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Analyzing riparian zone ecosystem services bundles to instruct river management

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Do riparian zones supply ecosystem service bundles? The ecosystem services approach as a test for riparian management

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Abstract

The ecosystem service framework is now well accepted for focussing management strategies to preserve and restore ecosystems. Its implementation remains challenging however, due to the environment's complexity and dynamics that interfere with ecosystems' ability to provide the services. Here, we question whether we can show where and how to intervene in riparian corridors to restore specific ecosystem services without endangering others. Specific hypotheses in this context are for the spatial aggregation of ecosystem services delivered by riparian corridors with respect to naturalness (1), and to the existence of bundles of ecosystem services (2), and finally for the scale-sensitivity of this congruence (3). Within a Geographical Information System framework we analyse the capacity of riparian corridors to provide ecosystem services over three river basins in one geographic region – the Bresse region of France. Specifically, we compare the ecosystem capacity to provide two services: in-stream water purification and riparian retention processes of nutrient control that are critical goals for river management and rehabilitation strategies. We observe little spatial association and high spatial variability for the two emphasized ecosystem services. Surprisingly, no overall congruence of ecosystem services with riparian corridor naturalness is present. The absence of associations between ecosystem services and their spatial variability will oblige environmental managers to identify underpinning environmental processes and patterns at local scales. In conclusion we plead for fine-grained multifunctional assessment of ecosystems' capacity to deliver services, especially in environments such as river corridors that exhibit high environmental heterogeneity.

Introduction

The overall frameworks to assess ecosystems' capacities to provide services are now well accepted and expected to deliver operational measures for management strategies and planning (Haines-Young and Potschin, 2010; Lautenbach et al. 2012; Allan et al. 2013). Especially the orientation to the supply of multiple functions and services in these frameworks is seen as a valuable asset for management strategies. Initially, it was strongly embraced as a framework to reconcile societal and ecological demands and visions, in an assumed harmony of services delivered, for planners and managers to "cherry-pick". Recently some limits to this harmonious picture have arisen from the observation that biodiversity is not always served by an ecosystem services targeted approach, and vice versa (Adams 2014), giving way to a strong debate and the new discipline of Biodiversity Ecosystem Services research (Cardinale et al. 2012). The concept of a spatial and temporally consistent association between services, or ecosystem service bundles sensu Raudsepp-Hearne et al. (2010) is a very attractive idea for management. Indeed in practice it is generally accepted and applied in that way. However, the dynamics of the ecosystem's ability to deliver the services in space and time, in relation to the societal demand for the service, still needs more attention. Most operational ecosystem service assessments undertaken (Burkhard *et al.* 2010; de Groot *et al.* 2010; Paetzold *et al.* 2010; Pinto *et al.* 2010) elaborated a comprehensive work to appraise a status at a specific point in time. Up to now these assessments pay little attention to the spatial and temporal dynamics of the ecosystems. Riparian corridors provide a unique opportunity to explore such a focus because they are hierarchical dynamic networks, influenced by strong directional connectivity that integrates processes across multiple scales and broad distances through time (McCluney et al. 2014). This flow and geographical context and network structuring of the river basins has not yet been investigated with respect to the delivery of ecosystem services.

The question we try to answer in this paper is whether the presumed ES bundles of riparian zones can be detected over larger territories with land cover-based matrix model methods. This not only points at the scale-sensitivity in the analysis of the cascade of ecosystem structure and functions to services (Burkhard et al. 2014), but also at the problem of riparian management options for improving ES delivery. We will address these issues via the following hypotheses:

1. Natural systems with undisturbed ecosystem functions offer maximal ES (within the specific geographic and societal context). Systems with maximum capacity to provide services are assumed to perform key ecological roles both for wildlife and for human well-being (Liquete *et al.* 2015). As such, we hypothesize the generally assumed strong association of service supply in so–called ES bundles.
2. The ES approach is a bridge between societal and ecological demands, embracing social and natural sciences, and as such requires inter- and multi-disciplinary methods; the more functions and services we will be able to detect and assess, the better the method is believed to reveal and reflect the whole picture of the ecosystem's services delivered (Schindler *et al.* 2014).
3. Spatial aggregation of societal and natural functions within ES approaches are sufficiently distinctive with low resolution spatial grids or entities (E.g. CORINE land cover units). The need for spatially detailed information to quantify services does not hamper the lower resolution ES assessments to reveal significant and accurate patterns.

Riparian corridors are deemed to deliver an exceptional amount of ecosystem services (Capon et al 2014; Thorp et al. 2010), thanks to their arterial form and locations in the landscape, agglomerating solid and liquid fluxes above- and below-ground. Riparian corridors and wetlands have been ranked the 2nd best ecosystem globally for ecosystem services provision (Costanza 2008, Acreman et al. 2011). Riparian forests are generally appraised to deliver services for water quality control especially nutrient retention both by plant uptake and denitrification (Hill 1979, 1996; Haycock et al. 1993; Dodds & Oakes 2006; Curie et al. 2011; Van Looy et al. 2014). However, strong disparities in proposed strategies exist when ES frameworks are applied to their rehabilitation (Bark et al. 2016). This can be illustrated by different proposed strategies to solve eutrophication problems in Chesapeake Bay in the U.S.A. Firstly, a catchment-scale analysis of riparian buffer zone effects on nitrogen retention suggested restoration of 70% riparian forest cover over the basin would limit eutrophication problems (Weller et al. 2011). Simultaneously, a denitrification-oriented analysis suggested in-stream flow restoration as the most effective solution (Filoso et al. 2015). Both studies investigated the social-ecological system and the ecosystem service of water quality improvement but in terms of biogeochemical processes and functions one focused on catchment and riparian buffer retention and the other on aquatic denitrification. Making recourse to ES frameworks to validate these approaches gives the false hope of an integrated and multidisciplinary vision to the question. This example illustrates clearly the problems of association, multi-disciplinarity and the dynamics in the capacity to deliver services.

Here we direct attention to specific ecosystem functions as the “means” of ES provision (Wallace et al. 2007), that we assume as delivery of services (Danley 2016). For consistency in our arguments, we follow the ES nomenclature of Villamagna et al. (2013). Generally, due to inherent complexity in ecosystems, a single process or function intervening in the delivery of services is investigated within a wide array of intervening processes (Bennett *et al.* 2009), as illustrated above for the eutrophication problem of Chesapeake Bay. Even though some straightforward solutions might arise, most ecosystem processes involved are highly complex with many biotic and abiotic factors entering the analysis. As an example of this, in an attempt to model the different processes and pathways of a freshwater ES, Johnston et al. (2011) highlighted over 7000 variables. Moreover the processes underpinning the capacity of an ecosystem to deliver services are often strongly spatially variable depending on local climatic, geomorphic and biotic factors (Feld et al. 2009; Grêt-Regamey et al. 2014). As such, using riparian corridors we highlight some methodological and practical issues in the deployment of the ES approach. It should be noted that assessment of ES on rivers is still in its infancy (Gilvear et al. 2013). Exceptions include the incorporation of nitrogen retention (Grizzetti et al. 2008; Liquete *et al.* 2011; Lautenbach *et al.* 2012; Natho *et al.* 2013), water quality (Keeler et al 2012; Brauman 2015), water provision (Notter *et al.* 2012) and flood regulation (Nedkov & Burkhard 2012) within the river network. Gilvear et al. (2013) have proposed a framework for assessing range of ecosystem services within river networks and Large and Gilvear (2014) have identified potential river attributes and data sources for undertaking such assessment. In this work, within a Geographical Information System (GIS) framework we examine ES delivered by riparian corridors over three river basins in one geographic region - namely the Bresse region of France. More specifically, we compare two processes: in-stream and riparian retention processes of nutrient control by river management. To answer the hypotheses cited above, a scale-sensitive fine-grained analysis to the continuity of riparian (forest) cover is needed to identify and to infer physical and biotic responses (Tormos et al. 2014a) and associated ecosystem functions (Tormos et al. 2014b). For this purpose, geospatial data within a GIS are analysed to characterize the physical nature of the riparian zones with a focus on riparian forests. Furthermore, a set of spatial indicators, available over the whole of the river network of France, is deployed in this regional study.

We can translate the stated hypotheses to our specific question for ecosystem service provision capacity of in-stream and riparian nutrient retention: are these two ecosystem functions spatially associated? Are they congruent with the provision of other ES? Are they different at small scale or more ‘regionally’ or upstream-downstream organized?

Study region and methods

Three stream catchments of the Chalaronne, Veyle and Reyssouze rivers, all tributaries of the Saône river, in the Bresse region in East-France were selected for study (Fig. 1). These all have catchments with a mixed agricultural-forest landscape with scattered villages and small towns. The climate is moderately continental with an annual precipitation of between 700 and 900 mm. Summer temperatures are high with a July average of between 19.6 and 21.5°C. The three river systems are rain-fed, creating strong flow contrasts between autumn/winter flows and severe summer low flows. The combination of these hydrological characteristics and the strong land use pressures, gives an overall strong risk of eutrophication in these catchments. Valley slopes are between 0 – 0.7 % and the basins between 300-700 km² in size.

Methods

Ecosystem function and service selection

Establishing the spatial congruence of services does not necessarily mean that they arise from the same process. Therefore, in our approach we applied an ecosystem function-based ES definition that distinguishes for the specific processes. A range of ecosystem functions and services provided by riparian zone and floodplain ecosystems have been identified (Costanza et al., 1997; Atkins and Burdon, 2006; Acreman et al. 2011). For our analysis we determined, based on expert knowledge, the main riparian zone functions and processes that determine the level of ES provision. These functions were: the effect of vegetation presence and structure in the riparian zone to (i) habitat availability and (ii) connectivity allowing movement of organisms through the river networks, the buffering functions of (iii) pollution retention and of (iv) microclimate control, the (v) water purification in the river bed and (vi) carbon sequestration in riparian zones. The riparian ES can be quantified at relevant scale and precision, using the matrix method (Burkhard et al. 2012; Grêt-Regamey et al. 2014).

River network segmentation

To be able to develop strategies focussed at nutrient control and riparian and in-stream rehabilitation, we must link and weight the ecosystem functions relevant to the riparian zone and processes present (Stürck *et al.* 2014). Therefore, an important step in ES valuation is to define the appropriate spatial scale and the possible service variation in space, especially in land use analysis (Bateman et al., 2011, Luisetti et al., 2011, Gilvear *et al.* 2013b). A river segmentation procedure applied to the river network undertaken in an earlier study (see Van Looy et al. 2015) produced a total of 292 river segments (homogenous hydromorphic units) between 0.8-8km in length, with an average value of 2.3km. For each of these segments land use and hydromorphological data was used to characteristise the segments. Catchments surfaces are between 300-700km², river lengths between 20 and 75km and annual average discharges between 2 and 7m^3/s (Chalaronne 333 km², 52km, 2m^3/s Veyle 670 km², 67km, 6m^3/s, Reyssouze 495km², 75km, 5m^3/s). For the riparian corridor specifically, elements of riparian forest cover and infrastructure/urbanization in riparian buffers of 10, 30 and 100m from the river's edge were identified (valley floors range from 0.2-2km in width) and mapped based on orthophotograph interpretation (0,5 x 0,5m resolution). This results in a spatially explicit dataset on riparian cover with calculation of continuity at river segment level and upstream corridor. To these segments we applied the method of Large and Gilvear (2015) for Ecosystem Services evaluation of river reaches. This was based on expert-judged scores per ES, with emphasis on selecting those services and functions relevant for this study.

Scoring and quantification

We apply the currently used ES framework of the matrix method (Burkhard *et al.* 2012; Crossman *et al.* 2013). Under this umbrella, the approaches still show panoply of specific methods and concepts to assess the delivery of ES (Schägner *et al.* 2013; Burkhard *et al.* 2014). Newly developed methods for ES assessment of riparian corridors are directed at gathering catchment-scale spatial information for the river network (Liquete *et al.* 2015). Even though well-known examples of economic valuation of river corridor services exist (Dubgaard et al. 2005; Murray et al. 2009), we chose a non-economic expert-based approach (Maes et al. 2012; Gret-Regamey 2013; Jacobs et al. 2015; Stoll et al. 2015). The scoring (Table 1) is based on evaluations of the general patterns of riparian ecosystem functioning, drawn from the literature and from expert knowledge (see Naiman et al. 2005, Mc Vittie et al. 2015, Gurnell & Grabowski 2016), and for most factors we had recourse to the evaluations developed for the hydromorphological conditions of the river segments (Van Looy et al. 2015). Where we make recourse to land use and other proxies for the functions we describe, according to the description of Lavorel and colleagues (2017), our approach is both proxy-based andphenomenological, and definitely to a higher resolution (0,5m x 0,5m) than the land cover proxy-based approaches mostly referred to.

All ES score assessments are normalised, i.e. converted to the same ordinal scale, (see Liquete et al. 2015), to allow an integration and comparison at river segment level. With our objective of evaluating the spatial configuration of delivery of ecosystem services, we present the services equally valid with our relative scoring, an objective way to evaluate geographical distributions of ecosystem services (Thomas et al. 2013).

To evaluate specific functions with regard to riparian corridor land use and configuration, the elements contributing to riparian retention and instream purification are based on the river retention model GREEN (Grizzetti et al. 2008; Bouraoui & Grizzetti 2011; La Notte et al. 2017). Nutrient retention was estimated based on documented retention rates from flow volumes, flood duration and habitat-specific retention rates (Olde-Venterink et al., 2003), and in-stream retention estimates from De Klein & Koelmans (2011). Carbon sequestration annual accumulation is documented for floodplain forest and marshland as 0.1 and 2 ton C ha^{-1} year^{-1} for wetlands and woodlands, respectively (Nabuurs & Schelhaas, 2002), allowing relative scoring of these land use types in the floodplain. For the biodiversity ES we looked at the river corridor habitat ecosystem function. We used a combination of the undisturbed hydromorphological character of the river bed, and a proxy for habitat availability, the area of natural areas in the floodplain. For the connectivity function, we combined the riparian corridor continuity with the aquatic environment's continuity with respect to weir presence. We do not incorporate provisioning services as they are either not relevant for the studied area (i.e. the riparian forests are not harvested, no hydropower is present), or not significant/measurably influenced by corridor management (e.g. commercial or recreational fisheries). Overall, the riparian forest continuity and cover is not the only element here under consideration from the river restoration perspective, but a recent overview study qualifies it as the index that is able to assess the largest number of ecosystem services in the fluvial and riparian system (Vidal-Abarca et al. 2017).

Analysis of associations and bundles of ecosystem services

The first step following determination of scores was to identify spatial patterns, across all three river networks in the services per river segment. We followed the proposed method of Mouchet et al. (2014) for quantifying ecosystem service associations namely correlation testing over the river segment ES matrix. Since we applied relative scoring, the Kendall correlation test was used in order to give the least weight to the actual values.

In a second step we define ES bundles. The analysis used the approach proposed by Raudsepp-Hearne (2010) and subsequently developed further (Mouchet et al. 2014). We identify ES bundles by hierarchical cluster analysis (using Ward's method). This identification of bundles confirms whether the identified associations are spatially consistent.

Analysis of river size, network and geographical structuring

To identify the spatial variation of services in relation to river type, network position and geographical context in general, we performed a correlation test to the major structuring elements of river and geographical context with respect to the hypotheses formulated earlier: 1) the river size determined by the Strahler system of stream ordering as a basic proxy of flow quantity; 2) the hydrological alteration risk determined by aspects of water abstraction (pumping and irrigation) and flow regulation (presence of ponds, impoundments and lakes); and 3) the upstream basin area as a measure of of the landscape-geographic setting.

Results

Associations of ES

A number of associations of ES were found to be present with varying levels of correlation present from near zero to nearly 0.7 (Table 2). In terms of level of correlation and numbers of correlations habitat, microclimate, pollution retention and carbon sequestration score highly. In-stream purification and connectivity score poorly.

Ecosystem Service bundles

Two bundles are identified by hierarchical cluster analysis (55% of variance grouped);

One group with Corridor habitat provision - Microclimate control -Carbon sequestration - Pollution retention, and a non-associated group of two separate functions: Connectivity and In-stream purification. Even though there is a high evenness of capacity to deliver services over the river network (averaged overall ES for river segments 2.5 with small standard deviation of 0.27), the associations are not that strong. Comparison of instream (auto-purification) with out-of-stream pollution retention shows only for the Reyssouze basin some congruence (Figure 2). Although this basin also shows a strong difference for the downstream tributaries: where the instream quality allows purification functioning, there is no contact with banks and valley for retention function. For Veyle and Chalaronne rivers in-stream and riparian retention capacity are strongly differing spatially, especially for downstream sections.

The scores for delivery, even averaged over all services (Fig. 3) show strong spatial heterogeneity and little continuity, with no geographic/environmental gradients (elevation, distance to source, tributary-river mainstem differentiation). For the riparian corridor functioning to pollution retention, only minor significant correlation to river size (Strahler order Kendall's tau coefficient 0,153) or discharge is present (Table 3). In contrast, the in-stream functioning has a minor negative correlation, due to higher rates of river hydromorphological alterations for the larger systems, especially for the mainstem of the rivers. Forest cover related services are generally stronger present downstream, since there is higher agricultural pressure to small streams on the upstream plateau, whereas connectivity and in-stream purification (Kendall's tau -0,261 and -0,138 respectively) are less downstream, since flow regulation and alteration is generally greater in downstream reaches.

The sum of the services (Fig. 3) delivered by these corridor functions is very weakly but significantly correlated to river size (Strahler order Kendall's tau coefficient and upstream basin surface Kendall's tau coefficient), meaning a slight accumulation of services downstream.

Discussion

It is well acknowledged that continuous forested corridors lead to an improvement of physical and biotic conditions of streams and rivers (Hill 1979, 1996; Haycock et al. 1993). Nevertheless, questions as to whether the configuration and specific rate of riparian canopy gaps is crucial in the pollution retention processes (Weller et al. 2011), and whether the upstream or downstream basin context prevails for biotic corridor functioning (Brown et al. 2011), remained unanswered. We present an ES framework that deals with these aspects in a multiple catchment context. To the presumed congruence of different services and the necessary scale of analysis, we show that when we look in more detail to the different services provided by riparian corridors, we find striking spatial separations and little congruence. Where some studies on ecological restoration indicated synergies between multiple ecosystem services (Jiang, Wang et al. 2016) here we find no real support to the strong spatial aggregation presumed in the ES bundles concept (Raudsepp-Hearne 2010). In line with the findings of Bai et al. (2011), the services could be divided in two groups that should be managed and conserved independently. Also supporting the findings of Bai et al. (2011), we found the corridor habitat biodiversity service was positively correlated with carbon sequestration, but contrary to their observation it was also positively correlated with nutrient retention. This difference can be attributed to the difference in scale and in landscape contexts of the analyses. The same is true when we compare our findings to national scale study in Great Britain by Thomas et al. (2011) who found biodiversity and carbon storage ES were negatively correlated. Clearly a different scale of analysis can lead to different observations, yet these authors also conclude for a ‘combined’ strategy of conservation.

For the delivery of the two specific services of water purification in-stream and nutrient retention in the corridor, there clearly is a strong spatial incongruence through the different catchments, without a clear pattern linked to geography or position along the river continuum. So, strategies oriented in-stream and at the river bank can be complementary, but emphasizing only one of the two processes lacks efficiency. Managing for in-stream auto-purification capacity does not enhance the other riparian ecosystem functions and services. Prioritizing riparian management at the river banks and floodplain has the benefit of improving a series of services. The same observation goes for the service of connectivity that is disconnected from the delivery of other riparian corridor services. Combining it with corridor habitat provision measures will highly improve the delivery of ES. So, we refute the first and third hypotheses that represent the premises of many actually used ES approaches and for the use of ES bundles.

For the second hypothesis, although the multidisciplinary analysis clearly adds information for planning and preserving ecosystem functions, the congruence of services is not increased by adding more functions and services to the analysis. Yet, we can identify specific strategies and operational bases for managers to improve the capacity to deliver services. The presented approach highlights features that are less obvious in the field, unexpected from just the mapping of land use and hydromorphology elements. For our three basins, we observe generally highest capacity to produce services for the Chalaronne, followed by the Veyle, and the Reyssouze lowest. The mapping of this capacity allows to identify significant spatial ‘gaps’ in ecosystem functioning, for which solutions can be proposed.

The identified incongruence confirms the reported risk that traditional conservation strategies oriented toward biodiversity may not be effective at protecting the economic benefits of an ecosystem, and vice-versa (Adams 2014). The pressure on ecosystems to provide various different and often conflicting services is immense and likely to increase (Moilanen et al. 2011). The spatial variability of the capacity to produce services stresses the importance of looking at the dynamics of ES. Ecosystem services exist at the point of interaction between ecosystem function and human activity (de Groot and others 2002). Therefore, even with a constant biophysical supply of an ecosystem service, changes in human activity can alter service delivery (Mitchell *et al.* 2013). Furthermore is the human influence on the ES delivery a crucial aspect in the assessment; here the nutrient status of these alluvial plain rivers lie close to adverse thresholds for the ecosystem. The heterogeneity in ES supply is also reported in other contexts of analyses of demand and provision of ES (Verhagen et al. 2016). But even in an absence of ES bundles, strategies to ES delivery are possible.

Riparian buffers are highly sensitive in their efficiency to filter pollution according to practices of drainage (Petersen and Petersen 1991; Petersen et al. 1992) and runoff (Weller et al. 2011). So, a fine-grained analysis of processes and functions, managing the relationships among ecosystem services can enhance the provision of multiple services, and help avoid catastrophic shifts in ecosystem's capacity to provide services (Bennett *et al.* 2009). The influence that spatial scale has on these relationships was recently illustrated comparing a national scale with a river basin assessment (Holland et al. 2011). Here we go up one scale level in spatial resolution to the functions at the level of individual riparian zones. Preserving and restoring riparian corridor green infrastructure will gain in importance and effectiveness when land use practices are more at risk. Filtering and purification services will be larger in intensive agricultural areas, and thus restoration of green infrastructures in these areas has the highest efficiency and priority.

With the application of the matrix method (Burkhard et al. 2012; Grêt-Regamey et al. 2014) we advocate ES delivery by land use as a proxy in the absence of detailed process models and system understanding. Nevertheless, we suggest high resolution information on riparian corridor features (canopy cover) and hydromorphological characteristics (weir presence, bed alteration) up to the phenomenological identification – according to Lavorel et al. (2017) - of the ecosystem functions assessed. Obviously even relatively good proxies are likely to be unsuitable for identifying hotspots (Eigenbrod et al. 2010). Still, Lavorel et al. (2017) do admit that perhaps the greatest obstacle to substantial progress in assessing ecosystem services is a lack of data – there is simply none available for most services in most of the world – and that it remains a crucial first step in global efforts to conserve key ecosystem services by mapping their spatial distributions – even if assessment precision is inaccurate. The services we deal with in this paper are highly variable - in time especially, for instance nutrient retention, making measurements and real estimations of the service very challenging scientifically and logistically. Therefore we rely mostly on the process understanding derived from modelling approaches (like SWAT model at the scale here applied) and these models are mostly developed at the catchment scale, obviously also the relevant scale for management and ecosystem service identification (Doody et al. 2016). This choice for the land cover ES approach, is in this study nevertheless brought to a detailed level, thanks to high resolution image analysis for the – identified in the scientific literature as most relevant factor - riparian forest continuity (see Weller et al. 2011). Vermaat et al. (2016) quantified ES for riparian corridors per reach, and summed the ES to annual economic value normalized per reach area. The resulting value ratio's differed more than tenfold between restored sites. Here, our relative scoring is a simplification compared to the more economic approaches, yet it clearly highlights managerial contexts and priorities, and especially for comparison between catchments, with its consistent scoring, this approach has strong merits for different management and planning approaches.

Generality approach

Can we generalize our findings? For the functions and services we regarded, the main drivers are the riparian corridor features and human alterations present; the geographical context only plays a minor role. For other regions, distinction in the presented ES delivery might be for the presence-absence of functional floodplains, for which in this region there is no natural limitation. The generalities of the described results are obviously limited to the landscape context of our selected catchments.

The observed correlations can be explained by their construction and interaction with the specific landscape context and ecosystem functioning. Carbon sequestration is correlated to pollution retention and habitat provision since these ES encompass the natural floodplain functioning. As these three are correlated, the overall capacity of service delivery is also strongest correlated to these three individual measures. But, even though correlated and thus congruent with several individual services, general corridor habitat ES not everywhere coincides with overall capacity. This implies that habitat enhancement and biodiversity oriented management does not always or univocally means overall ES enhancement.

A strength of the approach presented is that it shows for groups as well as individual ecosystem services where improvement is possible. This can be compared with societal demand within the catchment in determining what improvements are made. Options for restoration of riparian zones in watershed contexts oriented to restore general ecosystem functions are moreover presented (Capon et al. 2013; Zedler & Kercher 2005), also stressing the need for differentiated measures (Fullerton et al. 2009). There still needs however to be a good understanding of the key components of ecosystem functioning that are a prerequisite for a good description of ES delivery (de Groot et al., 2010). The paradox in the strategy selection for nutrient control in Chesapeake Bay, stated in the introduction, is linked to the identification of the trigger alteration of functioning; is the strongest potential for restoration in the in-stream nutrient control or is it the retention in the floodplain and at the riverbanks. If we bring the analysis to this distinction, immediately the appropriate strategy for restoration will evolve (Thorp *et al.* 2010). The choice for in-stream (dam removal, re-meandering, bed restoration and profiling) or corridor (bank replantation, floodplain/flood contact restoration) retention measures can be guided by the provided maps. Overall priorities need to be evaluated prior to this by evaluating the summed and other ecosystem function and services supply potential. With this analysis we point at some caveats for using the ES framework in the design of restoration strategies. Even though some straightforward aspects in spatial and geographic context might arise, most ecosystem processes involved are highly complex and need fine-grained analysis and many biotic and abiotic factors entering the analysis. This need for fine-grained analysis should never be left aside with the excuse of the multidisciplinarity and the larger scale societal demand side of the ES approach.

Conclusion

To evaluate the potential for delivery of ecosystem services the environmental and ecological processes behind the services need to be assessed at a relevant scale. Here, we looked at small rivers and the services they provide in relation to the riparian corridor functioning. The hydromorphological processes responsible for the delivery of services were evaluated at the scale of hydromorphological units and based on a specific evaluation scheme.

We oriented our analysis to the central questions for the restoration manager: where, why and how to intervene in riparian corridors? We can highlight the strength of this fine-grained analysis to identify the local potential of ES delivery, and subsequently the high resolution needed to consider and identify specific targets and functions to restore in riparian management. Ecosystem services appear as highly variable in space and associations or bundles of services are less evident than generally assumed.

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Figure Captions

Figure 1. Map presentation of instream (auto-purification) and riparian pollution retention ESS per river segment over the 3 catchments. Equal quantile distributions of the values are presented to show the relative contributions over the region. Underneath the graph plot of the same information with ESS scores for the 292 segments.

Figure 2. The averaged scores for the ESS of the individual stream segments over the three basins in map and graph (ESS scores for the 292 river segments).

Table 1 Rules relating to attributing river (corridor) features or land cover types to potential ecosystem service supply score (0 is very low/absent and 4 high)

Ecosystem Services Supply group	**Riverscape feature/ attribute or land cover**	**Score**				
		0	**1**	**2**	**3**	**4**
Pollution (nutrient) retention *(corridor)*	Riparian (30m buffer) woodland	Absent (<10%)	Very low (10-25%)	Low (25-45%)	Medium (45-55%)	High (>55%)
	Buffer continuity: frequency gaps	>8/km	4-8/km	2-4/km	0-2/km	absent
	lateral (floodplain) contact (risk alteration)	Very high (>70%)	High (50-70%)	Medium (25-50%)	Low (5–25%)	Absent (<5%)
Purification *(in-stream retention)*	Stream profile (Width:depth risk alteration)	Very high (>70%)	High (50-70%)	Medium (25-50%)	Low (5–25%)	Absent (<5%)
	Uniformity sinuosity (rectification rate)	Very high (>80%)	High (60-80%)	medium (40–60%)	low (20-40%)	Very low (<20%)
	Natural bed substrate (risk alteration)	Very high (>70%)	High (50-70%)	Medium (25-50%)	Low (5–25%)	Absent (<5%)
Microclimate control *(shading, light & temperature control)*	Riparian/riverbank woodland (10m buffer)	Very low (<20%)	Low (20–40%)	Medium (40–60%)	High (>60%)	Very high (>80%)
	Buffer continuity: length gaps (max per reach)	>500m	200-500m	50-200m	1-50m	absent
	upstream continuity (density gaps)	Very high (>80%)	High (60-80%)	medium (40–60%)	low (20-40%)	Very low (<20%)
Carbon sequestration	Floodplain forest	Very low (<20%)	Low (20–40%)	Medium (40–60%)	High (>60%)	Very high (>80%)
	Slope (retention capacity)	High (>1pm)	Medium (0.5-1pm)	Low (0.25.-0.5pm)	Very low (0.1-0.25pm)	Very low (<0.1pm
	Lateral (floodplain) contact (Risk alteration)	Very high (>70%)	High (50-70%)	Medium (25-50%)	Low (5–25%)	Absent (<5%)
Biodiversity + Habitat provision	Riparian/riverbank woodland	Very low (<20%)	Low (20–40%)	Medium (40–60%)	High (>60%)	Very high (>80%)
	Risk of channel rectification	Very high (>70%)	High (50-70%)	Medium (25-50%)	Low (5–25%)	Absent (<5%)
	Floodplain forest	Very low (<20%)	Low (20–40%)	Medium (40–60%)	High (>60%)	Very high (>80%)
Connectivity	continuity riparian forest: fragmentation	Very high (>80%)	High (60-80%)	medium (40–60%)	low (20-40%)	Very low (<20%)
	dam density (Risk alteration)	Very high (>70%)	High (50-70%)	Medium (25-50%)	Low (5–25%)	Absent (<5%)
	infrastructure/urbanisation	>50%	20-50%	10-20%	1-10%	<1%
	upstream continuity (mean number gaps)	>8/km	4-8/km	2-4/km	0-2/km	absent

Density of gaps: relative length of canopy openings; dam density: per length and slope relative number of dams/weirs. Risks of alteration are described in Van Looy et al. (2015).

Table 2. Kendall correlation coefficients between the ecosystem service supply (ESS) variables under study. Significant correlations are in bold.

Variables	Riparian Habitat	Connectivity	Micro-climate control	Purification	Pollution retention (corridor)	Carbon sequestration	ESS Total
Riparian Habitat	**1**	0,021	**0,527**	-0,030	**0,486**	**0,493**	**0,651**
Connectivity	0,021	**1**	-0,049	**0,274**	0,055	0,074	**0,184**
Microclimate control	**0,527**	-0,049	**1**	**-0,089**	**0,361**	**0,325**	**0,454**
Purification	-0,030	**0,274**	**-0,089**	**1**	0,016	0,046	**0,167**
Pollution retention	**0,486**	0,055	**0,361**	0,016	**1**	**0,552**	**0,656**
Carbon sequestration	**0,493**	0,074	**0,325**	0,046	**0,552**	**1**	**0,689**
No of significant correlations*	**3**	**1**	**4**	**2**	**3**	**3**	**6**
ESS Total	**0,651**	**0,184**	**0,454**	**0,167**	**0,656**	**0,689**	**1**

*(*Excluding the self-correlation)*

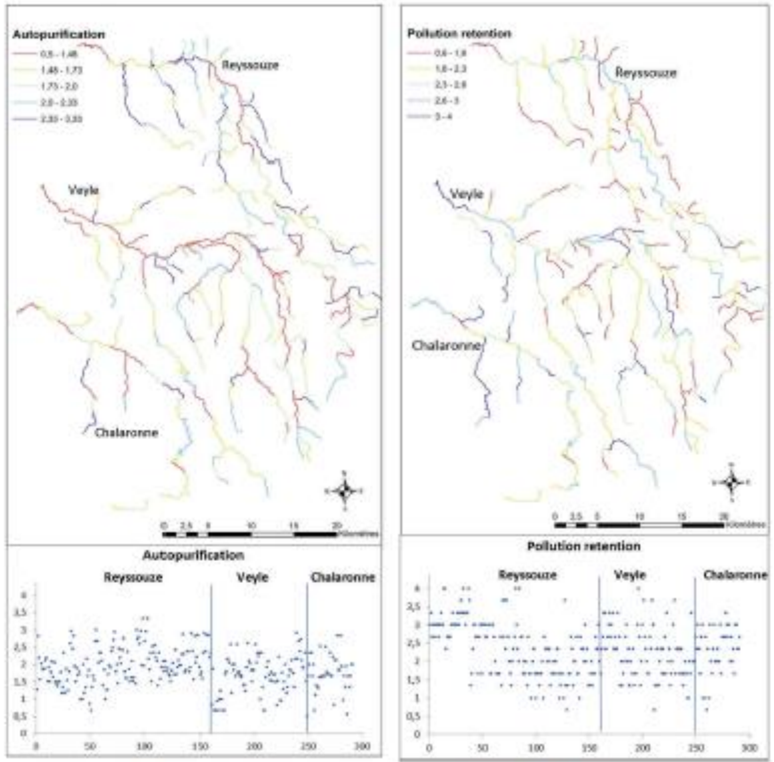

Figure 1. Map presentation of in-stream (self-purification) and riparian pollution retention ES provision per river segment over the three catchments. Equal quantile distributions of the values are presented to show the relative contributions over the region. Underneath the graph, plot of the same information with ES scores for the 292 segments.

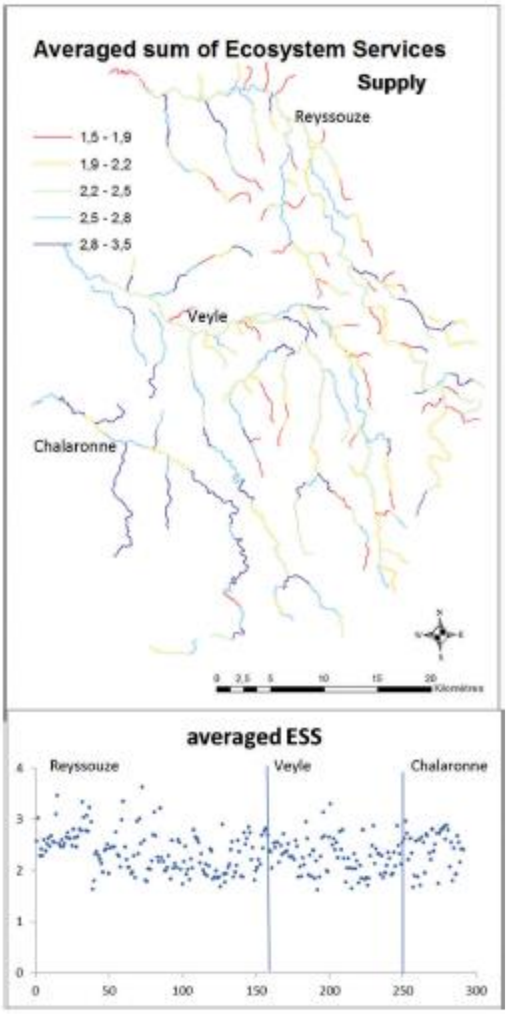

Figure 2. The averaged scores for the ES of the individual stream segments over the three basins in map and graph (ES scores for the 292 river segments).

Table 3. Correlation (Kendall) Kendall's tau coefficient result for flow and geography elements: the hydrological alteration risk (water abstraction and flow perturbation); the river size (Strahler order) as proxy of flow volume; the upstream basin surface. In bold the significant (alpha= 0,05) correlations.

Variables	Hydro_Q	Order	Surf_B
Connectivity	**0,228**	**-0,261**	**-0,171**
Riparian Habitat	**-0,182**	**0,240**	**0,209**
Microclimate control	0,074	**0,135**	0,037
Purification	**0,176**	**-0,138**	**-0,100**
Carbon_seq	-0,076	**0,152**	**0,187**
Pollution retention	**-0,186**	**0,153**	**0,168**
ESS Total	-0,074	**0,148**	**0,176**