

Ecosystem service bundles for analyzing tradeoffs in diverse landscapes

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A key challenge of ecosystem management is determining how to manage multiple ecosystem services across landscapes. Enhancing important provisioning ecosystem services, such as food and timber, often leads to tradeoffs between regulating and cultural ecosystem services, such as nutrient cycling, flood protection, and tourism. We developed a framework for analyzing the provision of multiple ecosystem services across landscapes and present an empirical demonstration of ecosystem service bundles, sets of services that appear together repeatedly. Ecosystem service bundles were identified by analyzing the spatial patterns of 12 ecosystem services in a mixed-use landscape consisting of 137 municipalities in Quebec, Canada. We identified six types of ecosystem service bundles and were able to link these bundles to areas on the landscape characterized by distinct social–ecological dynamics. Our results show landscape-scale tradeoffs between provisioning and almost all regulating and cultural ecosystem services, and they show that a greater diversity of ecosystem services is positively correlated with the provision of regulating ecosystem services. Ecosystem service-bundle analysis can identify areas on a landscape where ecosystem management has produced exceptionally desirable or undesirable sets of ecosystem services.

ecosystem services | landscape | spatial analysis | agriculture

A key challenge of ecosystem management is determining how to manage multiple ecosystem services across landscapes. Actions to enhance the supply of some ecosystem services, mainly provision of services such as food and timber, have led to declines in many other ecosystem services, including regulating and cultural services such as nutrient cycling, flood regulation, and opportunities for recreation (1–3). The Millennium Ecosystem Assessment (MA), a major international assessment of the world's ecosystem services, concluded that addressing this challenge requires identifying tradeoffs and synergies that exist among ecosystem services at different scales. The MA and others suggested that ecological management that considers and manages these ecosystem-service interactions is likely to be able to produce far better outcomes for societies (4–9). In this empirical study, we use a methodology to quantify the provision of and interactions among multiple ecosystem services across landscapes.

Interactions among ecosystem services occur when multiple services respond to the same driver of change or when interactions among the services themselves cause changes in one service to alter the provision of another (7). Ecosystem service tradeoffs arise when the provision of one service is enhanced at the cost of reducing the provision of another service, and ecosystem service synergies arise when multiple services are enhanced simultaneously. Both tradeoffs and synergies can be managed to either reduce their associated costs to society or enhance landscape multifunctionality and net human wellbeing, respectively (2, 8). For example, nutrient runoff from agriculture can be reduced by minimizing fertilizer use, using conservation tillage, or maintaining riparian zones, each of which can be done without causing undue food-production losses (10, 11). At the same time, enhancing one service, such as improving nutrient

retention through the promotion of vegetated riparian zones, can also enhance landscape beauty, wind protection, water quality, biodiversity, and crop production, increasing the benefits provided to society (4, 12).

We used the concept of ecosystem service bundles to analyze interactions among ecosystem services. Although it has been suggested that an ecosystem service-bundle approach may be a useful tool for improving the management of multifunctional landscapes (6) and identifying common ecosystem service tradeoffs and synergies (7), there have been no empirical investigations of ecosystem service bundles. We extended previous work on multiple ecosystem services (1, 5, 12) and define ecosystem service bundles as sets of ecosystem services that repeatedly appear together across space or time. We empirically identified bundles and used them to identify common ecosystem service tradeoffs and synergies across a landscape.

In our study, ecosystem service bundles were identified using spatial data. Interactions among ecosystem services occur in space and time. We used spatial analysis to analyze service interactions; temporal data were often not available, and collection methods varied across time, making comparison difficult. The analysis of spatial patterns of ecosystem services helped us understand how services are distributed across the landscape, how the distributions of different services compare, and where tradeoffs and synergies among ecosystem services might occur (13). Although these patterns cannot definitively determine whether or not tradeoffs or synergies are occurring over time, they can indicate what services can be expected to interact based on where we find services repeatedly occurring together or not together.

Although previous studies have used ecological units to analyze tradeoffs and synergies among multiple ecosystem services (14–20), we used administrative boundaries, because social processes shape the production and consumption of ecosystem services. The use of socially defined boundaries allowed us to identify different social–ecological systems on a landscape. We also specifically analyzed interactions among provisioning, regulating, and cultural ecosystem services, because many regulating services underlie the production of provisioning and cultural services; understanding the dynamics between these categories of services is thought to be particularly important in maintaining resilient social–ecological systems (1, 5).

We identified patterns of interactions among 12 ecosystem services through the analysis of ecosystem service bundles in Quebec, Canada. We quantified provisioning, regulating, and cultural ecosystem services across municipalities ($n = 137$) and

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described their interactions on the landscape. Our approach comprised of three parts: (i) the analysis of spatial patterns of individual ecosystem services, (ii) the analysis of tradeoffs and synergies between all pairs of ecosystem services and between categories of ecosystem services, and (iii) the identification and analysis of ecosystem service bundles. We chose our study site, which covers two adjacent watersheds spanning 7,288 km² close to metropolitan Montreal (Fig. S1), because it is typical of peri-urban agricultural landscapes in many parts of the world. Municipal decision makers are actively trying to balance the goals of farmers, rural villagers, and exurban commuters, whose land-use activities sometimes conflict. The 12 ecosystem services included in the study reflect agricultural, residential, and recreational uses of the land (Table 1). We used publicly available datasets, such as census and remote sensing data that are typically available in this type of landscape, to develop methods that can be replicated in other locations.

Results

Spatial Patterns of Individual Ecosystem Services. All ecosystem services, except for tourism, were spatially clumped on the landscape rather than randomly distributed ($P < 0.01$; Fig. 1). Although there were similarities among the spatial patterns of different services (e.g., forest recreation and carbon sequestration), mapping the geographic distributions of the provision of each ecosystem service revealed that their individual patterns were distinct. Ecosystem services were clumped in relation to social, ecological, and geographic factors that have led to the concentration of human activities and associated ecosystem services in specific areas of the landscape. For example, crop production is found in the flattest areas of the landscape, extending radially from the most important agricultural town in the region, pork production is clumped in areas with low population density, and summer cottages are preferentially built in areas with forests, lakes, and views.

Interactions Among Ecosystem Services. *Interactions between pairs of ecosystem services.* Most of the ecosystem services interact with one another (Fig. S2). Of the 66 possible pairs of ecosystem services, 34 pairs were significantly correlated: 8 of which were highly correlated (Pearson coefficient; $r \geq 0.5$), 16 of which were moderately correlated (Pearson coefficient; $r \geq 0.3$), and 10 were weakly correlated ($r < 0.3$).

At the landscape scale, we observed a pattern of tradeoffs between provisioning ecosystem services and both regulating and cultural ecosystem services. The two intensively managed provi-

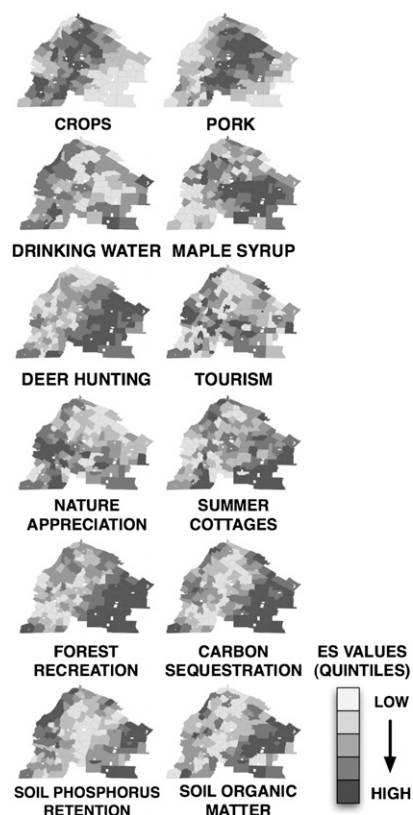


Fig. 1. Distributions of 12 ecosystem services shown in quintiles. The gradient of light to dark gray correspond to low to high values of ecosystem services. All ecosystem services are significantly clustered in space ($P < 0.01$), except tourism.

sioning ecosystem services, crop and pork production, were found to have the highest number of significant negative correlations with other services. Crop production was negatively correlated with nine other ecosystem services and positively correlated with one service—pork production (Fig. S2). Pork production was negatively correlated with five other ecosystem services. Both crop and pork production were negatively correlated with all regulating ecosystem services included in the study—soil organic matter, soil phosphorus retention, and carbon sequestration.

Table 1. Ecosystem services analyzed in Quebec case study

Ecosystem service	Unit	Data source*
Provisioning		
Crops	Percent of land in crop	Agriculture Census 2001
Pork	Pigs/km ²	Agriculture Census 2001
Drinking water	IQBP indicator (1–5)	Provincial water database
Maple syrup	Taps/km ²	Agriculture Census 2001
Cultural		
Deer hunting	Deer kills/km ²	Private hunting company
Tourism	Tourist attractions/km ²	Provincial tourism database
Nature appreciation	Observations of rare species/km ²	Provincial conservation database
Summer cottages	Tax value of cottages/km ²	Provincial tax database/municipal data
Forest recreation	Percent of land that is forested	Provincial land-use database
Regulating		
Carbon sequestration	kg C/km ²	Remote sensing data (MODIS)
Soil phosphorus retention	Percent	Provincial soil database
Soil organic matter	Percent	Provincial soil database

*Full references for databases are provided in *S1 Text*.

that are close to urban centers and have moderate amounts of agriculture and moderate values for regulating ecosystem services; it has the second highest value for nature appreciation. The Destination Tourism bundle type comprises municipalities that have moderate amounts of agriculture but that also each contain a unique natural or cultural feature that attracts nature and cultural heritage tourism (e.g., mountains or canals). The Corn–Soy Agriculture bundle type comprises municipalities that are a part of the agricultural center of the region with very high crop production, few forested areas, and also average-to-good water quality. The Feedlot Agriculture bundle type comprises municipalities that are primarily agricultural with high pork production and very low values for all other ecosystem services, including regulating services and water quality. The Villages bundle type comprises municipalities that have moderate amounts of agriculture, some village tourism, large amounts of deer hunting, and higher forest recreation values. Finally, the Country Homes bundle type comprises municipalities that have no agriculture, are highly forested, have high values of all regulating ecosystem services, and attract cottage dwellers in high numbers.

The municipalities that were clustered together did not change when three to five clusters were chosen in the cluster analysis instead of six clusters. Each reduction in the number of clusters analyzed resulted in the aggregation of two clusters. For example, with five clusters, the Country Homes bundle type aggregated with the Villages bundle type. A further reduction from five to four clusters resulted in the aggregation of the Exurban and Corn–Soy Agriculture bundle types.

Ecosystem service bundles and thresholds. The presence of scientifically based, socially accepted thresholds associated with three ecosystem services allowed us to objectively identify bundles of ecosystem services that are socially undesirable. Threshold values are associated with soil phosphorus retention ($P_{\text{sat}} > 12\%$) (21), soil organic matter ($\text{SOM} < 3.4\%$) (22), and drinking water quality [Quebec Water Quality Indicator (IQBP) < 3.5] (23). These thresholds correspond to socially defined levels of ecosystem services, below which there will be negative consequences for human wellbeing. The analysis and mapping of thresholds that have been crossed showed that 50 municipalities have crossed one of these thresholds. Five municipalities have crossed two thresholds, and four municipalities have crossed all three thresholds. Municipalities that have crossed two or three thresholds are all part of the Feedlot Agriculture bundle type. All municipalities in the Feedlot Agriculture bundle type have crossed at least one threshold; 70% of these municipalities have crossed one threshold, and the rest have crossed multiple thresholds. In contrast, within the Corn–Soy Agriculture bundle type, which also has very high crop production, only 24% of municipalities have crossed one or more thresholds. Within the Villages bundle type, which is adjacent to the Feedlot Agriculture bundle type and has the second highest level of pork production, 67% of municipalities have crossed one or more thresholds. To summarize the other bundle types, 50%, 27%, and 0% of municipalities in the Destination Tourism, Exurban, and Country Homes bundle types, respectively, have crossed one or more thresholds.

Discussion

This study presents methods for analyzing interactions among multiple ecosystem services and empirically identifies ecosystem service bundles in a landscape. Our analyses further showed strong tradeoffs between provisioning and other ecosystem services.

Bundling of Ecosystem Services. In this study, we present empirical identification of ecosystem service bundles across a landscape. The results of this work support existing theory about ecosystem service interactions (5, 7), suggesting that our methodological framework could be applied to other mixed-use landscapes. In particular, future work might investigate how tightly ecosystem services are

bundled in different landscapes (i.e., are certain ecosystem services always bundled together, or does this differ across landscapes, time, and space?), whether or not there are general social or ecological conditions that change how ecosystem services are bundled, and if some ecosystem services or categories of ecosystem services are more or less tightly bundled than others.

In our landscape, six types of ecosystem service bundles were identified. The strongly linked spatial distributions of multiple ecosystem services, identified by correlation analysis, translated into an emergent pattern of municipalities with similar sets of ecosystem services. Our framework of analysis was used to make sense of a complex social–ecological system that is difficult to analyze and understand. The simplified landscape produced by the ecosystem service-bundle analysis captured key patterns in the current provision of ecosystem services driven by past ecological and social dynamics. The ecosystem service-bundle types identified correspond to known social and ecological dynamics specific to different areas on the landscape, suggesting that there may be social–ecological subsystems on the landscape that produce characteristic ecosystem service bundles. For example, municipalities on the landscape that are known to be destinations for cottagers were grouped together by the Country Homes bundle type and had similar sets of ecosystem services. Understanding these subsystems, including the important social and ecological drivers, feedbacks, and management schemes, may allow for the prediction and modeling of ecosystem service bundles and thus, critical ecosystem service tradeoffs and synergies on the landscape.

Examining ecosystem service bundles emphasizes the linked nature of ecosystem services and could encourage the consideration of the multiple tradeoffs and synergies involved in land-management decisions (2, 6). Bundles capture how different ecosystem services interact. They are distinct from inventories of ecosystem services that can be added up to obtain a total quantity of services, because adding the services within a bundle would both double count ecosystem services that interact and ignore varying social values placed on different ecosystem services (24). Identifying areas where ecosystem service provision falls below known thresholds or where production occurs of high levels of desired ecosystem services can be used to discover areas that seem to be particularly ineffective or effective at producing desired ecosystem services. In the case-study system, some municipalities with high crop production have many crossed thresholds, whereas others with similarly high levels of crop production have no crossed thresholds, implying that these severe tradeoffs are not inevitable. Research that examines the causes of these differences may yield insights into what policies or management approaches could improve the provision of multiple ecosystem services across landscapes. In addition, the diversity of ecosystem service provision was positively correlated with regulating ecosystem services, suggesting that more multifunctional landscapes are better at producing regulating ecosystem services. Areas on the landscape with higher values for regulating ecosystem services have more options for the future, both for agriculture and other land uses, because this category of services underlies the production of other types of services (5).

Our analyses of ecosystem service distributions and pairwise interactions revealed that social–ecological systems produce ecosystem services in complex patterns in accordance with where humans desire specific ecosystem services, where it is possible to produce them, and how they will interact. Land cover explained only a modest amount of variation in the set of 12 ecosystem services (see principal components analysis results), and we believe that acknowledging the social component of ecosystem service production improved our ability to predict or model distributions of multiple ecosystem services across space and time. In addition, correlations between ecosystem services in this study were found to be much stronger than correlations between ecosystem services found in three other papers (14, 18, 19) that

focus on the production of multiple ecosystem services. This may be a function of the scales at which these other studies were conducted (much smaller for one and much larger for the other two), or of the set of ecosystem services analyzed. The scale of analysis will partially determine which ecosystem services are correlated. We suggest that the municipal scale is small enough that the factors that determine the average provision of a service will also have an impact on the average provision of other services, even for services that are distributed heterogeneously across municipalities. Replicating our analysis using other ecosystem services in other contexts would test the generality of our findings; however, we believe this type of research needs to be conducted at scales relevant to social processes and decision making, such as the municipality level.

Tradeoffs Between Provisioning and Other Ecosystem Services. Our results provide empirical evidence of strong tradeoffs between provisioning ecosystem services and both regulating and cultural ecosystem services in a peri-urban agricultural landscape. Tradeoffs between provisioning and regulating ecosystem services at different scales have been identified as cause for concern, because regulating ecosystem services are thought to underlie the sustainable production of provisioning and cultural ecosystem services and are important to the resilience of social-ecological systems (2). It has been suggested that the loss of regulating and cultural services in areas of high provisioning service production may undermine the sustainability of this production, diminish the possibility of diversifying economic activities, and impact local human wellbeing directly (2, 7). In the study landscape, food production in areas with low regulating ecosystem services is currently not affected by these tradeoffs. However, the loss of soil-regulating services is costly to farmers that have to replace these services, tourism operators that have to suspend water recreation, and governments that have to pay for water-quality treatment and improvement (25). Because these tradeoffs are not inescapable, as observed by a number of municipalities with weaker tradeoffs between categories of ecosystem services, knowing where these tradeoffs are occurring makes their management possible.

There are many possible mechanisms that can lead to tradeoffs among ecosystem services. Tradeoffs are sometimes the result of direct interactions between ecosystem services, such as between soil phosphorus retention and drinking water quality, and can be magnified, reduced, or removed by managing the process that creates the interaction. In other cases, the interactions are caused by spatial incompatibilities and societal feedbacks (e.g., human communities unwilling to live close to areas with industrial animal production). In these cases, knowledge of all tradeoffs associated with different organizations of social-ecological systems could lead to more informed societal choices about landscape management and planning. Future studies could help untangle tradeoffs, their causes, and possible interventions by conducting more empirical studies of tradeoffs in different landscapes and at different scales and by identifying the pathways of interaction among ecosystem services.

Conclusion

We have developed a methodological framework for analyzing interactions among multiple ecosystem services across landscapes. We provide an empirical demonstration of ecosystem service bundles and were able to link these bundles to areas on the landscape characterized by distinct social-ecological dynamics. Our results show landscape-scale tradeoffs between provisioning and regulating ecosystem services and show that a greater diversity of ecosystem services is positively correlated with the provision of regulating ecosystem services.

We expect that the patterns that we found in this region are similar to those in other agricultural landscapes in the world. Our results suggest that attempts to manage ecosystem services

should focus on interactions among ecosystem services and should recognize that the characteristics of these interactions are likely to be strongly shaped by both social and ecological forces. Similar studies in other areas of the world will provide more information on how the dynamics of ecosystem services identified in this study compare with other contexts and sets of ecosystem services.

Methods

Selection of Ecosystem Services. A total of 12 ecosystem services, including provisioning ($n = 4$), cultural ($n = 5$), and regulating services ($n = 3$), were assessed across the study area. We included ecosystem services in the study based on their importance to the region, the need to cover the range of ecosystem service categories (provisioning, regulating, and cultural) to fit the study design, and the availability of data.

Ecosystem Service Quantification. *SI Text* describes details of ecosystem service estimations.

Ecosystem services proxies. Measurable proxies were chosen for each of the 12 ecosystem services to measure a key aspect of ecosystem service condition or provisioning. We chose proxies that were relevant to the use of ecosystem services rather than their supply or stock, because we were interested in measuring the spatial patterns of current benefits associated with each ecosystem service. For example, observations of rare and endangered species by amateur nature enthusiasts were used as a proxy for nature appreciation rather than general biodiversity indices, because we were interested in where biodiversity was being appreciated. Similarly, hunting was represented by the number of deer killed rather than the total deer population. The exception was forest cover as a proxy of different types of forest recreation, because this was the only measurement available to represent the importance of forests to a diversity of local recreationalists. The proxies for regulating ecosystem services were associated with an aspect of the condition of the ecosystem service that is important to humans. For example, phosphorus saturation was used to quantify the ecosystem service soil phosphorus retention, because it is known that certain levels of phosphorus saturation in soil are still able to retain phosphorus to benefit both farmers and local users of surface water. Table 1 describes the proxies used to measure each ecosystem service and data sources used to estimate each ecosystem service. We purposefully employed publicly available data that are often available in many parts of the world to develop an approach that could be replicated in a variety of contexts. We recognized that the availability of better data to describe some of the ecosystem services more precisely could improve our analysis; however, the proxies that were chosen were sufficient to meet our research goals.

Spatial scale. Ecosystem services were assessed at the scale of municipalities. Municipalities provided a scale of analysis that was relevant for decision making, because they constitute the smallest unit of governance of ecosystem services in Quebec. The municipality is also the smallest level at which agricultural census data are available in Canada. There are 144 municipalities that intersect the Richelieu and Yamaska watersheds, and they are roughly equivalent in size (averaging 74 km²). Seven small municipalities were not included in Canada's agricultural census and thus, were discarded from the dataset, leaving a total of 137 municipalities that were included in the analyses.

Data specifications. Each ecosystem service was quantified using data for 2001 (or as close as possible to this date; *SI Text*). Land use and land cover have changed very little between 2001 and the date of publication because of laws limiting the conversion of agricultural land (26, 27). The municipal boundaries were taken from the 2001 Canadian Census, and the area of each municipality was calculated based on these boundaries. We quantified each service for each municipality and normalized for area, because the municipalities are not all of the same size. Ecosystem service data were transformed where necessary so that higher values of all ecosystem services corresponded to higher values for ecosystem services to enable data analysis and comparison. All data were transformed so that the maximum value of each ecosystem service in the landscape was set at one. Data were imported into an ArcGIS database (Environmental Systems Research Institute; <http://www.esri.com>) for data manipulation and analysis.

Analysis of Ecosystem Service Distributions and Interactions. *Spatial patterns of individual ecosystem services.* Individual ecosystem services were mapped in ArcGIS to visualize and compare their spatial patterns. The spatial clustering of all ecosystem services was determined using Moran's I (28) with queen contiguity.

Interactions Among Ecosystem Services. *Interactions between pairs of ecosystem services.* Correlation analysis was performed on each pair of services using

R statistical software ($n = 66$) (29). Correlations were analyzed using the Pearson parametric correlation test.

Ecosystem service diversity and regulating ecosystem services. We analyzed the diversity of the sets of ecosystem services associated with each municipality to estimate landscape multifunctionality using the Simpson's diversity index (30). This index is usually used to estimate biodiversity and has not been used to estimate the diversity of ecosystem services before this study. Because all 12 ecosystem services were found in almost all municipalities, the result was a measure of ecosystem service evenness across municipalities. High ecosystem service diversity may indicate areas where tradeoffs between ecosystem services are fewer and ecosystem service management is meeting a greater diversity of human demands. The important difference between using this index to estimate ecosystem service diversity versus biologic diversity is that higher biodiversity values are always considered to be better, whereas higher ecosystem service diversity values may only be considered better if the particular ecosystem services being measured are desired by society. We, therefore, compared the results of the Simpson's diversity analysis with the average values of regulating ecosystem services for each municipality to compare our estimate of landscape multifunctionality with an objective measure of landscape function. The average of the scaled values of the three regulating ecosystem services for each municipality was compared with the diversity index using regression analysis.

Ecosystem Service Bundles. Patterns of Ecosystem Service Bundles on Landscape.

Provision of ecosystem services by municipality was visualized using star plots in R statistical software (29). Cluster analysis was used to identify groups of municipalities with similar sets of ecosystem services, or ecosystem service bundle types, where tradeoffs and synergies between ecosystem services were consistent. Clusters in the ecosystem service data were identified and analyzed using cluster analysis by K-means in R with the cluster package (31). Scree plots

and dendrograms were used to determine an appropriate number of clusters. To stabilize the clusters, the number of iterations in the K-means procedure was set at 1,000 to ensure a global minimum of variance. Then, the clusters were mapped in ArcGIS to visualize the spatial pattern of data clusters.

Principal components analysis (PCA) in R was used to analyze quantitatively the variation in all 12 ecosystem services (i.e., the bundle) across the landscape and to determine the gradients along which the entire bundle of ecosystem services changed (29).

Ecosystem service bundles and thresholds. We mapped the number of known ecosystem service thresholds that have been surpassed in each municipality. Three ecosystem services included in the study have associated thresholds, or critical values, below which the ecosystem service is considered to be of unacceptable quality to the people who rely on that ecosystem service. Thresholds are associated with soil phosphorus retention, soil organic matter, and drinking water quality. For Quebec soils of the type found in these two watersheds, values above 12% phosphorus saturation are considered to be at high risk for phosphorus runoff into waterways (21). Organic matter in soil is widely thought to have a critical level of 3.4%, below which the productive capacity of agriculture is compromised by a deterioration in soil physical properties and the impairment of soil nutrient cycling mechanisms (22). For the water-quality index, we used the IQBP, and values below 3.5 are considered to be low water quality (23). We counted the number of thresholds (of a maximum of three) that were surpassed in each municipality and mapped the results.

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