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Who is Vulnerable to Ecosystem Service Change? Reconciling Locally Disaggregated Ecosystem Service Supply and Demand

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ABSTRACT

Those living in marginal conditions can be vulnerable to changes in ecosystem services. Assessing vulnerability to ecosystem service change at disaggregated and community-relevant spatial scales is virtually absent in the literature. In this paper we develop a method to spatially assess communities' vulnerability to ecosystem service change by estimating trends in ecosystem service supply and demand interactions over time. We apply this method to analyze supply and demand dynamics around water security for 3873 settlements in the Miyun Reservoir watershed near Beijing, China. Community settlements were identified with high-resolution satellite imagery, allowing for a disaggregated assessment of supply and demand dynamics at a very fine spatial scale. Settlement-level demand trends are calculated with commonly available government statistics. Supply trends are estimated with land use data and common ecosystem service modeling software. Notably, our calculation of settlement-level ES supply is spatially aware, taking into account upstream communities' water needs. Our results reveal patterns of community vulnerability across the landscape and suggest ways to identify mechanisms that underlie communities' vulnerability risk. By analyzing trends over two periods, we are able to identify clusters that appear to adopt more sustainable management practices over time, and places where vulnerability to ES changes seems to persist.

1. Introduction

Ecosystem services (ES) are the aspects of ecosystem functioning from which humans derive benefits (Fisher et al., 2009). Provisions from ecosystems are indispensable and provide us with a range of services such as clean water (Brauman et al., 2007; Zheng et al., 2016), crop pollination (Koh et al., 2016), and protection from storm surges and flooding (Arkema et al., 2013). The draw of ES as an organizing framework is that it provides sound theoretical and conceptual grounds for linking natural systems to human wellbeing and can lead to more informed decision-making for managing landscapes and ecosystems (Millennium Ecosystem Assessment, 2005).

Especially in rural contexts where markets are often missing, livelihoods can be vulnerable to changes in ecosystem services. While much of the literature on ES has focused on measuring the supply of ES that is delivered from the landscape, more recently attention has turned toward understanding the interaction of ES supply and demand (Koh et al., 2016; Maron et al., 2017). Understanding the dynamics between ES supply and demand is fundamental to the relationship between poverty and ES (Daw et al., 2011). While the literature focusing on this intersection is growing, there is little guidance for looking at these in a dynamic or spatially disaggregate way. For example, in a generally static sense, ES supply and beneficiaries' demand have been studied for forested areas (García-Nieto et al., 2013; Górriz-Mifsud et al., 2016; Morri et al., 2014), water use (Burkhard et al., 2012; Nedkov and Burkhard, 2012; Stürck et al., 2014), pollination (Koh et al., 2016; Schulp et al., 2014), and urban ES (Baró et al., 2016; Casado-Arzuaga et al., 2013; Kroll et al., 2012; McDonald, 2009). Spatial mismatches between ES supply and demand have been conducted in some of this literature, but the analyses still tend to be aggregated to administrative units or a landscape scale (Morri et al., 2014; Schulp et al., 2014).

ES flows are mitigated and mediated by "upstream" populations, by locally available complements and substitutes for the ES, and by the precise physical and ecological makeup of the landscape from which the ES flows (Boyd, 2008). Thus, many ES values are inseparable from the location in which they are received. However, understanding how

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supply and demand are reconciled at disaggregated and community-relevant spatial scales is virtually absent in the literature (Rieb et al., 2017). Disaggregated ES analysis is crucial for identifying how communities use and relate to ES, to identify winners and losers from policies that affect ES flows, and to identify communities that are most vulnerable to ES change (Daw et al., 2011; Ferraro et al., 2011; Howe et al., 2014; Suich et al., 2015; Tallis et al., 2008; Wieland et al., 2016). Understanding how ES supply-demand dynamics affect local livelihoods, such as when areas with low supply are matched by areas of high demand, would help determine where to further investigate the well-being of local communities.

This paper introduces a framework for analyzing the spatial and temporal change of ES supply and the quantity of ES demanded to identify communities that are vulnerable to ES change. Vulnerability is largely a contextually-dependent condition that depends on adaptive capacity, sensitivity, and exposure to stressors (Adger, 2006; Weis et al., 2016). Here we look at conditions that may indicate exposure to water security stressors, highlighting places where further on-the-ground work could be done to investigate communities' sensitivity or adaptive capacity to observed ES changes. To do this, we track mismatches in ES supply and demand trends, incorporating a novel spatially-aware calculation of local supply that takes into account upstream supply and demand dynamics. Using high-resolution satellite imagery, we disaggregate these changes to the settlement level, which we define as visibly contiguous clusters of houses. Our methods for tracking changes in revealed demand are based on commonly-available government population data. Comparing changes in ES supply and demand trends allows us to identify communities that may be vulnerable to ES change. As a demonstration of our methods, we analyze trends in water resource security in the Miyun Reservoir watershed, in northeastern China, for 3873 population settlements over two periods: 1990–2000 and 2000–2009.

Our analysis of positive and negative co-occurrences of supply and demand trends yields several noteworthy findings. By categorizing communities into a matrix of positive and negative changes in supply and demand, we find spatially distinct clusters of communities that appear vulnerable to ES change and others that stay relatively stable or have low-risk changes over our two-period analysis. The aggregate patterns over the watershed broadly match our expectations based on local economic development and policy initiatives within each time period. However, disaggregating our results to the finer settlement level reveals great heterogeneity in who seems most and least at risk of ES change. By analyzing water trends over two periods, we are additionally able to identify clusters that appear to have improved management practices over time, and places where vulnerability seems to be persistent. Researchers or policymakers may then look to these places for potential lessons in adaptive capacity or factors that relate to greater exposure to water stressors, respectively.

2. Methodological Overview

Our goal is to estimate the supply of water delivered to individual settlements, and the quantity of water demanded by those settlements. To identify communities vulnerable to ES change, we compare trends in supply and demand. An underlying assumption is that if a community currently exist on available water resources, supply S must be greater than the quantity demanded D: $S > D$. Therefore, a community vulnerable to ES change, that is, vulnerable to supply being less than demand, $S < D$, must be in a situation where the change in supply is less than or equal to the change in the quantity demanded:

$$\Delta S \leq \Delta D.$$

While this is a necessary condition for a community to become vulnerable to ES change, it is not a sufficient identifying condition since a community with a decreasing but vast amount of water could meet increasing demand, at least temporarily. The core challenge in defining a sufficient condition is that the magnitude of supply and demand estimates are often uncertain, making a simple comparison of S and D alone inappropriate (Koh et al., 2016; Maron et al., 2017). As is consistent with the current literature, here we focus on the changes in trends in supply and demand.

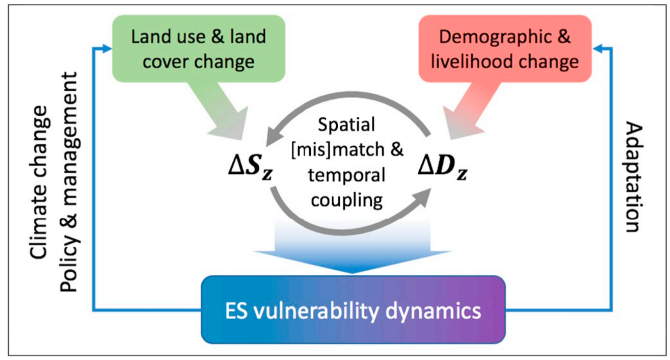

Fig. 1. A framework for assessing vulnerability to ES change.

We characterise ES vulnerability as fundamentally related to the dynamics between changes in ES supply and the quantity of ES demanded (Fig. 1). How these changes are paired for individual communities determines their exposure to stressors that may indicate vulnerability. Many factors can affect changes in ES supply and landscape dynamics on long time scales, such as climate change, or near-term scales, such as seasonal changes in biota or weather patterns. Here, we focus on estimating changes in ES supply, as indicated by the green box in Fig. 1, on medium-term (annual to decadal) scales that largely come from biophysical changes in the landscape such as changes in the quantities and configurations of land uses. On this same time scale, changes in the quantity of ES demanded (red box in Fig. 1) come from changes in preferences, consumption patterns, demographics, or other livelihood changes. Fig. 1 also indicates that communities' vulnerability may influence demand dynamically through adaptive behaviors, such as changes in consumption behavior or migration ('Adaptation' arrow). ES vulnerability can also be buffered on the supply side through ecological or social mechanisms ('Climate change; Policy & management' arrow). These feedback arrows are important and can endogenously determine vulnerability dynamics. However, in this study we primarily focus on the center of Fig. 1.

There are the three main steps in our methodology. First, using available data we calculate changes in the total quantity of water demanded for livelihood, agricultural, and industrial needs for each settlement. Second, we estimate changes in water supply for each settlement with a novel spatially-aware method. Third, we identify areas of concern by comparing differences in trends in ecosystem service change across the two periods. We discuss each of these steps in turn.

2.1. Estimating Demand Trends

To estimate demand trends, we calculate demand at each time points for which we have data, and then calculate changes between those time points. We focus on the quantity of water demanded by settlement z at a particular point in time, $D_{z,t}$, and track changes in that quantity demanded over time. Literature estimating water demand often focuses on deriving price elasticities to estimate potential changes in consumption for different price or policy scenarios (e.g., Klaiber et al., 2014; Olmstead et al., 2007). Our interest here, however, is in understanding how total quantities have changed, and whether those changes might signal impending scarcity. The quantity of water demanded (consumed) by settlement z at time t, $D_{z,t}$, is:

$$D_{z,t} = N_{z,t} * Q_{j,t} \quad (1)$$

where $N_{z,t}$ is the population of settlement z at time t and $Q_{j,t}$ is average per-capita water consumption in township j at time t. In this way, we describe patterns in the temporal changes in the quantity of water demanded over time. However, we do not explicitly explore the underlying dynamic mechanisms that drive changes in supply and demand.

2.2. Estimating Supply Trends

To estimate ES supply, we first use a spatially-explicit process-based water supply model to estimate water resources available in the landscape. Various models can be used for this, but most common for hydrologic ES seem to be the InVEST and SWAT models, often applied in data poor and (relatively) data rich contexts, respectively (Dennedy-Frank et al., 2016). In this paper we use InVEST 3.3.1 to estimate annual water yield from watersheds (Sharp et al., 2016), and thus water that is available to meet quantities demanded by communities. InVEST models relate changes in land use to changes in the ability of a landscape to supply some ES, and is one of the most widely used models for assessing ES supply (Nemec and Raudsepp-Hearne, 2013). InVEST's water yield model, especially, has received much attention, and has been empirically validated (Boithias et al., 2014; Redhead et al., 2016; Xiao et al., 2015) and tested against other models (Dennedy-Frank et al., 2016; Englund et al., 2017).

With spatial estimates of where water comes from on the landscape, we use a settlement's "serviceshed", or the spatial area from which the ES originates for a given population (Mandle et al., 2015; Tallis et al., 2015), to delineate the areas of the landscape from which the service is supplied. For a change in water provision, the serviceshed is simply the hydrologic catchment area for a given settlement. We identified each settlement's serviceshed within our study area using the "DelineateIT" tool in InVEST 3.3.1. The sum of the water yield pixel values within a serviceshed is the amount of water available to settlement z at time t, $W_{z,t}$.

However, other consumers of water may live within a settlement's serviceshed (Fig. 2). Accounting for the quantity demanded by upstream communities $D_{i,t}$, where i indicates a settlement upstream of settlement z at time t, we estimate the total annual water supplied to settlement z at time t as:

$$S_{z,t} = W_{z,t} - \sum D_{i,t}.$$

In this way the calculation of settlement-level supply is spatially aware: water supply for one settlement is the water yield from the whole serviceshed minus the total demand of all other upstream settlements located within its serviceshed.

2.3. Identifying Vulnerable Settlements

As mentioned above, here we focus on the *changes in trends* in supply and demand. While some literature has directly compared the quantity of ES supply and demand (Nedkov and Burkhard, 2012; Schröter et al., 2014; Schulp et al., 2014; Stürck et al., 2014; Syrbe and Walz, 2012), the magnitude of supply from spatial water yield models, which are based largely on annual precipitation and evapotranspiration raster data, can often be imprecise (Dennedy-Frank et al., 2016; Sharp et al., 2016). We follow Maron et al. (2017) and Koh et al. (2016) who use trends in the supply and demand to identify or categorize areas of concern.

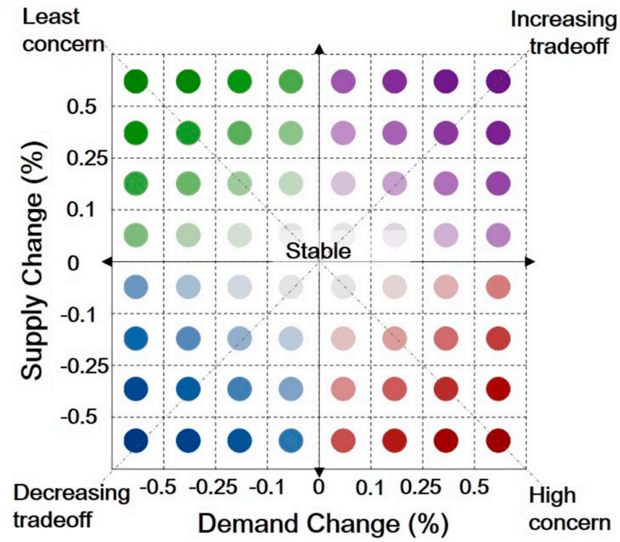

Fig. 3. Classification of communities' vulnerability. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For two points in time, t and $t+1$, the change in supply and quantity demanded for settlement z are respectively calculated as a percent change relative to time t:

$$\Delta S_z = \frac{S_{z,t+1} - S_{z,t}}{S_{z,t}} \text{ and } \Delta D_z = \frac{D_{z,t+1} - D_{z,t}}{D_{z,t}}.$$

Looking at changes in ES helps reveal the nature of the stability from both the social and ecological sides of the system. For example, a settlement that has an equivalent quantity of water supply over both periods may have no, little, or high risk of being vulnerable to ES change depending on local demographic and consumptive changes over the same periods.

To show how we classify settlement-level vulnerability to ES change based on these changes in supply and demand, Fig. 3 divides settlements into five distinct cases. First, settlements where changes in supply are positive $\Delta S_z > 0$ and changes in demand are negative $\Delta D_z < 0$ are of little concern (top left, green). If $\Delta S_z < 0$ and $\Delta D_z > 0$ then demand is growing while supply is decreasing, and these areas are of the of highest concern (bottom right, red). In cases where ΔS_z and ΔD_z are both positive or negative, supply and demand trends are increasing (top right, purple) or decreasing (bottom left, blue), respectively. We call these "tradeoff" regions since increasing (decreasing) supply may be

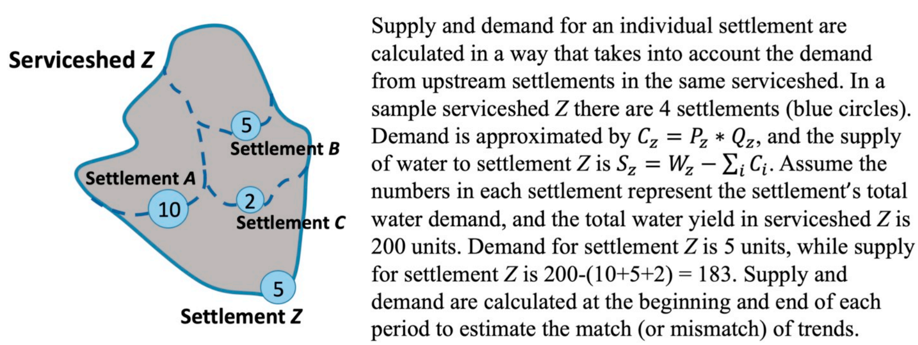

Fig. 2. Spatial accounting of upstream supply and demand dynamics.

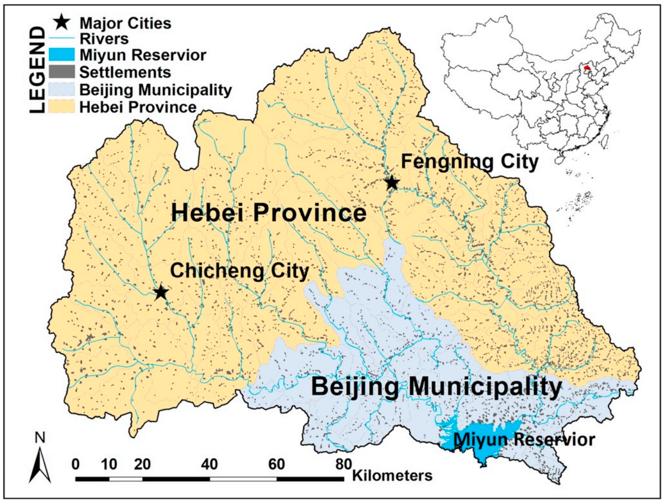

Fig. 4. The Miyun Reservoir watershed.

traded off with increasing (decreasing) demand. These are still areas to watch since the rate of increase in demand may be greater than that of supply, or the rate of decrease in supply may be greater than that of demand. However, categorizing these as potentially vulnerable would require certainty in the magnitude of supply and demand. A fifth case arises when $\Delta S_z \approx \Delta D_z \approx 0 \pm 10\%$, which we consider relatively stable (center, grey). Thus, the further away from the stable center, the more extreme is the settlement's condition.

3. Case Study

We use data from the Miyun Reservoir watershed, about 100 km north of Beijing, China, to demonstrate this method. Shown in Fig. 4, the watershed contains two river basins, the Bai and Chao Rivers, leading water from mountainous areas in the north and west to the Reservoir in the southeast. Out of 61 townships in the watershed, 20 belong to Beijing and 41 are in Hebei Province. The Miyun Reservoir was the only surface water source for domestic water in Beijing before 2015, and remains crucial for Beijing's water security as a reservoir for the North-South Water Transfer project (Liu et al., 2016). Besides providing water for the capital, this area is also important in combating desertification and preventing dust storms, providing nature-based recreational opportunities for the residents of Beijing, and providing livelihoods for nearly 1 million residents. Over the past two decades, the watershed has been host to a number of ecological and environmental conservation projects initiated by local and central governments (Peisert and Sternfeld, 2005).

We apply the methods outlined above to the Miyun context as summarized in Fig. 5. Supply and demand are calculated separately, two periods: 1990–2000 and 2000–2009. Our approach for calculating the quantity demanded and supplied is described below.

3.1. Estimating Demand in Miyun

Following the methods outlined above, we identify demand at the settlement level, which we define as contiguous housing clusters identified in high-resolution satellite imagery (ESRI, 2014). In the Miyun watershed we identified 3873 settlements (Fig. 4), each of which contains anywhere from several households to a small town.

To estimate N_{zt}, we use demographic and statistical yearbook data, some of which we collected directly from county government offices and others from statistical yearbooks (e.g., National Bureau of Statistics of China, 1991). We proportionally allocate township population in the years 1990, 2000, and 2009 to each settlement based on its residential area, assuming constant population density across settlements within the same township.

Here, the quantity of water demanded in township j at time t, $Q_{j,t}$, is the sum of three components that account for residential, agricultural, and industrial water consumption. The values and data sources used for these calculations are provided in the Appendix Table A.1. In each period (dropping the t subscript for the time being), residential average water consumption is weighted average of urban and rural per-capita consumption

$$Q_{res,j} = \frac{[(N_{u,j} * Q_{res,u}) + (N_{r,j} * Q_{res,r})]}{N_j}$$

where $N_{u,j}$ and $N_{r,j}$ are the urban and rural population of township j, respectively; $Q_{res,u}$ and $Q_{res,r}$ are the average per-capita water consumption of urban and rural residents, respectively; and N_j is total population of township j.

Agricultural water use is given as township-level per-capita averages by

$$Q_{ag,j} = \frac{A_{ag,j} * (irr/mu)}{N_{u,j} + N_{r,j}}$$

where $A_{ag,j}$ is the total cultivated area (in the Chinese area measure *mu*, 15 mu = 1 ha) in township j, and irr/mu is the average irrigation use per *mu*.

Industrial water use is only reported at the county level, so we assign this value to all townships within the county. Industrial water use is reported as consumption for a level of the industrial aggregate value added. Therefore, industrial consumption is

$$Q_{ind,j} = Q_{ind,k} = \frac{Q_{VA} * VA_k}{N_k}$$

where Q_{VA} is water consumption per 10,000 RMB value added, VA is the value added for county k in 10,000 s of RMB, and N_k is the county population.

Overall, Q_j for each of the townships is then:

$$Q_j = Q_{ag,j} + Q_{hh,j} + Q_{ind,j}.$$

These calculated values for township per-capita averages consumption quantities, Q_j, are given in the Appendix Table A.2. We then use these per-capita values of Q_j in Eq. (1), multiplying by the population of settlement z, N_z, resulting in settlement-level consumption estimates D_z. Notably, D_z, N_z, and Q_j all vary over the years 1990, 2000, and 2009.

3.2. Estimating Supply in Miyun

The key inputs to the InVEST water yield model follow a recent parameterization of this study region (Zheng et al., 2016), and are provided in Appendix Table A.3. Using InVEST, we estimate water yield from the landscape in the years 1990, 2000, and 2009. The model uses an expression of the Budyko curve (Baw-Puh, 1981; Zhang et al., 2004) to calculate the average annual runoff from each pixel, which is roughly equal to precipitation minus evapotranspiration, and is thus agnostic to whether water arrives at a point of consumption via surface, subsurface or base flow (Sharp et al., 2016). The output of the InVEST water yield model is a raster of water yielded from each pixel.

We create a polygon layer in ArcGIS with one polygon for each settlement's serviceshed. Servicesheds range from small catchments to catchments that cover the majority of the whole watershed for the most downstream communities. We aggregate InVEST's water yield results over all pixels within a serviceshed at each time point to estimate the total supply $W_{z,t}$ to each settlement z. We then subtract the quantity demanded $D_{i,t}$ by other settlements that fall within the serviceshed (if any) to calculate total supply for settlement z at time t, $S_{z,t}$.

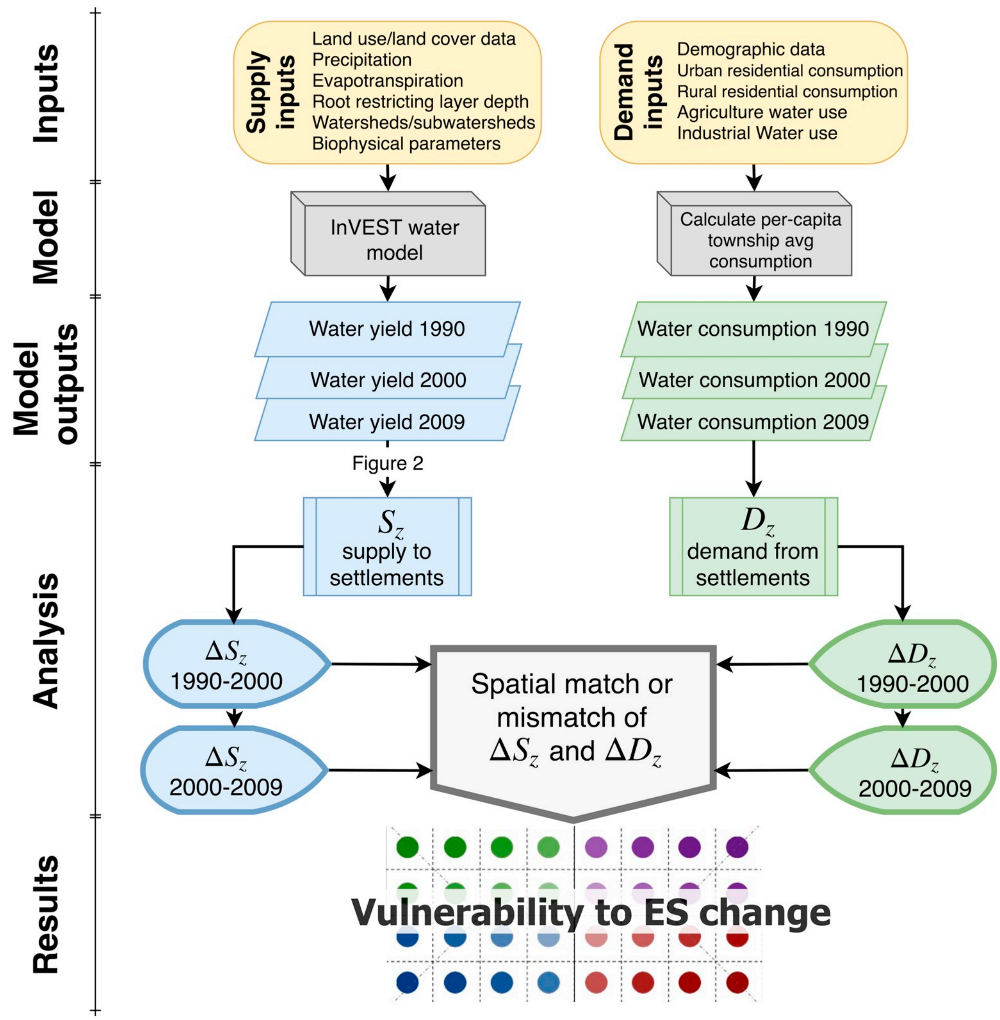

Fig. 5. Methodological workflow: schematic representation of how we assess ecosystem service change where supply and demand are estimated separately for each settlement.

3.3. Reconciling Supply and Demand in Miyun

To analyze the match or mismatch in supply and demand trends we look at changes in supply to a settlement, and the quantity demanded by that settlement, over the two time periods from 1990 to 2000 and from 2000 to 2009. As noted above in Section 2.3, we use trends in the supply and demand to identify areas of concern since we cannot be confident in the absolute magnitude of our models' estimates (although our measurements of supply and demand are quite comparable – see Table A.4).

4. Case Results

Fig. 6 presents the reconciliation of changes in supply and demand in the Miyun Reservoir watershed, as indexed by the vulnerability categories presented in Fig. 3. The size of the dot in the figure represents the total population of the settlements in the latter year of the time period. Clusters of spots indicate greater density of settlements.

During the 1990s (Period 1), 43% of the population (46% of settlements) fall into the quadrant of least concern (green), covering the north and middle of the Miyun watershed (Fig. 4.A). The second largest category is the high concern quadrant (red), with 22% of the population (22% of settlements), mostly gathered in the east and west of the study area. Increasing tradeoff (purple) and decreasing tradeoff (blue) settlements are scattered in the southern areas at 15% (10%) and 9% (12%) of the population (settlements), respectively. About 11% of the population (9% of settlements) are in areas where changes in supply and demand are relatively small and are thus deemed stable (grey).

The settlements across the watershed show various patterns of changes in vulnerability over the two periods. We have selected two regions in which to highlight spatial clustering that indicates the broad trends in the data. First we look at the cluster of settlements on the north shore of the Miyun Reservoir during the 1990s. The ES vulnerability of most of these settlements is relatively stable (lightly shaded in Fig. 6.A) but fall slightly into the quadrant of decreasing tradeoff. Second, in the cluster of settlements around Fengning City and to the north (a headwater of the Chao River), water supply increases (Fig. 6.C) and demand decreases (Fig. 6.D). Therefore, this area appears generally green (Fig. 6.A) and is not likely at risk of being vulnerable to water provisioning ES.

From 2000 to 2009 (Fig. 6.B), the portion of the population that falls into the red quadrant of high concern drops to 14% (22% of settlements), mainly clustered in the central eastern part of the watershed. Most settlements in Fig. 6.B are blue (46% of the population; 47% of settlements) or green (38% of the population; 32% of settlements), indicating a general decrease in demand from 2000 to 2009, as seen in Fig. 6.F. Areas where both supply and demand increase (purple) or are stable (grey) are relatively rare, making up 2% and 0.2% of the population (3% and 0.5% of settlements), respectively. Looking again at the example regions, water demand on the north shore of the Miyun

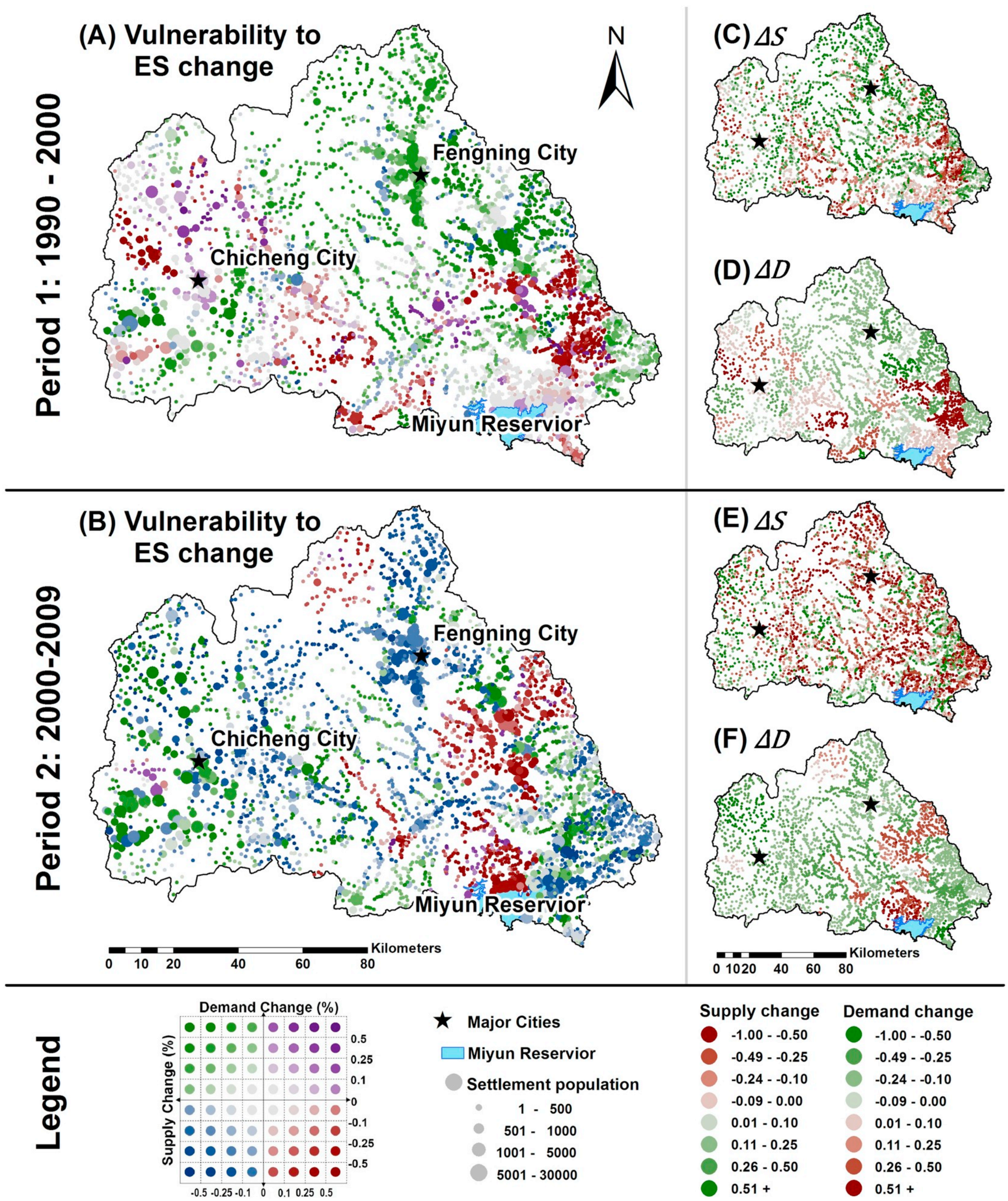

Fig. 6. Water supply and demand changes in period 1 and period 2 in the Miyun watershed. (A) Trend mismatches between supply and demand in period 1. (B) Trend mismatches between supply and demand in period 2. (C) and (E) are the water supply changes during period 1 and 2, respectively. (D) and (F) are water demand change during period 1 and 2, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Reservoir increases greatly (Fig. 6.F), with a corresponding decrease in water supply (Fig. 6.E) – now categorized as having a high risk of being vulnerable to ES change. Our second example cluster around Fengning City shows a general decrease in supply (Fig. 6.E) with the quantity demanded also decreasing (Fig. 6.F). This area's vulnerability to ES is uncertain, as most communities face a decreasing tradeoff (blue). In this case, a closer assessment of the local hydro-social dynamics is needed to determine whether the decrease in water supply is still adequate to meet the rate of decrease in the quantity the region demands.

While Fig. 6 focuses on the spatial distribution of vulnerability dynamics, Fig. 7 looks at the distribution of the watershed's aggregate population that falls into each category in each time period. For instance, in the first period, the green-most bar in the top left corner shows that there are almost 20,000 people living in this category ($\Delta D < 50\%$, and $\Delta S > 50\%$). Several trends are noteworthy. First, the 1990s were dominated by winners and losers, in other words, most of the population falls along the green-to-red diagonal. Second, over the 2000s demand decreased for most of the watershed residents. This puts most communities in areas that are at low ES vulnerability risk (green) or are in a decreasing tradeoff (blue). A smaller but tight cluster of communities are in the quadrant of high concern (red). Supply increases are almost non-existent. While the total population in the high concern category is similar over the two periods, comparing Fig. 6.A and B shows that the spatial distribution of those settlements is quite different.

5. Discussion

There are several interesting implications that come from our application of these methods. First, and perhaps most generally, our

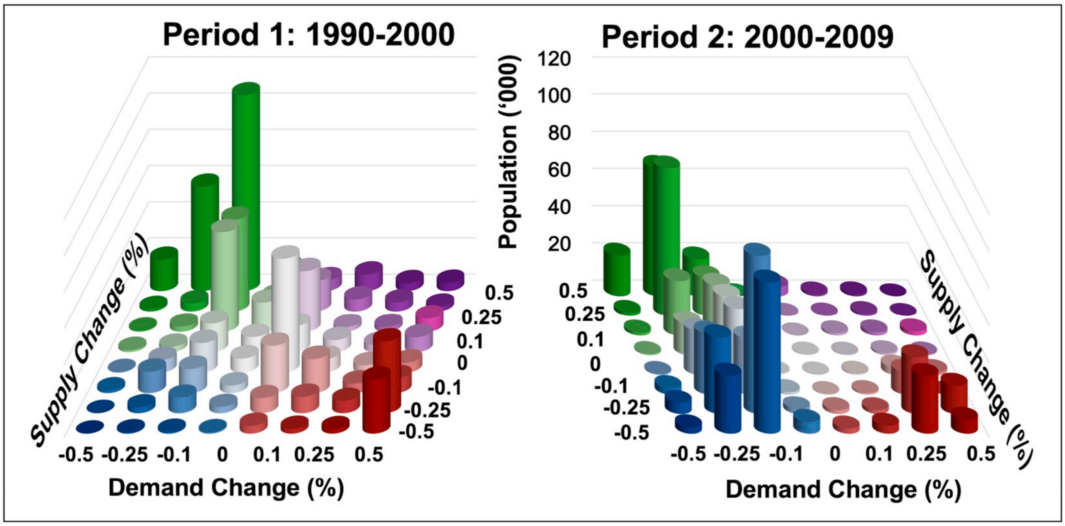

Fig. 7. Distribution of population in different vulnerability classes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

results show that just mapping the supply of the ES has little relationship to communities' potential vulnerability, highlighting the importance of taking into account the beneficiary side of ES dynamics. Thus, especially for application to policy, we must move beyond simply looking at the delivery of ES from the landscape but also better incorporate how populations need and use ES. Below, we further discuss implications for two other broad areas: policy development and uncovering drivers of change.

5.1. ES, Policy Impacts, and Scenario Development

Our results reveal different patterns over the two periods we investigate, reflecting the impact of policies, land use changes, and demographic trends in the region. For example, development in China during the 1990s largely focused on economic goals at the expense of other public goods, such as environmental quality, that might affect human well-being (Liu and Diamond, 2005) and induced wide-scale rural-to-urban migration (Rozelle et al., 1999; Zhao, 1999). The land use changes in the Miyun watershed during the first period from 1990 to 2000 show dramatic declines in forest and agricultural land, and gains in urban and grassland areas (Table A.5). In our water supply model, forest and agricultural land cover have higher evapotranspiration rates relative to grassland, which experienced the largest magnitude of growth over this period. Therefore, the overall land use changes (losses in forest and agriculture, replaced by grassland) translate to an increase in water yield across the watershed, which we observe in Fig. 6.C where supply increases (green) in much of the region.

Over the second period, the changes in land use (and thus ES supply) reflect other large-scale policies enacted during this period. Notably, national programs like the Grain for Green program and the National Forest Protection Program both aim to increase natural land cover, converting farmland and "wasteland" to forest and grassland (Xu et al., 2006). During the 2000s China also carried out massive afforestation/reforestation programmes that further increased forest cover (Lele, 2009; Lu et al., 2015). These changes lead to an overall decrease in water supply. Policies enacted in the early 2000s increased tree cover and other vegetation, increasing the portion of the landscape's water that returns back to the atmosphere through evapotranspiration. This, coupled with ongoing rural-to-urban migration in the region, meant that supply and demand both decreased, leaving many settlements in the blue *decreasing trade-off* category.

Looking forward, our results can help spatially target regions with vulnerable communities, and where risk could be mediated by related conservation programs, policies, or research investment. Scenarios could be used to explore the effect of enacting land use policies or programs, and the resulting change in distribution of ES benefits to the local population. A scenario that explores the effect of conserving certain land cover types, perhaps through a PES program, could help reveal where land protection could have the largest effect, and which communities might win or lose from such a change. Scenarios and modeling could be used to explore other expected changes, such as demographic change or other demand-side trends, to similarly analyze the likely winners and losers from enacting such ecosystem-based policies in the watershed.

5.2. Uncovering Driving Mechanisms of Vulnerability

Developing methods to show where changes in supply and demand trends co-occur positively or negatively is just the first step in relating ES dynamics to policy. The analysis above assesses supply and demand changes independently, but of course there are many ways in which the drivers of these changes may be related. We must also uncover the mechanisms behind those trends to really inform management decisions (Cord et al., 2017). By analyzing two periods of change, we open possibilities for highlighting locations where we might look to uncover specific mechanisms that drive community vulnerability. In our Miyun case, most settlements' ES vulnerability changed across the two periods, allowing us to look at vulnerability pathways over time. As one way to do this, Fig. 8 maps only the communities that are of least concern in the 2nd period. The colors of these communities in Fig. 8 are colored their categorization in period 1. By only focusing on communities that are least vulnerable to ES change, Fig. 8 highlights local "bright spots" for ES delivery (Bennett et al., 2016). These may be places that were vulnerable or questionable in period 1 (red, blue, or purple), but by period 2 were assessed as not of concern (green). These cases indicate areas where we could conduct further investigation into site-level dynamics through local interviews or models of site-level dynamics that seek to understand how or why those communities seem to do better over time. Fig. 8 also identifies clusters of settlements that were in the green quadrant in both periods, possibly revealing places further investigate how or why they have done consistently well over the two decades.

Being able to see supply and demand trends separately, and over two time periods, can provide further insight into mechanisms as well. For example, clusters of settlements that were originally blue (where supply and demand both decreased in period 1) but moved into the

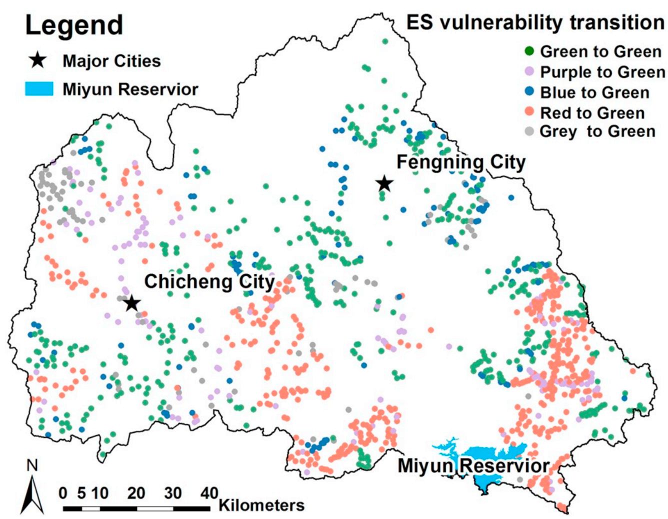

Fig. 8. Potential "bright spots" of ES change. Communities shifted into the green (least concern) quadrant from the first period to the second. Any settlements that changed to purple, red, or blue in the second period are not included. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

green category means that supply increased relative to demand over the two periods. Thus, the movement into the low-risk category is driven by (likely upstream) changes in land use characteristics associated with these communities. Indeed, we see the few communities shaded blue in Fig. 8 are in the watershed's headwaters, where landscape changes can have disproportionately larger influence on water supply. Following similar logic, locations that are purple in Fig. 8 represent a decrease in the quantity of water demanded relative to supply trends, indicating changes in consumption (such as more extensive emigration out of these areas) that may drive these results. The clusters that are red show communities that went from the highest concern to the lowest, where supply may have increased, demand may have decreased, or both. Looking deeper into these communities through field-based studies may reveal mechanisms that underlie these changes and broader lessons for sustainable management.

6. Conclusion

This paper presents a method for spatially and temporally disaggregating metrics of how ecosystem services relate to discrete communities at the settlement level. We do this by separately calculating the supply of ES delivery, and the quantity of those ES demanded at a settlement level. Importantly, our calculation of a settlement's supply is "spatially-informed" by taking into account any upstream consumption. Our data show the potential importance of looking at multiple periods of trends; looking at only one period oversimplifies potentially important temporal supply-demand dynamics.

Our methodology enables tracing changes in trends to clusters of communities that may be vulnerable to changes in ES. Too often communities at risk can be obscured by studies that aggregate results to administrative or watershed levels. Identifying potentially vulnerable communities can lead to better spatial targeting for policy initiatives where spatial heterogeneity would suggest a need for heterogeneous land management initiatives. Disaggregation to the settlement level also allows for a resolved understanding of possible winners and losers from ongoing land use changes due to policy implementation or general economic development, and how these might couple with demand dynamics that result from, for example, population change.

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Supplementary data

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