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Ecosystem service bundles in global hinterlands

Daniel Haberman and Elena M Bennett

1 Department of Natural Resource Sciences, McGill University, Ste-Anne-de-Bellevue, QC, H9X 3V9, Canada
2 McGill School of Environment, McGill University, Ste. Anne de Bellevue, QC, H9X 3V9, Canada
E-mail: daniel.haberman@mail.mcgill.ca

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Abstract

In the face of projected increases in globalization and urbanization, there is growing recognition that cities and their hinterlands will play a pivotal role in both creating and addressing the sustainability challenges of the future. Hinterlands, the rural areas that surround cities, are connected to cities as the source of many of the ecosystem services (ES) that are used in urban areas. While much is known about the provision of multiple ES in and around a few well-studied cities, there is a limited amount of consistently measured, global-scale data about the provision of multiple ES in urban areas and their hinterlands. We mapped eight ES globally, and examined how the production of ES varied between the hinterlands (within 200 km) of 768 major city centers (population > 500 000). We found that there are seven archetypes of ES supply bundles in global hinterlands. Hinterlands near wealthy cities are specialists in regulating ES production while the poorest and most populated hinterlands are specialists in food production, with low levels of regulating and cultural ES provision. These hinterlands also experience different synergies and tradeoffs between ES, with interesting implications for landscape management. Global teleconnections have likely also played a role in the ES bundles of hinterlands, since they have allowed cities to exploit remote areas to meet their demand for ES, undermining the traditional supply-demand relationship between each city and its proximal hinterland. These results emphasize the diverse, and sometimes inequitable, ways that urbanization and globalization are influencing ES supply in the planet’s most human-modified landscapes.

1. Introduction

Ecosystem services (ES) play an important role in cities, where two-thirds to three-quarters of the global population will live by 2050 (Gómez-Baggethun et al 2013). Studies of urban ES have flourished in recent years (Kremer et al 2015), resulting in increased knowledge about food supply (Altieri et al 1999), temperature regulation (Ziter et al 2019), air purification (Escobedo et al 2011), and recreation (Chiesura 2004), among other services. While much of this work has focused on a handful of ES in a single city, some multi-city comparisons have shown that cross-city comparisons are fundamental to better understanding urban ES (see e.g. the URBES project, which studied seven cities in the US and Europe; Kremer et al 2016). However, although there a growing body of work on urban ES, most studies typically measure only a single service in a single city, which precludes assessment of ES synergies and trade-offs (Ziter 2015). The variety of indicators used for each service further impedes cross-city comparisons (Luederitz et al 2015, Ziter 2015). Furthermore, few studies consider both services provided in urban areas as well as those provided in the areas surrounding cities.

Many of the ES used in cities, such as food and water, are produced in hinterlands, the rural areas that surround cities (Badcock 2002, Burkhard et al 2012, Jansson 2013, Seto et al 2013, He et al 2014). As the world’s population grows, and becomes increasingly urban, there is increased pressure on rural ecosystems to produce the ES needed to sustain people living in cities (Grimm et al 2008, Seto et al 2015). Yet the types and quantities of ES produced in different hinterlands around the world, and the types of ES tradeoffs faced in hinterlands as a result of both local and faraway
demand, remain poorly understood (Larondelle et al. 2014). Understanding the production of ES in hinterlands, and the factors that determine variation in the amounts and types of services produced, would provide insight into how these areas are being used to provide ES that benefit urban residents at multiple scales around the world.

Landscapes that provide multiple ES often experience tradeoffs and synergies between particular services, leading to bundles of ES that repeatedly occur across different landscapes (Bennett et al. 2009, Raudsepp-Hearne et al. 2010). In hinterlands, the makeup of common ES bundles can be driven by urban processes because it is largely urban demand, in combination with the biophysical nature of the landscape, that drives ES production in rural areas (Hamann et al. 2015, Renard et al. 2015). Case studies of individual cities around the world have shown that their proximal hinterlands produce different types and quantities of ES (Burkhard et al. 2012, Kroll et al. 2012, Larondelle and Haase 2013, Larondelle et al. 2014). The supply of, or demand for, sets of ES produced in these hinterlands can sometimes be predicted with socioeconomic and biophysical variables, such as population density, income, soil quality, and distance to a city (Hamann et al. 2015, Renard et al. 2015). However, these factors have been assessed only within the context of specific case studies, and have never been assessed using a globally consistent set of indicators that enables comparisons among hinterlands. Furthermore, previous case studies on ES production in hinterlands do not discuss the implication of teleconnections from other cities globally (Seto et al. 2012). To fully understand the relationship between urbanization and rural ES and its implications for sustainable development, ES science must do a better job of explicitly linking the ES bundles that are produced in hinterlands to the people in cities around the world that drive a majority of the demand for ES (Güneralp et al. 2013, Kremer et al. 2016).

We aim to answer the following three questions: (i) what are the archetypes of ES bundles produced in hinterlands around the world, (ii) what patterns exist between these ES bundles and biophysical and socioeconomic variables that describe the regions, and (iii) how are ES tradeoffs and synergies different across different hinterlands? We map eight ES globally and examine how these ES are supplied within the planet’s major hinterland landscapes. Contrary to traditional definitions of a hinterland, which encompass only rural areas (Badcock 2002), we examine rural hinterlands together with their nearby cities in order to examine the full array of ES supply that occurs in these heterogeneous landscapes (Burkhard et al. 2012). We focus on ES supply (rather than demand) because we are interested in understanding how bundles of multiple ES are produced in a wide variety of cities and city types around the world, and especially in whether some types of cities favor the production of certain types of ES over others. We examine the archetypes of ES bundles that are produced in different hinterlands of the world using an affinity propagation clustering algorithm and test how these bundles relate to biophysical and socio-economic variables of each hinterland. Lastly, we discuss how processes in urbanization and globalization have led to the current distribution of ES bundles across the world’s major hinterlands.

2. Methods

2.1. ES models

We quantified and globally mapped the supply of eight ES for the year circa-2000 using diverse datasets and models; three provisioning (crop, livestock, water), four regulating (carbon sequestration, carbon storage, air quality, water quality), and one cultural (nature recreation). With the exception of the indicator for water quality, we selected the ES indicators to represent the supply of ES, rather than the demand, flow, or pressure, so that the indicators could be combined into a service bundle and represent a consistent aspect of ES production. We used phosphorus loading as the indicator for water quality, which is an ecosystem pressure, but has been used to represent ES supply in multiple other studies (Nelson et al. 2009, Qiu and Turner 2013). Table 1 describes each ES, its associated indicator, and data sources. Where available, we used pre-existing datasets that represented an ES indicator directly or required minimal transformation. In cases where we used a model, we chose input datasets that had global coverage and temporal coverage for the year 2000. Information on the individual ES models, justification for ES indicators, and how the data sources were modified are presented in appendix B is available online at stacks.iop.org/ERL/14/084005/mmedia.

2.2. Delineating hinterlands

We examined the mean supply of ES in the year 2000 in the hinterlands of all cities with populations greater than 500 000 (n = 768) (United Nations 2014) (figure A.1). The hinterland for each study site was delineated using a buffer distance of 200 km from each city center, and included the entire urban-rural gradient therein. When any part of the 200 km buffer overlapped with coastal or aquatic systems, the hinterland assessed included only the land area. The urban areas encompassed in each landscape are capable of producing important ES (Gómez-Baggethun et al. 2013) and so were included in the assessment, although they represent a relatively small area of each landscape. The buffer distance was selected to be adequately large to rigorously measure ES supply from some of the coarser resolution ES supply maps, while not overly large to represent an area outside of the cities’ sphere of influence. To verify that the size of the hinterland did not have a large effect on the results, we re-analyzed the data post hoc with 250, 150, and 100 km
Table 1. Ecosystem services quantified using a mix of global datasets and models.

| Ecosystem service  | Indicator/unit                                                                 | Resolution | Data year | Datasets                                                                                     | Model          |
|--------------------|-------------------------------------------------------------------------------|------------|-----------|---------------------------------------------------------------------------------------------|----------------|
| **Provisioning**   |                                                                               |            |           |                                                                                             |                |
| Crop               | Harvested crops (kg)                                                          | ~10 km     | 2000      | Monfreda et al (2008)                                                                        | N/A            |
| Water              | Provision to downstream humans km\(^{-2}\)                                   | ~50 km     | 2000      | Green et al (2015)                                                                           | N/A            |
| Livestock          | Calories from cows, pigs, chicken, sheep, and ducks                            | 1 km       | 2005      | (Robinson et al (2014), US Department of Agriculture (1992, 2015))                         | N/A            |
| **Regulating**     |                                                                               |            |           |                                                                                             |                |
| Carbon sequestration| Net ecosystem exchange (kgC yr\(^{-1}\))                                     | ~50 km     | 2000      | Zhao et al (2005), Climatic Research Unit (CRU) (2013)                                      | Hashimoto et al (2015) |
| Carbon storage     | Above and below-ground storage (kgC)                                          | 1 km       | 2000      | Ruesch and Gibbs (2008), Hiederer and Kochy (2011)                                          | N/A            |
| Air quality        | SO\(_2\) and NO\(_2\) dry deposition index                                  | ~10 km     | 2005      | Nowlan et al (2014)                                                                         | N/A            |
| Water quality      | Inverse phosphorus loading index                                              | ~50 km     | 1995      | Vorosmarty et al (2010)                                                                     | N/A            |
| Cultural           |                                                                              |            |           |                                                                                             |                |
| Recreation in nature| Recreation index                                                              | 1 km       | 2000      | Sanderson et al (2002), Nelson (2008), IUCN and UNEP-WCMC (2015), Wessel and Smith (2016) | Paracchini et al (2014) |

Indicators were chosen based on the availability of data, as close to the year 2000 as possible. Details of how the datasets and models were used to produce the final ES are provided in supplementary information.
radius hinterlands (table C.1) to ensure the radius size did not have a large impact on the ES bundle results. Although the sphere of influence of each city encompasses areas outside a simple 200 km buffer in its surroundings, globally these 768 major urban hinterlands compromise nearly all of the word’s croplands, with the leftover land surface comprising largely remote forest, bare ground, and tundra (see figure A.1 and table A.1).

2.3. ES bundles and interactions
ES bundle archetypes were identified using an affinity propagation clustering algorithm (Frey and Dueck 2008). Affinity propagation works by creating a similarity matrix of the input data and iteratively choosing subsets of the data and identifying representative archetypes from each subset. The user specifies the shared preference of each point to become the representative archetype of its own cluster. Since clustering is an exploratory analysis with no objectively correct answer, this value could be the median of the input similarities for a moderate number of clusters, or the minimum of input similarities for a small number of clusters. Affinity propagation has been shown to produce cluster groupings faster and with lower error than other methods such as k-means (Frey and Dueck 2008).

Prior to clustering, the provision of each service was standardized using z-scores to account for the different magnitude of units between ES indicators. A PCA was run on the eight ES to reduce the dimensionality in the data and the processing time of the clustering algorithm. Following Kaisers criterion (Kaiser 1960), the first 2 axes of the PCA were maintained. For comparison, the affinity propagation was run on the PCA axes, in addition to the raw standardized data. The affinity propagation was carried out in R (R Core Team 2014) with the apcluster package (Bodenhofer et al 2011). The input preference was set to the minimum of the input similarities, searching for a relatively low number of clusters. The analysis using the PCA data resulted in a 7 cluster solution whereas the raw data produced a solution with 11 clusters. The four additional clusters produced from the raw data were all very similar to one of the clusters from the PCA solution, therefore the 7 cluster solution was selected to present the results.

To assess interactions between services, we computed Pearson’s correlations of the mean supply of ES in all hinterlands. We repeated this process for a subset of each bundle archetype to examine how interactions change within each archetype.

2.4. Ancillary data
We used existing global datasets for socio-economic and biophysical variables that we expected to have a relationship with the provision of one or multiple ES; these variables and their sources are presented in table 2. These variables were selected based on their availability at high resolution, sub-national scale, and were selected to match the dates of the ES models (circa-2000). The value of each variable was extracted for each hinterland (for more information see appendix C). We used these variables to look for patterns in the ES bundles that were determined.

3. Results and discussion

3.1. ES bundles and interactions in global hinterlands
The cluster analysis revealed seven archetypes of ES supply bundles that occur in the hinterlands of large cities around the world. An archetype is distinguished by its unique mix of service provision. We have named each archetype according to a well-known city that is a member of that bundle type; these cities are not necessarily the most representative of their ES archetype but are used as archetype names for clarity (figure 1). In the Paris and Toronto archetypes, hinterlands produce average and below-average amounts of all ES, respectively, and are not specialized producers of any particular ES. The other archetypes are more specialized, producing more than average amounts of one or two particular ES and less than average amounts.

Table 2. Covariates used to predict hinterland membership in ES bundles.

| Independent variable | Data source | Resolution | Data year |
|----------------------|-------------|------------|-----------|
| Socio-economic variables | | | |
| Total population | Center for International Earth Science Interaction Network | 1 km | 2000 |
| Gross domestic product (GDP) per capita | Nordhaus (2006) | 1° | 2000 |
| Impervious surface area | Elvidge et al (2007) | 1 km | 2000–01 |
| Biophysical variables | | | |
| Growing degree days | Harris et al (2014) | 0.5° | 2000 |
| Precipitation | Harris et al (2014) | 0.5° | 2000 |
| Elevation | Jarvis et al (2008) | 90 m | 2000 |
| Slope | Jarvis et al (2008) | 90 m | 2000 |
| Latitude | United Nations (2014) | N/A | N/A |
| Distance to coast | Wessel and Smith (2016) | N/A | 2016 |
of others. The Las Vegas archetype is degraded in its production of almost all ES, except water quality. The Shanghai and Mumbai archetypes are especially good at producing crops and livestock; however, they have a reduced ability to provide water quality. The Berlin and Singapore archetypes specialize in regulating services (e.g. carbon sequestration and storage), but offer little in terms of provisioning ES.

Figure 1. Seven distinct ES bundle archetypes found in hinterlands around the world.

Figure 2. Location of all hinterlands (n = 768), their population size, and their ES bundle archetype.
The dashed gray line represents the mean value of ES supply (z-score = 0) from all examined hinterlands. The error bars in each panel depict the standard deviation of each service within that bundle archetype. For convenience, each archetype is named after a major city that produces that ES bundle.

Some of the ES bundle archetypes are geographically dispersed whereas others are geographically concentrated (figure 2). The Shanghai and Mumbai archetypes, the agricultural specialists, are highly concentrated in the most populated region on the planet, Southern Asia; the Shanghai archetype occurs predominantly in China and the Mumbai archetype exclusively in India. The Las Vegas archetype is globally dispersed among the world’s major deserts. Similarly, the Singapore archetype is located mainly in tropical or sub-tropical regions. The remaining archetypes (Toronto, Berlin, and Paris) do not follow any clear geographical pattern.

The Shanghai and Mumbai bundles are geographically clumped in China and India, respectively. Europe and the Americas feature more heterogeneity in ES bundle archetypes.

Although we found many of the typical interactions between services when examining all hinterlands together (e.g. tradeoffs between agriculture and most other services), the strength, and even sometimes the direction of these interactions is diverse across archetypes (table 3). Across all hinterlands, there is a negative correlation between crop production and four ES: water quality \( r = -0.32 \), nature recreation \( r = -0.37 \), and carbon sequestration \( r = -0.33 \), and carbon storage \( r = -0.32 \). However, within certain ES bundle archetypes, the tradeoffs typically associated with agriculture can be insignificant, and sometimes can even become synergies (e.g. \( r = 0.49 \) between crop production and carbon sequestration within Las Vegas archetype hinterlands). These differences in agricultural tradeoffs amongst hinterlands might relate to differences in hydrology, land use, or farm management in these regions.

The Mumbai and Shanghai archetypes are both agriculture specialists, however they provide different amounts of non-food ES. Compared to the Mumbai archetype, the Shanghai archetype provides marginally more crop and marginally less livestock, and has much worse water quality (figure 1). In addition, the Shanghai archetype has much higher air quality regulation and water provisioning. The tradeoffs between food production and non-food ES also differ within these two archetypes (table 3); for hinterlands in the Mumbai archetype, crop provision is positively correlated with carbon sequestration \( r = 0.32 \) whereas in the Shanghai archetype this relationship is negative \( r = -0.49 \). The relationship between livestock provision and air quality in these same archetypes also diverge \( r = 0.42 \) and \( r = -0.41 \), respectively. Surprisingly, the tradeoff between crop production or livestock production and water quality is not significant within either archetype. Instead, the strength of this tradeoff appears to be greatest within the Berlin \( r = -0.66 \) and Singapore archetypes \( r = -0.35 \).

### 3.2. Patterns between ES bundles and ancillary variables

The biophysical environment displayed clear patterns with the membership of hinterlands in some ES bundle archetypes, whereas the membership in other archetypes seems to be more related to socio-economic variables, or a mix of the socio-economic and biophysical factors (figure 3). The Shanghai bundle occurs principally under conditions of extremely high population and impervious surface area. Additionally, they tend to appear in low elevation areas that are relatively close to coastlines. Likewise, the Mumbai bundle, which produce a similar ES bundle, also occurs in areas with large populations, however these areas tend to have less impervious surface area, are closer to mid-latitude, have more growing degree days, and often coincide with extremely low GDP per capita.

The Las Vegas bundle appears mostly in high elevation areas with extremely low amounts of precipitation, and low levels of population and impervious surface area. These hinterlands tend to be prevalent in desert environments, which explains their degraded ability to provide all services except water quality and recreation, since our indicator for water quality is the inverse of phosphorus loading, which is near zero under dry conditions (Vorosmarty et al 2010). Mirroring these pattern in many ways, the Singapore bundle also appears under high elevation, less urbanized landscapes, however these landscapes tend to have higher GDP per capita and receive much more precipitation, often appearing in extreme high and low latitudes.

Each panel depicts a socio-economic of biophysical variable. The area at top represents the proportion of each bundle type that is prevalent. For added context, the overall number of hinterland sites is also provided as a black line.

The Paris and Toronto bundles, two of the most common and ‘jack-of-all-trade’ bundles, occur in very different contexts, although their ES bundles are similar. The Paris bundle is more probable closer to coastline, under more urban conditions and higher levels of precipitation. Conversely, the Toronto bundle generally occurs in areas with higher GDP per capita, lower slope, and further from coastlines. Since, according to our delineation of hinterlands (using a buffer), coastal hinterlands had a smaller land area, we examined the distribution of ES bundle types as distance from a coastline increases and found no clear patterns in the affected hinterlands that are within 200 km from a coastline (figure C.2), indicating that this assumption did not strongly influence our findings.

The Berlin bundle, although the least common bundle overall, is most probable in landscapes with
Pairwise Pearson correlations showing interactions between services in all hinterlands and within each ES bundle group.

| ES type | ES type          | All        | Toronto    | Shanghai   | Mumbai     | Las Vegas  | Berlin     | Singapore  | Paris      |
|---------|------------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Provisioning | Regulating       |            |            |            |            |            |            |            |            |
| Crops   | Carbon storage   | −0.29*     | 0.20*      | −0.34*     | −0.26*     | −0.15      | −0.10      | −0.19*     | 0.10       |
| Livestock| Carbon storage   | −0.05      | 0.06       | −0.11      | 0.00       | 0.37*      | −0.13      | 0.16*      | 0.23*      |
| Water   | Carbon storage   | −0.17      | −0.12      | −0.16      | −0.06      | 0.02       | −0.31*     | −0.12      | −0.02      |
| Livestock| Air quality      | −0.45*     | −0.09      | −0.41*     | 0.42*      | 0.26*      | 0.38*      | 0.19*      | −0.15      |
| Livestock| Water quality    | −0.38*     | 0.34*      | 0.06       | 0.32*      | −0.05      | −0.40*     | −0.29*     | 0.06       |
| Water   | Carbon storage   | −0.08*     | −0.20*     | −0.13      | 0.13*      | 0.06       | −0.18      | 0.08       | −0.18*     |
| Livestock| Carbon storage   | −0.17      | −0.12      | −0.16      | −0.06      | 0.02       | −0.31*     | −0.12      | −0.02      |
| Livestock| Air quality      | −0.45*     | −0.09      | −0.41*     | 0.42*      | 0.26*      | 0.38*      | 0.19*      | −0.15      |
| Livestock| Water quality    | −0.38*     | 0.32*      | 0.44*      | 0.10       | −0.01      | −0.11      | −0.19*     | 0.26*      |
| Water   | Carbon storage   | −0.07*     | 0.05       | 0.42*      | 0.06       | −0.10      | −0.09      | 0.12*      | 0.30*      |
| Water   | Air quality      | 0.53*      | 0.02       | −0.50*     | −0.22      | 0.26*      | 0.25       | 0.47*      | 0.10       |
| Water   | Water quality    | −0.38*     | 0.32*      | 0.44*      | 0.10       | −0.01      | −0.11      | −0.19*     | 0.26*      |
| Provisioning | Cultural         |            |            |            |            |            |            |            |            |
| Crops   | Recreation       | −0.37*     | −0.01      | −0.29*     | −0.11      | 0.14       | 0.42*      | 0.06       | 0.33*      |
| Livestock| Recreation       | −0.24*     | −0.07      | −0.13      | 0.09       | 0.03       | 0.35*      | 0.01       | 0.10       |
| Water   | Recreation       | 0.56*      | 0.17*      | 0.00       | −0.15      | 0.00       | 0.11       | 0.20*      | 0.26*      |
| Provisioning | Cultural         |            |            |            |            |            |            |            |            |
| Carbon  | Recreation       | 0.27*      | 0.34*      | 0.54*      | −0.38*     | 0.01       | −0.12      | −0.22*     | −0.10      |
| Carbon  | Carbon storage   | −0.01      | 0.31*      | 0.68*      | 0.40*      | 0.08       | 0.31*      | −0.37*     | 0.20*      |
| Air quality | Recreation   | 0.13*      | 0.40*      | 0.03       | −0.42*     | −0.02      | 0.42*      | 0.06       | −0.20*     |
| Water quality | Recreation | 0.15*      | 0.03       | −0.04      | −0.28*     | −0.08      | −0.40*     | 0.06       | 0.15       |

Positive correlations ($r > 0$) indicate synergies between services whereas negative correlations ($r < 0$) denote tradeoffs. Tradeoffs with a magnitude greater than 0.3 are emboldened. The star subscript shows which interactions are significant ($p < 0.05$).

relatively high levels of wealth and impervious surface area, and medium levels of population and growing degree days (figure 3). Overall, Wealth had different relationships with the provision of each individual ES in hinterlands (figure C.1). All provisioning services were negatively correlated with GDP per capita, whereas all regulating and cultural services were positively correlated with GDP per capita. The highest concentrations of people live in cities where their proximal hinterlands have low levels of wealth, and produce average or below average amounts of all services. At extreme low levels of wealth there is a large range in the quantities of ES provided; some impoverished hinterlands produce extremely high levels of livestock, water provisioning, crops, or carbon storage, whereas few of these hinterlands produce high amounts of other ES.

3.3. Urban development and trade influence ES bundle in nearby hinterlands

Our results show that the richest hinterlands tend to produce more regulating ES, whereas, at extreme levels of poverty, these hinterlands tend to produce more provisioning ES, and none of them produce the Berlin ES bundle—which is a regulating ES specialist (figure B.1 and 3). It may be that the economies of richer cities are dominated by the service sector (Taylor 2011), sparing their hinterlands from the primary industries and agricultural uses that tend to erode regulating and cultural services.

Cumming et al (2014) posited that poorer and less developed agrarian societies use more domestically-produced ES, whereas wealthier industrial societies extract more of their ES remotely, have little direct contact between residents and their local ecosystems, and place higher value on regulating services. Our results provide empirical evidence to support this hypothesis, and elucidate the types of ES bundles that occur in hinterlands under varying levels of urbanization and wealth. ES demand and land requirements increase with affluence (Mcdonald et al 2013, Weinzettel et al 2013); however, residents in high-income cities may be able to consume more overall ES per capita while at the same time sparing regional land for the provision of regulating services by purchasing their provisioning services from elsewhere (Srinivasan et al 2008, Weinzettel et al 2013, Berbes-Blazquez et al 2016). In contrast, while we did not track ecosystem
disservices, other studies have shown that disservices mirror socio-demographic trends (Dobbs et al 2014), and are also important to understand for urban management (von Döhren and Haase 2015).

Hinterlands are increasingly used to provide ES to distant cities through teleconnections, creating a global network of winners and losers associated with ES provision to multiple stakeholders with differing needs and exploitative power (Rodríguez et al 2006, Seitzinger et al 2012, Felipe-lucia et al 2015, Berbes-Blazquez et al 2016). We use the term ES teleconnection to mean the coupled relationship between areas of human consumption and areas required to produce an ES that occur over a broad geographic extent, including trade (e.g. food) and global-scale flows of ES benefits that occur without direct trade (e.g. carbon storage). For example, deforestation throughout the tropics (in 2000–2005) was positively correlated with increases in agricultural exports and urban populations (DeFries et al 2010), suggesting that these areas were deforested to produce ES benefits that were experienced elsewhere while agriculture-related ES costs such as losses in water quality were experienced locally. These cross-scale flows of ES can lead to inequitable sharing of ES benefits, and inequitable sharing of the costs or tradeoffs required to produce these ES (Srinivasan et al 2008, Lambin and Meyfroidt 2011, Weinzettel et al 2013).

The hinterlands belonging to the Shanghai and Mumbai archetypes are among the most populated areas and provide exceptionally high amounts of food at the cost of producing regulating and cultural services; however, the interactions among ES indicate that in some ways these hinterlands may be more suitable to produce large quantities of food in that they face fewer trade-offs of agricultural production than other hinterland bundle types (table 3). Although globally, some ES tradeoffs are avoided by producing high levels of agriculture in hinterlands of the Shanghai or Mumbai archetype, the brunt of the resulting ES tradeoffs may be borne by some of the world’s poorest people as a result. However, the majority of
crop-related ES tradeoffs in these areas are unlikely to be caused by teleconnections, since neither China nor India export an exceptionally large fraction of their food production, and China imports more calories than it exports (Macdonald et al. 2015). Even if this crop production is destined for local consumption, by focusing on efficient production of food that minimizes ES tradeoffs with regulating services, the long-term resilience in these agricultural landscapes may be undermined (Bennett et al. 2014), and the rural communities that live nearby must live with the resulting ecological degradation and pollution.

Better understanding of the mechanisms between urbanization and the types of ES bundles that hinterlands produce might allow purposeful transitions between bundles, or creation of entirely new bundle archetypes. As the principle consumers of ES, urban areas have the ability to enact innovations with resounding consequences on ES production in rural hinterlands (Folke et al. 1997). For example, programs to encourage stewardship of green infrastructure by urban residents can help to reconnect residents to the biosphere and restore their instincts to preserve ecosystems (Seitzinger et al. 2012, Andersson et al. 2014). While our results uncovered general patterns between wealth, population size, and ES bundles, the mechanisms underlying these relationships within the global urban-rural nexus lack adequate empirical evidence, although some progress has been made (Gumming et al. 2014).

Our study expanded on previous efforts to produce global, spatially-explicit ES models by updating data sources and providing models for eight (as opposed to four) ES (Naidoo et al. 2008); however, there were some limitations. The ES chosen for this study were those that were possible to be mapped globally, and may not accurately reflect the entire array of ES that are important around the world, or ES that have great importance within specific regions (especially cultural ES). As with other global research, our study relies on highly aggregated datasets that can mask dynamics occurring on smaller scales or that are not accurately reflected in our choice of ES indicator (e.g. although phosphorus loading has been used as an ES indicator in countless studies, it does not accurately reflect all the dimensions of water quality). Similarly, by using a snapshot approach and modeling all service for the year circa-2000 due to the limits of data availability, the slight temporal differences between data sets may have impacted the types we identified, we may have overlooked spatio-temporal aspects of interactions between services (Renard et al. 2015) and some cities may have since changed bundle types within the last two decades. Lastly, our definition of a hinterland landscape included the city itself and the surrounding rural area, rather than the traditional definition which includes only the rural areas that are under the sphere of influence of a city (Jansson 2013). We assumed that hinterlands were circular and extended 200 km from city centers, an area vast enough that impervious surface occupied a very small portion of each study site. Our study sites were distributed according to the geographic distribution of urban populations, which is spatially uneven and likely influenced the types of archetypes that were produced. Due to teleconnections, it is nearly impossible to delineate the true area of influence of each city; instead, our hinterland definition serves mainly as a unit of analysis to examine how ES are supplied in cities and in their proximal areas.

Better data, especially updated, globally-consistent measures of both ES provision and ES demand across space and time will further improve our understanding of ES provision in cities and their hinterlands. While the implications of teleconnections have been incorporated into other natural sciences (e.g. biodiversity science (Lenzen et al. 2012)), ES science has lagged behind in addressing how teleconnections are altering the supply and demand of ES, and potentially leading to inequitable sharing of the costs and benefits associated with ES production (Liu et al. 2013). While progress has been made in ES supply mapping, more information is needed on the consumption of ES in cities, and the supply chain of ES delivery from areas of supply to areas of demand (Serna-Chavez et al. 2014). Others have called for a national monitoring system of ES (Tallis et al. 2012); high-resolution monitoring systems would allow for better understanding of how urban development effects the ES supply in hinterlands over different phases of development. Overall, this type of information would help to identify cases where cities are inequitably driving ecological degradation, and could potentially offer multi-scale solutions to meeting ES demand in cities without degrading nearby or distant hinterlands.

4. Conclusion

Around the world, hinterlands, important producers of ES, differ markedly in the bundle of ES they provide. Biophysical variables alone do not explain the ES bundle produced in the hinterland of any given city; socio-economic variables such as wealth and population size are also show distinct patterns with the types of the services produced. ES bundles specializing in food production occur primarily in hinterlands that are poor and highly populated, whereas hinterlands in rich countries tend to feature mostly regulating ES with very little food production. Understanding the socio-ecological processes that have led to this distribution of ES bundles amongst the planets’ hinterlands is essential for more equitable and sustainable use of these important regions.

Cities are increasingly shaping the Earth system (Elmqvist et al. 2013). Understanding the ecological impacts on rural areas due to the ES demands of urban residents will be critical to increasing both global and
local sustainability (Seitzinger et al 2012). Cities will play a pivotal role in both causing and overcoming the challenges of the Anthropocene (Elmqvist et al 2013); urban residents’ demands for ES have led to the domestication of nature and consumption of natural capital (Grimm et al 2008), yet cities are also engines of innovation that have historically developed and enacted solutions to challenges as they arise (Bettencourt et al 2007). Meeting the ecological demands of an increasingly urban population will require policies that consider the interconnected relationships between the global network of cities in concert with the types of ES produced in rural hinterlands.

ORCID iDs

Daniel Haberman @ https://orcid.org/0000-0002-9672-9674
Elena M Bennett @ https://orcid.org/0000-0003-3944-2925

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