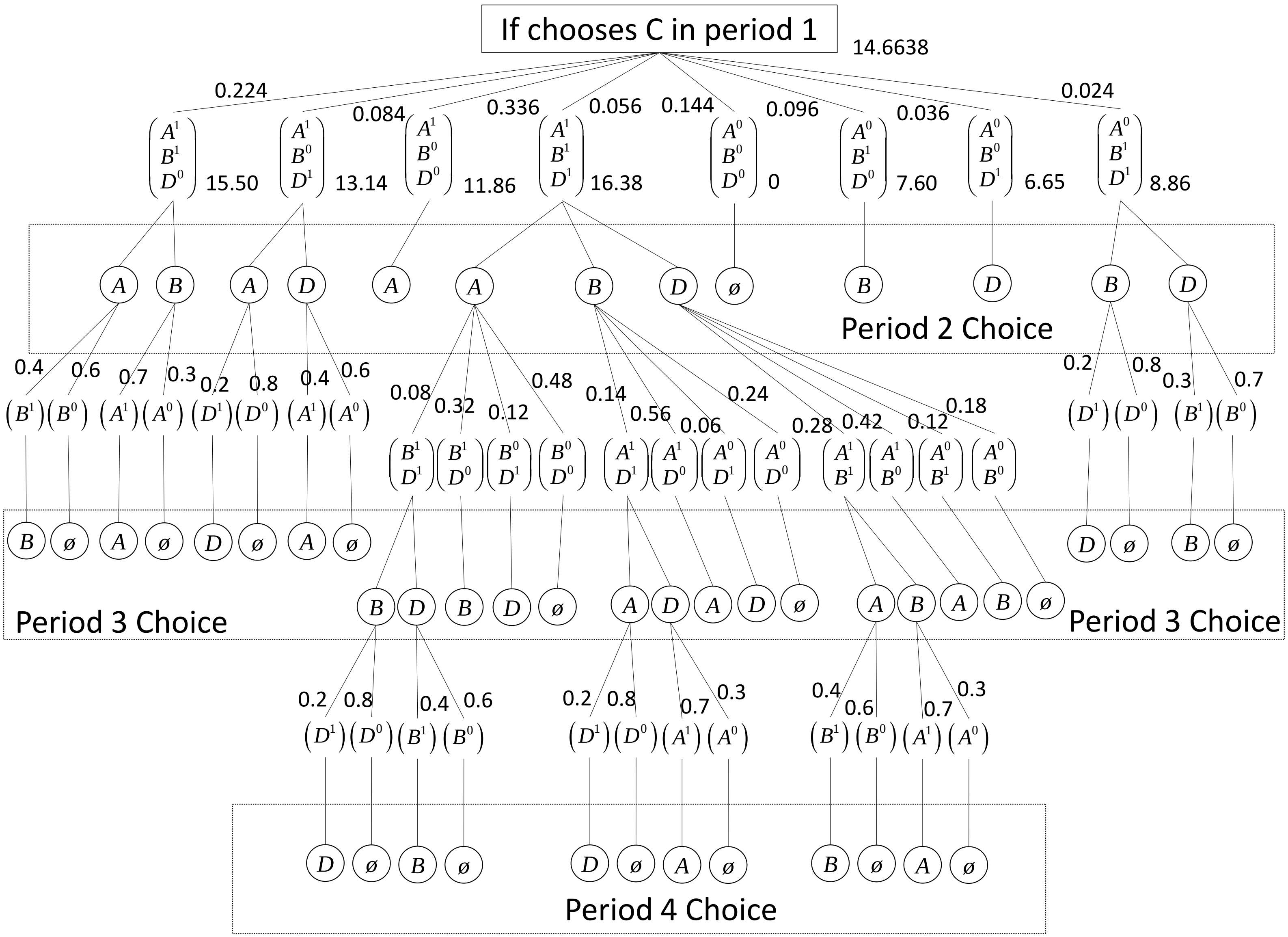

Figure SI-10. The decision tree when Tract C is chosen in period one (additionality and spatial spillover)

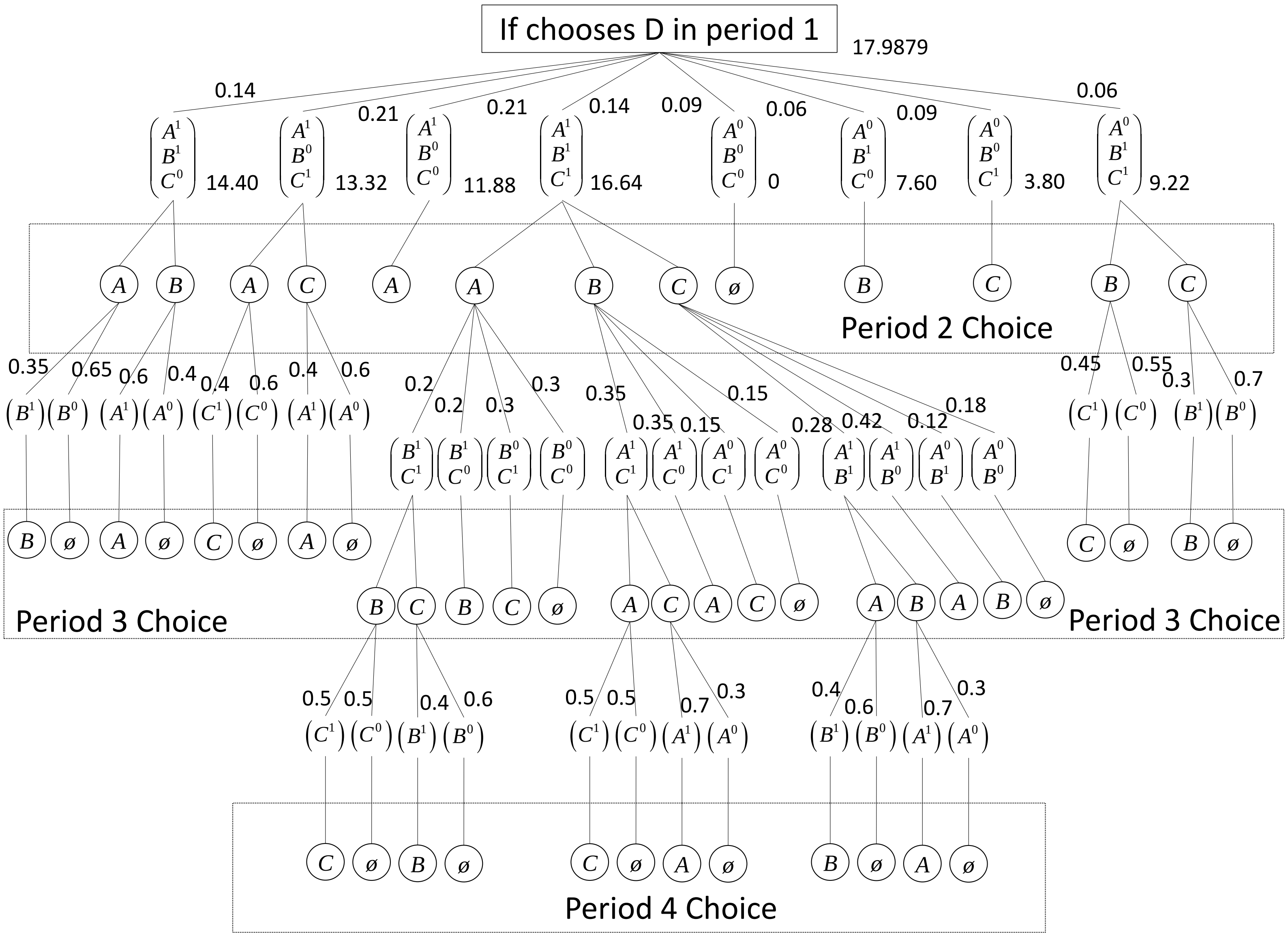

Figure SI-11. The decision tree when Tract D is chosen in period one (additionality and spatial spillover)