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Methods for assessing spillover effects between concurrent green initiatives ☆

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ABSTRACT

This research presents the methods that are used to examine the dynamics and potential spillover effects of various global environmental conservation programs. We specifically show the data and models that we use to analyze the interactions and mutual influences between the U.S.'s Conservation Reserve Program (CRP) and Environmental Quality Incentives Program (EQIP), as well as those between China's Grain-to-Green Program (GTGP) and Forest Ecological Benefit Compensation (FEBC). Additionally, this study illustrates information about global initiatives, their interconnected impacts, and the associated policy strategies for environmental conservation. By utilizing multivariate regression, logistic regression, eigenvector spatial filtering, and scenario modeling, the research aims to understand the collective influence of these initiatives on broader environmental objectives. The findings of this study provide valuable insights for improving conservation policy designs and effectiveness.

- Multivariate and logistic regression analyses to dissect global environmental conservation program interactions and mutual influences.
- Eigenvector spatial filtering to address spatial autocorrelation and enhance the accuracy of the model results and our interpretations.
- Scenario modeling to project potential future outcomes and impacts.

Specifications table

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Method details

Green initiatives

With degradation and destruction of nature's various structures and functions, humans are losing essential goods and services from Nature, including water, food, soil, clean air, and biodiversity [9,23]. In response, the United Nations launched the 2030 Sustainable Development Goals to combat this crisis, and among all goals, Goals 14 and 15 aim specially to conserve life below water and on land. In this context, we define green initiatives as programs, funds, payments, policies, or any endeavors that aim to restore, sustain, or improve nature's capacity to benefit human beings. Aside from the examples presented in the main text, other prominent green initiatives include programs for integrated conservation and development projects (ICDP), the so-called payments for environmental (ecosystem) services (PES), and many measures that aim to preserve nature and its services vital to humans.

Generally speaking, green initiatives involve endeavors to protect certain physical environmental structures and/or functions. Green initiatives may take the form of subsidies, area-based conservation measures comprised of protected areas, tax exemptions, and "other effective area-based conservation measures" (OECMs; [16,22]). Among such initiatives, one kind of target is to conserve the ozone layer in Earth's stratosphere, assuring that life on the Earth is not jeopardized by Sun's ultraviolet radiation [19]. Similarly, glaciers, gushers, volcano sites, and other geological features and processes that provide essential services to humans may also be conserved. Green initiatives are those that aim to conserve environmental structure or processes that possess intrinsic, cultural, aesthetic, scientific, or educational value ([1], pp. 1–2).

Within the context of green initiatives, it is important to consider 'spillover effects.' These effects occur when one initiative unintentionally influences another either in the same geographic area or involving same recipients, positively or negatively. They can impact policies, behaviors, and environmental outcomes, emphasizing the interconnectedness of conservation efforts. Our research focuses on identifying and evaluating these spillover effects within concurrent green initiatives, aiming to enhance positive impacts and mitigate negative ones. Understanding these dynamics is essential for maximizing the effectiveness of green initiatives and ensuring they work together towards sustainable development and nature conservation. Recognizing spillover effects highlights the importance of coordinating the design, implementation, and assessment of green initiatives to not only meet specific goals but also contribute positively to the broader environmental and socio-economic wellbeing.

Concurrent green initiatives in the USA

Concurrent green initiatives: CRP and EQIP

We first considered two major concurrent green initiatives in the United States: The *Conservation Reserve Program* (CRP) and the Environmental Quality Incentives Program (EQIP). CRP was authorized by the 1985 Farm Security Act, aiming to retire farmland in environmentally sensitive areas (mostly highly erodible places) from agricultural activities for 10 to 15 years [29]. CRP, operated by the U.S. Department of Agriculture, dominated the USA agri-environmental policy before 2002. CRP funds were used to financially support retired farmers, i.e., those who live on farms but do not depend on farming; CRP also aims to support low-income farmers [6]. EQIP, administered by Natural Resources Conservation Service, provides incentive payments to producers so that they can adopt environmentally friendly practices on their registered farmlands [27]. At the national level, CRP enrollment has steadily declined since 2007 such that the 2018 CRP enrollment (22 million acres) was much below 27 million acres, the cap specified in the 2018 Farm Bill [39]. According to the Bill, CRP and EQIP are concurrent green programs, where eligible landowners can participate in or switch between the two programs [12]. Moreover, a literature review suggested potential spillover effects between them, but no systematic studies have been explicitly devoted to the nature and impacts of such effects ([1], pp. 48–49).

Owing to land scarcity, along with higher pay rate and continued economic return under EQIP [35,38], a large proportion of landowners with land eligible for both programs declined or quit CRP contracts and registered their land for EQIP instead, which happened, e.g., in the Topashaw Canal watershed, Mississippi, U.S. [40]. As EQIP's and CRP's goals of preserving soil, water, and wildlife habitat overlap significantly, many landowners own lands that are eligible for both EQIP and CRP. Given that CRP was started earlier and there was some evidence for EQIP's influence on CRP enrollment [40], we hypothesize that EQIP may (at least partially) account for CRP's decline since 2007.

We collected county-level EQIP and CRP data in 2018, which are comprised of 3106 records (or counties) in the continental U.S [37,38]. We downloaded income data, farmland data, and population data from the relevant governmental agency's websites ([31,34], pp. 2010–2019; [36]). We took a random subset (15 %) of all data records to avoid the negative impacts of spatial autocorrelation in regression coefficients, which resulted in a dataset with 462 counties. For further discussion about minimizing the negative effects of spatial autocorrelation, we refer to [1,5,15].

We then performed multivariate linear regression controlling several socio-economic variables. The Sustainable Livelihoods Framework indicates that a particular entity's human, social, natural, physical, and financial capitals may substantially affect the entity's relevant livelihood decisions [33]. We regressed the area of EQIP enrollment (y; acres) against the area of CRP enrollment (X_1; acres) with control of Farmland_Area (X_2), M_HH_Inc (X_3), and CountyPop (X_4; Table 1 in the main text), which represent total planted farmland (acres; as natural and physical capital), median household income (dollar; as financial capital), and population size (as human and social capital), respectively (Eq. (1)). The multivariate linear regression takes the following form:

$$y = b_0 + b_1 X_1 + \sum_{i=2}^{4} b_i X_i + e \tag{1}$$

where b_o is the intercept, b_1 is the coefficient of X_1 (EQIP_Area), the variable that represents contracted land in EQIP (acres), b_i are the coefficients of the three control variables ($I = 2$, 3, and 4), and y is the dependent variable CRP_Area that represents land enrolled in CRP (acres). The data and relevant code are posted here (http://complexities.org/papers/Green-initiative/) for all the interested audience.

Our regression results show that each acre of land enrolled in EQIP caused a reduction of 0.22 acre in CRP enrolment (Table 1 in the main text). With a standard deviation of 0.0509 and t score of −4.28, the 95 % confidence interval for the coefficient −0.22 goes from −0.12 to −0.32. This detractive spillover effect is reflected in Figure 3B (−22 %).

This offsetting spillover effect from EQIP to CRP may come from several reasons. First, land scarcity may be an influential variable, which is indicated by the positive coefficient of total planted farmland (0.0312 with $p < 0.0001$): there are more enrollments in CRP in counties with more working farmland. Second, land-use competition may be another reason for this offsetting impact. When landowners face two choices of CRP and EQIP, they choose the more profitable one when all other conditions are met. As CRP is a land retirement program, there is no (or very little) agricultural income once the land is enrolled in CRP. On the other hand, EQIP does not require land retirement but pays landowners for more environmentally beneficial practices, implying that agricultural income is still available.

A scenario analysis of spatial reallocation

To explore how leveraging the spillover effects may save costs but still maintain total acres enrolled in CRP and EQIP, we performed a scenario analysis to convert various proportions of EQIP land located at areas eligible for both programs back to CRP. We consider a situation in which some landowners may withdraw part or all of their land from CRP—though more appropriate under this program from an ecological perspective—and enroll such land to EQIP for higher income. We start the scenario analysis with 22.0 and 18.02 million acres of CRP and EQIP enrollment in 2019, respectively. This is the baseline, in which there is no reallocation. According to our finding shown above, each acre of EQIP would cause a reduction of 0.22 acres in CRP. Given this rate, the total of 20.23 million EQIP land (the average from 2009 to 2020) should have reduced CRP enrollment by $20.23 \times 0.22 = 4.5$ million acres. Given that the total CRP area is 22.0 million acres, this reduction of CRP area by 4.5 million acres is equal to 20.45 % of total CRP area in 2019. Then we consider the following six scenarios: zero (no reallocation, baseline), 20 % ($4.5 \times 20\ \% = 0.90$ million acres reallocated from EQIP to CRP), 40 %, 60 %, 80 %, up to 100 % restoration (all 4.5 million acres reallocated from EQIP to CRP). Under such scenarios, the total acres of land enrolled in both programs should remain the same, but the overall payment declines because more land is devoted to CRP with a lower pay rate ($76.36/acre) than to EQIP with a higher pay rate ($137.98/acre). As a result, we find that 1 %~7 % of the total expenses can be saved while still keeping the total acreage of both EQIP and CRP unchanged (detail in Table A1; the Excel file with calculation equations is posted here http://complexities.org/papers/Green-initiative/).

Local evidence of spillover effects

To examine other potential spillover effects (Figure 1 in the main text), we examined publications about the Neuse River Basin in North Carolina, USA [28]. The North Carolina Department of Transportation paid $3.5 million for wetland credits (Policy 1 for wetland) in 2000, which was designed to restore ecosystem services on 438.5 acres of wetlands (Gain 1 for wetland restoration). Of these 438.5 acres, another government agency—the Division of Water Quality—used 69.5 acres to certify nutrient offset credits (Policy 2 for nutrient offset) in 2008. Of these 69.5 certified acres, 46 acres received $698,372 for nutrient offset credits in 2009. This payment of $698,372, temporally stacked on the same 46 acres that had received wetland payment, generated no additional value. Therefore, the payment of $698,372 was considered “double-dipping”, leading to controversy and public pressure. In this context, the North Carolina Division of Water Quality decided to stop this kind of stacked payments in the future. If we assume that the payment rate can be applied to the 438.5 acres of wetland, then 46 acres of wetland should have received $367,160 for wetland credits in 2000.

As pointed out earlier, the same 46 acres of wetland had also received a payment of $698,372 through the nutrient credits program in 2008, such a stacking of payments has amounted to a “double-dipping” rate of 190 % (i.e., 100 % × $698,372 / $367,160). This suggests a big waste in conservation payments. This “double-dipping” effect makes the nutrient payment 100 % waste, which is shown in Figure 3B of the main paper. So, both *Gain-Gain* and *Gain-Policy* spillover effects are observed at the basin, where Gain 1 (protected wetland on 46 acres) should have involved nutrient offset (Gain 2), thus leading to rescindment of Policy 2 (nutrient offset credits).

We also examined a publication related to a *Policy-Policy* spillover effect. At Jordan Lake, North Carolina, two payments can be stacked, but whether such a staking may function well hinges on the relative sizes of the payments [26]. In this case, the primary gain is reducing N loads into Jordan Lake (Gain 1) by all farmers in the watershed, which is mandated by the water quality trading program in North Carolina. In a hypothetical scenario, reduction of P through providing P credits is made possible, which is considered as Gain 2. Yet both gains (Gain 1 and Gain 2) can come out of a single conservation practice: building or extending a vegetated riparian buffer (Behavior 1). When Policy 2′s (for P reduction) payment is greater than 20 % and less than 30 % of Policy 1′s (for N reduction) payment, a stacked payment (Policy 2) increases farmers’ revenue but does not change their conservation behavior (Behavior 1), representing a “double-dipping” effect. This is a *Policy-Policy* spillover effect.

In addition, nitrogen reduction (Gain 1) comes with constructing riparian buffers (Behavior 1 or 2), which would reduce phosphorus (Gain 2) because of synergistic processes in N and P cycling [26]. This is a *Gain-Gain* spillover effect.

Concurrent green initiatives in China

We further explored potential spillover effects based on two of the most extensive concurrent green initiatives in China. The first is China's Grain-to-Green Program (GTGP), launched by the central government in 1999 (and still in operation), aiming to convert eligible cropland to forestland in the upper reach of the Yangtze River Basin and the upper and middle reaches of the Yellow River Basin. GTGP aims to restore vegetation and reduce surface runoff and soil erosion through payments made to cropland holders (and thus resembles CRP in the U.S.). The second green initiative is China's Forest Ecological Benefit Compensation (FEBC) program, which was officially launched in 2004. FEBC seeks to establish, nurture, protect and manage selected natural forestlands with essential ecological benefits through a strict logging ban ([8]; Ministry of Finance & [24]). The payment is made to the corresponding forestry entrepreneur, community, or individual(s). Since 2004, these two programs have been implemented simultaneously in China's 20 provinces, autonomous regions, and municipalities. In many regions, parcels of both types of land are contracted to the same households [42], making spillover effects possible between the two programs.

The cases of Fanjingshan and Tianma

We independently collected data from Fanjingshan National Nature Reserve and Tianma National Nature Reserve in China, where GTGP and FEBC have been implemented for over a decade. We chose two sites to simultaneously examine the FEBC-GTGP spillover effects to minimize the probability that any resultant spillover effects, if detected, are site-specific. At both sites, GTGP started earlier, and local farmers had more decisive power for participation in GTGP. On the other hand, FEBC participation was primarily government prescribed. We then modeled the total area of land a particular household pledged in GTGP (dependent variable) using ordinary least-square regression as follows:

$$y = b_0 + b_1 X_1 + \sum_{j=2}^{k} b_j X_j + e \tag{2}$$

Where y stands for the area of cropland enrolled in GTGP, X_1 for payment from FEBC (at Fanjingshan) or area of forestland enrolled in FEBC (at Tianma), and the rest (i.e., X_j) for the controlled variables that represent household various capitals according to the Sustainable Livelihoods Framework [33]. In Eq. (2), e is the residual. For what the control variables are, their coefficients, and other statistics at each site, see Tables A2 and A3. The data and relevant code are posted here (http://complexities.org/papers/Green-initiative/) for all the interested audience.

At both sites, we found a significant *Policy-Behavior* beneficial spillover effect from FEBC to GTGP enrolment: FEBC payments increased GTGP enrollment at Fanjingshan (FEBC payment's coefficient = 0.4393, p = 0.0703; Table A2) and Tianma (FEBC area's coefficient = 0.467, p = 0.002; Table A3).

To test whether the above FEBC-GTGP spillover effects may evolve, we surveyed local farmers' willingness to participate in GTGP under a set of hypothetical conditions and performed discrete choice modeling. In 2015, we selected a set of farmland plots at Fanjingshan, including those already enrolled in GTGP and ones not enrolled yet at the survey time. Then for each specific plot, we asked the following question: "under this combination of hypothetical conditions, would you be willing to enroll *this specific farmland plot* in the assumable GTGP?" Coding the answer as a binary variable (1 for yes and 0 for no), we built a logistic model to test how FEBC payment amount may affect this choice considering control variables. For survey and model details, see Yost et al. [42] and An et al. [[1], pp. 106–113] .

Interestingly, we found that the beneficial *Policy-Behavior* spillover effect mentioned above turned out to be detractive: more FEBC land *decreases* the likelihood of enrolling land in GTGP (coefficient = −0.0030, p = 0.0509; Table A4). We can interpret this negative coefficient this way: for every additional mu of FEBC land (AllFstAmt), there is a 0.3 % decrease (−0.0030; Table A4) in the odds of enrolling GTGP because the odds ratio is $e^{(-0.0030)} = 0.9970$. We know that by the definition of odds, odds = $p/(1-p)$, where p is the probability that an event happens. We can show that when p is small, the change in probability is very close to the change in the corresponding odds (Table A5). Therefore, each additional mu of FEBC land should lead to a decrease of odds by 0.30 %, which can translate to approximately a 0.30 % decrease in the probability of GTGP land enrollment due to the negative coefficient (−0.0030; Table A4). This result, contrary to the one above (Table A2), turns to be negative as it is based on data for potential enrollment in the future when most of the marginal croplands should have already been enrolled in GTGP. At Fanjingshan, the median FEBC area is 10 mu (0.67 ha; [1], Ch 5), which can generate a 10 * 0.30 % or 3 % decrease in the likelihood of enrolling more land.

There is evidence for the *Time-Time* spillover effect (detail in Section Time-Time and intertwined spillover effects). We explained this detractive effect from the perspectives of livelihood strategy and food security [42]: with FEBC payments, local farmers may have more cash for whatever expenses that were paid by GTGP payments. Instead, they may enroll zero or less land in GTGP to maintain the remaining farmland for food security as most of the marginal croplands had already been enrolled in GTGP.

We also found evidence for *Gain-Gain* spillover effects at Fanjingshan and Tianma. Forests established under GTGP (often closer to households; Gain 1) would better protect FEBC forests (Gain 2) because GTGP forests may act as buffers for human activities such as fuelwood collection and grazing that would otherwise occur in FEBC forests [30].

Implications of FEBC-GTGP spillover effects

We extrapolated the above beneficial FEBC-GTGP spillover effects to the whole of China and calculated the associated ecological consequences (Appendix 1). Specifically, running FEBC in GTGP eligible areas might have generated a co-benefit of 6.6924 million mu forestland, accounting for 8.10 % of total GTGP-induced forestland (i.e., 82.65 million mu). Out of the total 82.65 million mu of farmland enrolled in GTGP as of 2006, 6.6924 million mu came as a co-benefit of FEBC payment, giving a 9 % of increase due to FEBC's spillover effects. If using the results from Tianma, 10 % is the increase rate (see Appendix 1). On average the increase rate is 9.5 %. This extra GTGP enrollment may translate into 1423.07 billion t carbon sequestration per year (detail in Appendix 1). This beneficial spillover effect is reflected in Figure 3C (9 % ~ 10 %).

If implementing the hypothetical GTGP program, as shown above, the potential loss of GTGP-related forestland would be 0.1653 million ha, which is 3 % of China's total GTGP land (5.51 million ha). This lost GTGP land may reduce carbon sequestration at the magnitude of 503.17 billion t (Appendix 1).

The case of Wolong Nature Reserve

We explored spillover effects in Wolong Nature Reserve, China, for giant panda conservation based on a publication that explores two green initiatives: the combined Grain-to-Bamboo Program and Green-to-Green Program (thus named GTGB) and Natural Forest Conservation Program (NFCP; similar to FEBC) [41]. If the two green initiatives were implemented separately, we calculated the income growth under each initiative by setting the payment of the other initiative to the mean value for all households; if implemented together with spillover effects allowed, we also calculated the subsequent income growth by considering their interaction effects. If the latter is greater (or less) than the sum of the two separate predicted income growths, we may attribute such a difference to spillover effects between the two green initiatives.

Following existing data and modeling results ([1], pp. 106–113; [41]), we assume there was a household that had total household income in 1998 at 6.285 k, GTBP payment at 2.888 k, NFCP payment at 0.948 k, and household income in 2007 at 6.285 + 21.988 = 28.273 k (unit: yuan), which were averages of all sampled households. In 1998, the percentage of NFCP and GTBP payment in household income in this household were [0.948/6.285] = 0.1508 or 15.08 % and [2.888/6.285] = 0.4595 or 45.95 %. According to the regression results, each unit (percent) of NFCP would change the income growth by −128.11 k (yuan). Similarly, each unit (percent) of GTBP would change the income growth by −15.535 k (yuan).

Below we estimate how much additional gain may come out of the interaction of the two programs. The indicator of this additional gain is measured in the total household income in 2007 or the increase in total household income from 1998 to 2007.

(1) If there is only NFCP, what would be the household income in 2007?
First, calculate the income growth if there was only NFCP, which is 21.988–128.811×15.08 % =2.5633 k (yuan).
So, the HH income in 2007 if only NFCP was available: Y1 = 6.285+2.5633 = 8.8433 k (yuan).
(2) If there was only GTBP, what would be the household income in 2007?
In the same way, this income Y2 = 6.285 + (21.988–15.535×0.4595)
=6.285+14.8497 = 21.1347 k (yuan).
(3) If both NFCP and GTBP are implemented but there is no interaction, the HH income in 2007 Y3 = 6.285+2.5633+14.8497 = 23.6980. But the actual income (with NFCP/GTGP interaction) = 6.285+21.988 = 28.273 k (yuan).
(4) So, the household income growth rate due to interaction Ra = (28.273–23.698)/23.698 = 19.31 %.
If we only consider the impact of such interaction on increase growth—i.e., the interaction makes the increase bigger: 2.5633+14.8947 is the growth without interaction between the two programs, and [21.988 - (2.5633+14.8947)] is the "extra" growth due to such interaction. Thus, the income growth rate is

Rb= [21.988 - (2.5633+14.8947)]/(2.5633+14.8947)=25.95 %

which is graphically shown in Figure 3D (the main text). This surprising outcome may arise from local people's changes in livelihood strategy. If implementing NFCP alone (Policy 1), then local people adopt the strategy of "incremental changes" (Behavior 1), such as growing more cash income crops and increasing the use of fertilizers and pesticides (an internal *Policy-Behavior* impact). These agricultural intensification activities may lead to relatively slow growth of total household income in the long run compared to more lucrative non-agricultural activities. When jointly implementing GTGB (Policy 2), then local people may feel strongly inclined to adopt a livelihood strategy of "transformational changes" (Behavior 2), such as out-migration and substantial reduction (even termination) of farming activities (a *Policy-Behavior* spillover effect), to compensate for significant losses in cropland and agricultural income. In this instance, as farmers shifted livelihoods from on-farm work to off-farm activities, an emerged *Behavior-Behavior* spillover effect emerged that replaces "incremental changes" (Behavior 1) with "transformational changes" (Behavior 2).

In summary, the income growth from 1998 to 2007 was jointly affected by GTGB and NFCP. When GTGB and NFCP were implemented separately, each caused agricultural intensification (Behavior 1) and impeded the growth of household income between 1998 and 2007. However, if implemented both simultaneously, a new behavior, i.e., out-migration (Behavior 2), would be adopted by local households to diversify income sources and minimize potential financial risks, leading to a positive impact on the income growth. Therefore Behavior 2 would cancel Behavior 1, representing a *Behavior- Behavior* spillover effect.

Concurrent green initiatives worldwide

Based on the literature review (Section Green initiatives) and concurrent green initiatives in the U.S. (Section Concurrent green initiatives in the USA) and China (Section Concurrent green initiatives in China), we extended our exploration for more evidence.

We searched in several online data sources or archives including Web of Science, Google Scholar, and the journal *Ecosystem Services* (https://www.sciencedirect.com/journal/ecosystem-services) for papers with the keywords of "payment(s) for ecosystem services", "payment(s) for environmental services", "PES". For each paper thus obtained, we read its abstract and key paragraphs (e.g., methods, conclusion) for clues to concurrent PES programs. Once a paper was found to involve concurrent PES programs potentially, we used a snowball approach to find related papers or websites for more evidence and/or more sites with concurrent PES programs. We also considered other concurrent green initiatives, such as protected areas ([1], p. Ch 8). In this way, we collected nine more cases with evidence for the spillover effects identified (Figure 2 in the main text), resulting in a total of 15 cases. We collected some descriptive data for all these 15 cases, showing their country or continent, population size, area, whether located in an urban or rural area, whether located in developed or developing countries or regions, funder type, and name of concurrent programs.

We reviewed the related papers and documented the spillover effects for the nine cases outside the U.S. and China. When necessary, we contacted the associated author(s) or others with knowledge of the case to confirm our findings. Based on the concurrent green initiative framework (Figure 1), we assigned all detected spillover effects into the categories explained in the main text: three vertical (*Policy-Behavior, Behavior-Gain* and *Gain-Policy*), three horizontal (*Policy-Policy, Behavior-Behavior* and *Gain-Gain*), and other more complex (*Time-Time* and intertwined) spillover effects. Finally, we summarized all the 15 cases. Through this analysis from a global perspective, we have unveiled the popularity of concurrent green initiatives and their potential spillover effects across the three domains of policy, behavior, and gain, which are emerging in different countries and regions. Examples include carbon farming policies and biodiversity conservation measures in Australia, protection projects for the Páramo grasslands in Ecuador, and transnational efforts to combat severe eutrophication in the Baltic Sea. These cases showcase the complex interplay among environmental policies, socio-economic conditions, and ecosystem services. The study emphasizes the importance of considering these spillover effects when designing, implementing, and evaluating environmental policies. Furthermore, our work helps realize the potential benefits of integrating multiple initiatives simultaneously to maximize environmental and societal gains.

From here on we focus on the nine cases outside of the U.S. and China. To be comprehensive, we still mention the findings from the six cases in the U.S. and China, but refer to Sections Concurrent green initiatives in the USA and Concurrent green initiatives in China, respectively, for detail.

Policy-Behavior spillover effects

See the Fanjingshan and Tianma cases in Section The cases of Fanjingshan and Tianma and the Wolong case in Section The cases of Fanjingshan and Tianma.

Behavior-Gain spillover effects

Our case in Australia illustrates *Behavior-Gain* spillover effects. Australia has intensive agricultural land, which is measured to be 85.3 million hectares and subject to reforestation under carbon farming policies. Modeling work by Bryan et al. [4] shows that under a payment scheme that focuses on carbon sequestration, people may establish "carbon plantings" (Behavior 1; planting fast-growing Eucalyptus monocultures). Such plants can sequester a large amount of carbon, suggesting a strong internal Behavior-Gain effect (here "internal" means within the same green initiative; see Figure 2 of main text); however, carbon plantings have little impact on biodiversity, which stands for a weak *Behavior-Gain* spillover effect. There arises another payment scheme, which aims to enhance both carbon and biodiversity services, called the practice of "environmental plantings" (Behavior 2; a mix of native trees and shrubs). This scheme can not only lead to high levels of carbon sequestration (again it is a strong internal *Behavior-Gain* effect; with only 1.32 % of total carbon stock sacrificed), but also generate a significant gain in biodiversity: the associated gain is 96 times bigger than that from the carbon plantings, which is a strong *Behavior-Gain* spillover effect [4].

The Páramo grasslands in Ecuador [3] had evidence for *Behavior-Gain* spillover effects aside from those from Australia. One PES program named PROFAFOR (Programa FACE de Forestación del Ecuador; Policy 1) seeks to promote afforestation with *Pinus* species and some native Andean species (Behavior 1); the expected outcome is to increase carbon sequestration (Gain 1). There is a concurrent PES program named SocioPáramo (a sub-program of the more extensive SocioBosque program; Policy 2) in the same region, which aims to exclude burning in Páramo grasslands (Behavior 2). SocioPáramo has multiple goals including carbon storage, biodiversity protection, and water provision (Gain 2). Empirical evidence shows that at a study site in Southern Ecuador, afforestation (Behavior 1) leads to decreases in soil moisture and loss of native plant diversity, compromising the goal related to water provision (Gain 2), representing a *Behavior-Gain* spillover effect. At the same site, the *Behavior-Gain* spillover effect is manifested in another way: burning-exclusion (Behavior 2) may not achieve optimal carbon sequestration results (Gain 1).

Gain-Policy spillover effects

See the Neuse case in Section Local evidence of spillover effects.

Policy-Policy spillover effects

Severe eutrophication is a significant problem in the Baltic Sea and the catchment areas, including nine countries of Denmark, Finland, Germany, Poland, Sweden, Estonia, Latvia, Lithuania, and Russia. To counter this problem, these countries agreed to reduce nitrogen (N) and phosphorus (P) loads that enter the sea [14]. Several abatement measures are in operation to reduce the total N and P loads to a level that is below predetermined annual limits. N and P emission permits are allowed to trade on market among various actors (e.g., abatement firms), between upstream and downstream areas, and/or across different abatement measures. The goal is to minimize total abatement costs while observing the total N and P caps [14]. Mathematical work shows that payments for N and P abatement (Policies 1 and 2) cannot be made separately: If only one payment is made, the outcome would be much worse, e.g., either cost is higher, or caps are not observed. Instead, they must be stacked to be cost-effective [14].

In Bolivia's Rio Grande catchment, individuals receive concurrent payments, through different contracts, on their parcels. It appears that payments at level 1 (Policy 1) downgraded or nullified payments that targeted other areas of the landscape made at levels 2 and 3 (Policy 2). To conserve biodiversity and improve water quality (Gain 1), payments made at level 1 (Policy 1) are much higher in amount and stricter in monitoring for compliance [2]. However, such payments seem to downgrade or nullify payments made at levels 2 and 3 to the same individual recipients; note that payments made at levels 2 and 3 are targeting different lands (Policy 2) to stop farming. Given the higher economic incentive and stronger monitoring of Policy 1, local farmers turned to be less compliant with their contracts under Policy 2 (i.e., stop farming on their other land parcels). Additional evidence for the *Policy-Policy* spillover effect is available at the Jordan River case (Section Local evidence of spillover effects).

Behavior-Behavior spillover effects

The Australian case provides evidence for this type of *Behavior-Behavior* spillover effect. The aforementioned two actions, i.e., the establishment of "carbon plantings" (CP; Behavior 1) and "environmental plantings" (EP; Behavior 2) must be subjected to a quantitative relationship: the sum of the CP area, the EP area, and the traditional cropland area should be held at 85.3 million ha. As a consequence, any increase in CP should lead to a decrease in EP (and vice visa) if traditional cropland area is to be maintained for food security and other reasons. This phenomenon arises due to the constraints in total budget and areas of land available [4].

Mexico has been implementing a nationwide Payment for Ecosystem Services-Hydrological program (PSA-H) to protect critical forests for water provision and regulation services. Also in Mexico, another concurrent PES program has existed named the Forest Ecosystems Conservation and Restoration Program (PROCOREF in Spanish). We obtained, translated, and compiled the data from Ezzine-de-Blas et al.'s survey of 77 communities (*ejidos*) in 2013 in Southern Yucatán [10]. The results show that the area of PROCOREF enrollment is positively correlated with PSA-H area ($r = 0.3453$, $p = 0.1360$) and PSA-H payment ($r = 0.3500$, $p = 0.1303$). Although only being marginally significant (i.e., p is slightly greater than the $\alpha = 0.10$ level), we might still want to pay attention to the potential *Behavior-Behavior* spillover effect. These two relationships were based on a small sample (20) due to missing data. Such missing data may be explained by the lack of considering concurrent green initiatives during survey design and implementation stages. For another *Behavior-Behavior* spillover effect, we refer to the Wolong case (Section The case of Wolong Nature Reserve).

Gain-Gain spillover effects

For *Gain-Gain* spillover effects (Figure 1), we focus on the Foglia River Basin and Marecchia River Basin in Italy, where soil protection (Gain 1) and CO_2 sequestration (Gain 2) were linearly correlated because they are both functions of forest type and size. There are several forest-based ecosystem services identified by Morri et al. [25], among which water retention (Gain 1) and drinking water supply (Gain 2) are linked well for several reasons. First, water retention is a function of forest type, which helps determine the percentage of runoff retained. The water thus retained is the source of drinking water. Also, the two gains of soil protection and CO_2 sequestration are also linked with each other and subject to some quantitative relationship as they are both a function of forest type and its area (with control of a few other variables). For additional evidence for *Gain-Gain* spillover effects, we refer to the Neuse River basin, Jordan river (Section Local evidence of spillover effects), and Wolong (Section The case of Wolong Nature Reserve).

The New World (the Americas and Oceania) & Great Britain provide more evidence for understanding these *Gain-Gain* spillover effects. On the one hand, we may have a carbon-only strategy, which aims at carbon sequestration (Gain 1). On the other hand, a combined carbon-biodiversity strategy can be designed via weighting the two goals and adjusting subsequent spatial allocation. Empirical data have shown that the combined strategy could simultaneously achieve the two goals to a great extent: protecting 90 % of carbon stocks and more than 90 % of the biodiversity protected under a biodiversity-only (Gain 2) strategy. With adjusted spatial distribution, this combined strategy produces various levels of co-benefits, which is dependent on the relative magnitude of each individual strategy. The joint benefits could go from −10 % to 1700 % with an average of 310 % (Appendix 3; Table A6). We also report this average in Figure 3D of the main text.

This win-win outcome can be explained by heterogeneous spatial distributions of biodiversity and carbon services as well as site-specific interactions between these two services [32]. The Australia case also shows similar win-win outcomes due to reallocating payments to sites with abundant biodiversity and carbon services [4].

Time-Time and intertwined spillover effects

The PVPF-KPWS case in Cambodia provides empirical evidence for the Time-Time spillover effects [7]. The Bird Nest Protection (BNP) program (Policy 1) made payments to eligible individuals such that they were engaged to identify, monitor, and protect the remaining nesting sites (Behavior 1a). However, in villages receiving such BNP payments, in-migrants were allowed to settle down (Behavior 1b). Once settled down, these in-migrants would clear forests, causing more significant loss of bird habitat. So the negative outcome may come later in time, offsetting the conservation effects of BNP in the long run.

A different green initiative named payments from the Ecotourism and Agri-Environment programs (Policy 2) may have impacts on local ecosystems. It may take several years for this policy to take effects, e.g., through building up the capacity of all participating villages and individuals. Once such capacity is set up, the payments related to Policy 2 may lead to actions including restraining in-migration (Behavior 1b) and the associated deforestation, promoting bird conservation. The Bird Nest Protection program (Policy 1) should be implemented first, which may provide an immediate effect; following that, the Ecotourism and Agri-Environment program (Policy 2) should be executed, which may contribute to long-term protection. This example manifests a *Time-Time* spillover effect. For additional evidence for *Time-Time* spillover effects, see the Fanjingshan case (Section The cases of Fanjingshan and Tianma).

Finally, we found multiple spillover effects—as described above—could occur in the same area over the same time, manifesting an intertwined, multi-dimensional style. The spillover effects are evident in Nepal. The REDD+ (Reducing Emissions from Deforestation and forest Degradation) program aims to enhance forest carbon stocks by preventing deforestation and degradation. The concurrent Community-based Forest Management (CFM) program is designed for both sustainable forest management and livelihood improvement, with both conflicting and complementary goals with REDD+, giving rise to a *Gain-Gain* spillover effect. In many instances, the payment by REDD+ to local people for the carbon storage may or may not make up the loss of livelihood support they used to derive from the community forests depending on the level of payment and local contexts [20,21]. As a result, CFM may stimulate local people to harvest trees from community forests (Behavior 1), leading to decreases in forest carbon stocks (Gain 2), suggesting a *Behavior-Gain* detractive spillover effect. Finally, we summarized all the cross-initiative spillover effects in Table 1 in the main text.

Conclusion

Our in-depth analysis of concurrent green initiatives in various contexts emphasizes the importance of understanding spillover effects in environmental conservation efforts. By examining examples from the United States, China, and other nations, we have highlighted the challenges and opportunities that stem from the interactions between different green initiatives such as CRP, EQIP, GTGP, and FEBC. Our research demonstrates that while these programs share common environmental goals, their interplay can result in unintended consequences, both positive and negative, impacting policy efficacy, environmental sustainability, and community well-being. It is imperative to acknowledge and address these spillover effects to enhance synergies among concurrent green initiatives and maximize their collective impact on conservation and sustainable development. In the future, we will extend our research to more case study sites to finetune the methods and further verify the conclusions. Future policies and initiatives should take a comprehensive approach that anticipates and integrates potential spillover effects, promoting more cohesive and efficient environmental conservation strategies on a global scale.

Ethics statements

Our data collection in Fanjingshan and Tianma complies with the related requirements under the IRB of San Diego State University (Protocol #: 1732093) and University of North Carolina, Chapel Hill (Protocol #: 11–1253).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Li An: Conceptualization, Writing – original draft, Project administration, Funding acquisition. **Conghe Song:** Resources, Data curation. **Qi Zhang:** Formal analysis, Writing – original draft. **Xiaoxiao Wei:** Writing – review & editing.

Data availability

Data will be made available on request.

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Appendix

1. Ecological co-benefits of FEBC program

Liu et al. suggest that the total accumulative forestland and grassland due to implementation of GTGP in China was 8.80 million ha by the end of 2009 [18]. As the total area of GTGP land leveled off since 2005 [17], we can reasonably assume that China has GTGP-induced forestland and grassland at the magnitude of 8.80 million ha since 2006. From here, we seek to partition the total area of 8.80 million ha into the portion for forestland and that for grassland based on the data in 2006.

China's total forestland converted from farmland due to GTGP was 5.51 million ha or 82.65 million mu (1 ha = 15 mu); we also know a total of 104 million ha (1560 * 10^6 mu) of FEBC land was protected in 2006. The consequent annual compensation should

Table A1
EQIP and CRP land reallocation scenario analysis.

			Reallocation rate (% of reallotting 4.5 million acres back to CRP*)									
	Baseline		20 %		40 %		60 %		80 %		100 %	
	Area	Pay **	Area	Pay	Area	Pay	Area	Pay	Area	Pay	Area	Pay
CRP	22	1680	22.9	1748.64	23.8	1817.37	24.7	1886.09	25.6	1954.82	26.5	2023.54
EQIP[3]	18.02	2486	17.12	2362.22	16.22	2238.04	15.32	2113.85	14.42	1989.67	13.52	1865.49
Total	40.02	4166	40.02	4110.86	40.02	4055.40	40.02	3999.95	40.02	3944.49	40.02	3889.03
Change	N/A	N/A	0	−55	0	−111	0	−166	0	−222		−277
Change%	N/A	N/A	0	−1 %		−3 %	0	−4 %	0	−5 %		−7 %

* Base 4.5 The base of restoration is 4.5 million acres, which is the total loss of CRP due to EQIP.
** CRP rate 76.36 ($/acre)EQIP rate 137.98 ($/acre).

Table A2
Modeling results for impacts of selected variables on GTGP enrollment at Fanjingshan, China.

Variable	Description	Parameter Estimate	Standard Error	t score	Pr > |t|	Variance Inflation
Intercept		0.1663	0.3941	0.42	0.6734	0
FstMnyAmt	FEBC payment amount	0.4393*	0.2418	1.82	0.0703	1.0713
DryLdAmt	Dryland amount	0.5708***	0.0599	9.54	<0.0001	1.0787
PadLdAmt	Paddyland amount	0.2605***	0.0474	5.50	<0.0001	1.0251
HHCshInc	Household cash income	−0.0019	0.0018	−1.08	0.2828	1.0557
HH_Size	Household size	0.0797	0.0932	0.86	0.3931	1.0575
TLGPDst	Distance from GTGP land to home	0.1763**	0.0745	2.37	0.0186	1.0174
R^2 (adjusted R^2)	0.3907(0.3769)					

Note: FstMnyAmt is in Eq. (2), representing FEBC enrollment.
* $p < 0.10$;.
** $p < 0.05$;.
*** $p < 0.01$; .

Table A3
Modeling results for impacts of selected variables on GTGP enrollment at Tianma, China.

Variable	Description	Coefficient	Standard Error	T score	p-value
Intercept		1.0010	0.8007	1.25	0.212
ewfpArea100	Area of forest enrolled in FEBC (100 mu)	0.4669***	0.1503	3.11	0.002
hhSlope	Slope at house location (degree)	0.0071	0.0203	0.35	0.728
hhElev1000	Elevation at house location (1000 m)	0.3892	0.9701	0.40	0.688
headAge	Age of household head	−0.0024	0.0084	−0.28	0.778
hhSize	Household size	0.1826***	0.0556	3.28	0.001
numOut	Number of individual out-migrants	0.1644**	0.0679	2.42	0.016
numOffFarm	Number of local off-farm labor	−0.1237	0.1170	−1.06	0.291
landOwnHA	Area of cropland owned (ha)	0.2920	0.4866	0.60	0.549
abanAreaHA	Area of cropland abandoned (ha)	1.0479	0.8491	1.23	0.218
ifGE	Whether obtain forest resource (0/1)	−0.2545	0.1788	−1.42	0.155
ifAnimal	Whether raise domestic animals (0/1)	0.0055	0.2575	0.02	0.983
income1000USD	Gross income (1000 USD)	−0.0157	0.0145	−1.09	0.278
R^2 (adjusted R^2)					

Note: * $p < 0.10$; The model uses data collected from both 2013 and 2014 household surveys with a sample size of 408 who are participating in both GTGP and FEBC.
** $p < 0.05$;.
*** $p < 0.01$;.

Table A4
Modeling the impacts of FEBC on willingness to participate in GTGP in the future at Fanjingshan, China.

Effect	Description	Estimate	Standard Error	t score	Pr > |t|
Intercept		−1.4750	0.4747	−3.11	0.0021
AllFstAmt	FEBC forestland amount	−0.0030*	0.0015	−1.96	0.0509
DryLdAmt	Dryland amount	0.0941*	0.0497	1.89	0.0587
PadLdAmt	Paddy land amount	0.0681*	0.0404	1.68	0.0925
HHCshInc	Household cash income	0.0006	0.0014	0.44	0.6621
FstMnyAmt	FEBC payment amount	0.0849	0.1959	0.43	0.6649
HHLbr	Household labor	−0.2394**	0.1163	−2.06	0.0398
TLGPDst	Total distance from GTGP parcel to house	−0.0906	0.0674	−1.34	0.1791
PlotInGP	Plot already in GTGP	0.9494***	0.1565	6.07	<0.0001
Plot_Dst	Distance from plot to household	0.0131***	0.0034	3.81	0.0001
Plot_Area	Area of plot	0.0585	0.1007	0.58	0.5618
Mny	Hypothetical amount of GTGP pay	0.1797***	0.0345	5.20	<0.0001
span	Hypothetical amount of GTGP span	0.0486*	0.0252	1.93	0.0545
fallow	Hypothetical status for the land parcel left fallow	−0.2990*	0.1739	−1.72	0.0858
NB	Hypothetical percent of neighbors agreed to join GTGP	0.0119***	0.0041	2.92	0.0036
−2 Res Log Pseudo-Likelihood		5708.20			
Generalized Chi-Square / DF		0.71			

Note: The variable AllFstAmt represents FEBC enrollment.
* $p < 0.10$;.
** $p < 0.05$;.
*** $p < 0.01$;.

Table A5
The relationship between change in probability and change in the corresponding odds.

p	odds	change in prob	Change in odds
0.06	0.0638		
0.07	0.0753	0.01	0.0114
0.08	0.0870	0.01	0.0117
0.09	0.0989	0.01	0.0120
0.1	0.1111	0.01	0.0122
0.11	0.1236	0.01	0.0123
0.12	0.1364	0.01	0.0128
0.13	0.1494	0.01	0.0131

Note: odds = *p*/(1-p).

Table A6
The rate of increase in gain due to different combinations of R1 and R2, where R1 is a number representing the percent of BOS initiatives in COS initiatives, and R2 is the percent of the initiatives of the combined strategy in the BOS initiatives.

		R2									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
R1	0.1	8.90	3.95	2.30	1.48	0.98	0.67	0.41	0.24	0.10	**−0.01***
	0.2	9.80	4.40	2.60	1.70	1.16	0.83	0.54	0.35	0.20	0.08
	0.3	10.70	4.85	2.90	1.93	1.34	1.00	0.67	0.46	0.30	0.17
	0.4	11.60	5.30	3.20	2.15	1.52	1.17	0.80	0.58	0.40	0.26
	0.5	12.50	5.75	3.50	2.38	1.70	1.33	0.93	0.69	0.50	0.35
	0.6	13.40	6.20	3.80	2.60	1.88	1.50	1.06	0.80	0.60	0.44
	0.7	14.30	6.65	4.10	2.83	2.06	1.67	1.19	0.91	0.70	0.53
	0.8	15.20	7.10	4.40	3.05	2.24	1.83	1.31	1.03	0.80	0.62
	0.9	16.10	7.55	4.70	3.28	2.42	2.00	1.44	1.14	0.90	0.71
	1	**17.00***	8.00	5.00	3.50	2.60	2.17	1.57	1.25	1.00	0.80

* The minimal (10 %) and maximal (1700 %) of growth in gains due to interaction.

then be [1560 * 10^6 mu * 9.75 yuan/mu] = 1.521×10^{10} yuan. For collective or individual-owned FEBC forestland, the compensation was 9.75 yuan/mu ([1], Ch 5).

At Fanjingshan, each 1000 yuan of FEBC payment increased the area of land enrolled in GTGP by 0.44 mu (Table A2). We can convert this to a rate of 4.4 * 10^{-4} mu/yuan through dividing 0.44 mu by 1000 (yuan). Therefore, the extra GTGP land due to FEBC payment is (1.521 * 10^{10} yuan) * 4.4 * 10^{-4} mu/yuan = 6.6924 * 10^6 mu (i.e., 6.6924 million mu). Out of the total 82.65 million mu of farmland due to GTGP as of 2006, 6.6924 million mu came as a co-benefit of FEBC payment, corresponding to 8.10 % (6.6924 /82.65) of total GTGP land or an increase rate of 9 % [i.e., 6.6924 /(82.65–6.6924) = 0.0.0881, rounded to 9 %].

Next, we switch to the case of Tianma, where we found that every 100 mu of FEBC land generated 0.47 mu more GTGP land (Table A3). This finding indicates that each mu of FEBC land would lead to an additional 0.0047 mu of GTGP land. Given that the FEBC pay rate was 8.75 yuan/mu in Tianma, the rate can be calculated as [1000 * 0.0047 / 8.75] = 0.54 mu per 1000 yuan, i.e., 5.4 * 10^{-4} mu/yuan. Given that the total FEBC land was 104 million ha (1560 * 10^6 mu) in 2006 (see above), we can calculate the total additional GTGP land enrollment caused by FEBC to be 1560 * 10^6 mu * 0.0047= 7.3320 * 10^6 mu = 7.3320 million mu. This amount came as a co-benefit of FEBC payment, which is 7.3320 / 82.65 = 8.87 % out of 82.65 million mu GTGP forestland in 2006. The increase rate, if we use the pre-FEBC amount of GTGP land as the base, is 10 % [i.e., 7.3320 /(82.65–7.3320) = 9.73 %, which is rounded to 10 %]. Therefore, the average co-benefit of GTGP enrollment due to FEBC payments is approximately 82.65 million mu * (8.87 % + 8.10 %) / 2 = 7.0129 million mu.

Here we estimate the reduction in carbon sequestration due to the relationship between GTGP and FEBC. According to Feng et al.'s work [13], the average annual net ecosystem production (NEP) of woodland in the semi-humid forests was 304.40 g C m^{-2}. Our study site Fanjingshan is in a sub-tropical climate zone with a higher carbon biomass. To derive a conservative estimate (e.g., to be used as a lower bound), we still use the rate of 304.40 g C m^{-2}. As shown earlier, the FEBC payments have induced an additional enrollment of 7.0129 million mu or 0.4675 million ha of GTGP land by 2010. The increase in carbon sequestration due to the FEBC-GTGP spillover effect is estimated to be:

0.4675 million ha * 304.4 g C m^{-2} = 0.4675 * 1000,000 * 10,000 * 304.40 g C m^{-2} = 142.3070 * 10^{10} g C = 1423,070 million t C = 1423.07 billion t C (1 $t = 10^6$ g)

Next, we estimate how much carbon sequestration loss may arise from the hypothetical GTGP policy (detail in Section The cases of Fanjingshan and Tianma). Following the same rationale, the FEBC-induced reduction in potential GTGP land if implementing GTGP under the hypothetical conditions was 3.0 %, as shown in Section The cases of Fanjingshan and Tianma, which translates to 5.51 million ha (China's total GTGP land) * 0.03 = 0.1653 million ha. The corresponding loss in carbon sequestration is:

0.1653 million ha * 304.4 g C m^{-2} = 0.1653 * 1000,000 * 10,000 * 304.40 g C m^{-2} = 50.3173 * 10^{10} g C = 503,173 million t C = 503.173 billion t (1 $t = 10^6$ g).

2. Identification of concurrent payments for environmental services

We used a conservative method to determine whether each of the 55 PES programs identified by Ezzine-de-Blas et al. [11] was/is concurrent with others and estimated the level of certainty in our decision. First, we reviewed Ezzine-de-Blas et al. [11], and other relevant documents (e.g., journal articles, official reports, book chapters) with a keyword of a program name or alternative names. If there was at least one document providing strong evidence that the program is concurrent with others by our definition, we determined this program is concurrent with high certainty. For instance, if a paper evaluated two PES programs and explicitly described that they targeted the same geographical area(s) or made payments to the same participant(s) simultaneously, these two programs were decided to be concurrent programs with a high level of certainty.

3. Calculation of the growth in gains due to interaction

As shown in Section Gain-Gain spillover effects, the combined strategy may retain 90 % of gain in the Carbon-Only Strategy (COS) and 90 % of the gain in the Biodiversity-Only Strategy (BOS). Assume that X units of COS initiatives generate M units of carbon gain and R1*X units of BOS initiatives generate N units of biodiversity gain, where R1 is a percent number that goes from 0 to infinity representing the percent of BOS initiatives in COS initiatives. For practicality, we let R1 range from 0.1 (10 %) to 1 (100 %), implying that BOS initiatives are from 10 % to 100 % of COS initiatives. Let R2*X be initiatives of the combined strategy generate 0.9*$(M + N)$ gains in both carbon and biodiversity, where R2 is the percent of the initiatives of the combined strategy in the BOS initiatives. As (1 + R1)*X initiatives lead to $(M + N)$ gains in carbon and biodiversity when spillover effects do not occur (i.e., X initiatives gives rise to $(M + N)/(1 + \mathrm{R1})$ gain), and R2*X combined initiatives lead to 0.9*$(M + N)$ gains (i.e., X initiatives gives rise to0.9*$(M + N)/\mathrm{R2}$). So the increase rate of gains should be

$$\mathrm{Rate} = \frac{0.9*(M+N)/\mathrm{R2} - (M+N)/(1+\mathrm{R1})}{(M+N)/(1+\mathrm{R1})} = \frac{0.9*(M+N)*(1+\mathrm{R1})/\mathrm{R2} - (M+N)}{(M+N)} = \frac{0.9(1+\mathrm{R1})}{\mathrm{R2}} - 1$$

We tested a range of R1 and R2 values in Table A6, representing the increase rate of gains due to implementing the combined strategy at different combinations of R1 and R2 values. The average of the whole matrix is 3.095 or 310 % (Table A6).

References

[1] L. An, C. Song, Q. Zhang, E. Bohnett, Conservation Effectiveness and Concurrent Green Initiatives, Taylor & Francis, 2022.
[2] P. Bottazzi, E. Wiik, D. Crespo, J.P.G. Jones, Payment for environmental "Self-Service": exploring the links between farmers' Motivation and additionality in a conservation incentive programme in the Bolivian Andes, Ecol. Econ. 150 (2018) 11–23, doi:10.1016/j.ecolecon.2018.03.032.
[3] L.L. Bremer, K.A. Farley, O.A. Chadwick, C.P. Harden, Changes in carbon storage with land management promoted by payment for ecosystem services, Environ. Conserv. 43 (4) (2016) 397–406 Cambridge Core, doi:10.1017/S0376892916000199.
[4] B.A. Bryan, R.K. Runting, T. Capon, M.P. Perring, S.C. Cunningham, M.E. Kragt, M. Nolan, E.A. Law, A.R. Renwick, S. Eber, R. Christian, K.A. Wilson, Designer policy for carbon and biodiversity co-benefits under global change, Nat. Clim. Chang 6 (2015) 301.
[5] Y. Chun, Modeling network autocorrelation within migration flows by eigenvector spatial filtering, J. Geogr. Syst. 10 (4) (2008) 317–344, doi:10.1007/s10109-008-0068-2.
[6] R. Claassen, A. Cattaneo, R. Johansson, Cost-effective design of agri-environmental payment programs: U.S. experience in theory and practice, Ecol. Econ. 65 (4) (2008) 737–752.
[7] T. Clements, A. John, K. Nielsen, D. An, S. Tan, E..J. Milner-Gulland, Payments for biodiversity conservation in the context of weak institutions: comparison of three programs from Cambodia, Special Sect. - Payment. Environ. Serv.: Reconcil. Theory Practice 69 (6) (2010) 1283–1291, doi:10.1016/j.ecolecon.2009.11.010.

[8] L. Dai, F. Zhao, G. Shao, L. Zhou, L. Tang, China's classification-based forest management: procedures, problems, and prospects, Environ. Manage. 43 (6) (2009) 1162–1173.
[9] G.C. Daily, P.A. Matson, Ecosystem services: from theory to implementation, Proc. Natl. Acad. Sci. U.S.A. PNAS, Proc. Natl. Acad. Sci. 105 (28) (2008) 9455–9456, doi:10.1073/pnas.0804960105.
[10] D. Ezzine-de-Blas, C. Dutilly, J.-A. Lara-Pulido, G.L. Velly, A. Guevara-Sanginés, Payments for environmental services in a policymix: spatial and temporal articulation in Mexico, PLoS ONE 10 (2016) 1371.
[11] D. Ezzine-de-Blas, S. Wunder, M. Ruiz-Pére, R. Moreno-Sanchez, P. del, Global patterns in the implementation of payments for environmental services, PLoS ONE (2016), doi:10.1371/journal.pone.0149847.
[12] Federal register. (2019). *Conservation reserve program: a rule by the commodity credit corporation*. https://www.federalregister.gov/documents/2019/12/06/2019-26268/conservation-reserve-program
[13] X. Feng, B. Fu, N. Lu, Y. Zeng, B. Wu, How ecological restoration alters ecosystem services: an analysis of carbon sequestration in China's Loess Plateau, Sci. Rep. 3 (2013) 2846 PMC, doi:10.1038/srep02846.
[14] I.-M. Gren, K. Elofsson, Credit stacking in nutrient trading markets for the Baltic Sea, Mar. Policy 79 (2017) 1–7, doi:10.1016/j.marpol.2017.01.026.
[15] D.A. Griffith, A linear regression solution to the spatial autocorrelation problem, J. Geogr. Syst. 2 (2) (2000) 141–156, doi:10.1007/PL00011451.
[16] H.D. Jonas, V. Barbuto, Jonas, A. Kothari, F Nelson, New steps of change: looking beyond protected areas to consider other effective area-based conservation measures, PARKS 20 (2) (2014) 111–128, doi:10.2305/IUCN.CH.2014.PARKS-20-2.HDJ.en.
[17] J. Liu, S. Li, Z. Ouyang, C. Tam, X. Chen, Ecological and socioeconomic effects of China's policies for ecosystem services, Proc. Natl. Acad. Sci. 105 (28) (2008) 9477–9482, doi:10.1073/pnas.0706436105.
[18] J. Liu, Z. Ouyang, W. Yang, W. Xu, S. Li, Evaluation of ecosystem service policies from biophysical and social perspectives: the case of China, in: S.A. Levin (Ed.), Encyclopedia of Biodiversity, Academic Press, 2013, pp. 372–384.
[19] R. Luken, T. Grof, The Montreal Protocol's multilateral fund and sustainable development, Ecol. Econ. 56 (2) (2006) 241–255, doi:10.1016/j.ecolecon.2004.04.013.
[20] T.N. Maraseni, P.R. Neupane, F. Lopez-Casero, T. Cadman, An assessment of the impacts of the REDD+ pilot project on community forests user groups (CFUGs) and their community forests in Nepal, J. Environ. Manage. 136 (2014) 37–46, doi:10.1016/j.jenvman.2014.01.011.
[21] K. Marquardt, D. Khatri, A. Pain, REDD+, forest transition, agrarian change and ecosystem services in the hills of Nepal, Hum. Ecol. 44 (2) (2016) 229–244, doi:10.1007/s10745-016-9817-x.
[22] S.L. Maxwell, V. Cazalis, N. Dudley, M. Hoffmann, A.S.L. Rodrigues, S. Stolton, P. Visconti, S. Woodley, N. Kingston, E. Lewis, M. Maron, B.B.N. Strassburg, A. Wenger, H.D. Jonas, O. Venter, J.E.M. Watson, Area-based conservation in the twenty-first century, Nature 586 (7828) (2020) 217–227, doi:10.1038/s41586-020-2773-z.
[23] Millennium Ecosystem AssessmentEcosystems and Human Well-Being, Island Press, 2005 https://www.millenniumassessment.org/documents/document.356.aspx.pdf.
[24] Ministry of Finance, & State Administration of Forestry. (2007). *Central government sponsored forest ecological benefit compensation fund: management rules*. http://www.mof.gov.cn/zhengwuxinxi/caizhengwengao/caizhengbuwengao2007/caizhengbuwengao20075/200805/t20080519_26401.html.
[25] E. Morri, F. Pruscini, R. Scolozzi, R. Santolini, A forest ecosystem services evaluation at the river basin scale: supply and demand between coastal areas and upstream lands (Italy), Ecol. Indic. 37 (2014) 210–219, doi:10.1016/j.ecolind.2013.08.016.
[26] M. Motallebi, D.L. Hoag, A. Tasdighi, M. Arabi, D.L. Osmond, R.B. Boone, The impact of relative individual ecosystem demand on stacking ecosystem credit markets, Ecosyst. Serv. 29 (2018) 137–144.
[27] C. Ogg, G. Keith, New federal support for priority watershed management needs, J. Am. Water. Resour. Assoc. 38 (2) (2002) 577–586, doi:10.1111/j.1752-1688.2002.tb04339.x.
[28] Program Evaluation Division, *Department of Environment and Natural Resources Mitigation Credit Determinations* [Special Report to the General Assembly Report Number 2009-04], North Carolina General Assemb. (2009) https://www.ncleg.net/PED/Reports/documents/Wetlands/Wetland_Report.pdf.
[29] T. Riley, Private-land habitat opportunities for prairie grouse through federal conservation programs, Wildl. Soc. Bull. 32 (1) (2004) 83–91, doi:10.2193/0091-7648(2004)32[83:PHOFPG]2.0.CO;2.
[30] C. Song, R. Bilsborrow, P. Jagger, Q. Zhang, X. Chen, Q. Huang, Rural household energy use and its determinants in China: how important are influences of payment for ecosystem services vs. Other factors? Ecol. Econ. 145 (2018) 148–159, doi:10.1016/j.ecolecon.2017.08.028.
[31] The US Census. (2018). *Small area income and poverty estimates*. https://www.census.gov/data/datasets/2018/demo/saipe/2018-state-and-county.html; https://www.census.gov/programs-surveys/saipe.html.
[32] C.D. Thomas, B.J. Anderson, A. Moilanen, F. Eigenbrod, A. Heinemeyer, T. Quaife, D.B. Roy, S. Gillings, P.R. Armsworth, K.J. Gaston, Reconciling biodiversity and carbon conservation, Ecol. Lett. 16 (s1) (2013) 39–47, doi:10.1111/ele.12054.
[33] United Nations Development ProgrammeGUIDANCE NOTE: Application of the Sustainable Livelihoods Framework in Development Projects, United Nations Development ProgrammeRegional Centre for Latin America and the Caribbean, 2017 https://www.undp.org/content/dam/rblac/docs/Research%20and%20Publications/Poverty%20Reduction/UNDP_RBLAC_Livelihoods%20Guidance%20Note_EN-210July2017.pdf.
[34] US Census Bureau. (2018). *County population Totals: 2010–2019*. (https://www.census.gov/data/tables/time-series/demo/popest/2010s-counties-total.html.
[35] US Department of Agriculture, Farm Service Agency, 2018 CRP Rental Rates and Grassland Rental Rates, Conservat. Reser. Program Stat. (2018) https://www.fsa.usda.gov/programs-and-services/conservation-programs/reports-and-statistics/conservation-reserve-program-statistics/index.
[36] USDA - Farm Service Agency. (2018). *Farm Service Agency Crop Acreage Data*. https://www.fsa.usda.gov/news-room/efoia/electronic-reading-room/frequently-requested-information/crop-acreage-data/index.
[37] USDA CRP program. (2020). *USDA Farm Service CRP Program and Statistics Reporting Portal*. https://www.fsa.usda.gov/programs-and-services/conservation-programs/reports-and-statistics/conservation-reserve-program-statistics/index.
[38] USDA Farm Production and Conservation Business CenterCounty-Level CRP and EQIP Dataset in the USA, Economics and Policy Analysis Division, Data Services Branch, 2020.
[39] USDA Farm Service Agency. (2019). *News Release of USDA to Open Signup for Conservation Reserve Program on December 9* [Government news release]. https://www.fsa.usda.gov/news-room/news-releases/2019/usda-to-open-signup-for-conservation-reserve-program-on-december-9.
[40] G.V. Wilson, F.D. Shields Jr., R.L. Bingner, R. Reid-Rhoades, D.A. DiCarlo, S.M Dabney, Conservation practices and gully erosion contributions in the Topashaw Canal watershed, J. Soil. Water. Conserv. 63 (6) (2008) 420–429 SI, doi:10.2489/jswc.63.6.420.
[41] W. Yang, F. Lupi, T. Dietz, J.(Jack) Liu, J. Liu, W. Yang, Dynamics of economic transformation, in: V. Hull, A. Viña, X. Chen, Z. Ouyang, H. Zhang (Eds.), Pandas and People: Coupling Human and Natural Systems for Sustainability, Oxford University Press, 2016, pp. 109–119.
[42] A. Yost, L. An, R. Bilsborrow, L. Shi, X. Chen, W. Zhang, Linking concurrent payments for ecosystem services in a Chinese nature reserve, Ecol. Econ. 169 (2020) 106509.