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Partition of some key regulating services in terrestrial ecosystems: Meta-analysis and review

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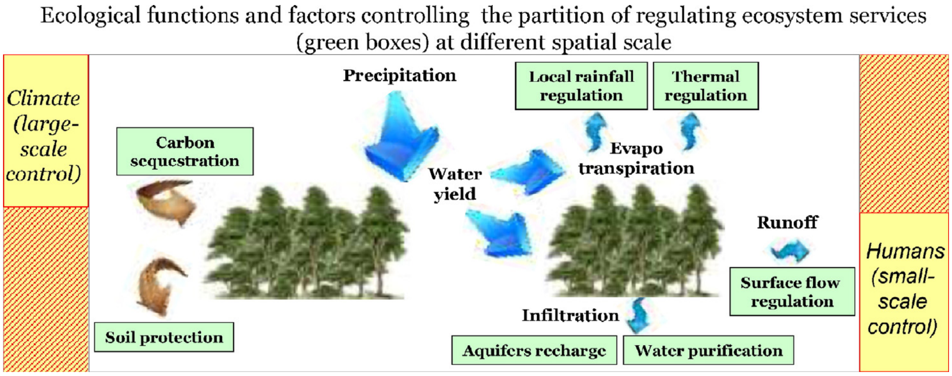
HIGHLIGHTS

- The partition of regulatory services in ecosystems poses a major policy challenge.
- We examined how partitions occur at the hydrosphere-anthroposphere intersection.
- Five data sources were processed through meta-analysis.
- Humans can exert some control ES partitioning through aboveground biomass changes.
- Human control on ecosystem service partition increases at decreasing spatial scales.

GRAPHICAL ABSTRACT



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ABSTRACT

Our knowledge about the functional foundations of ecosystem service (ES) provision is still limited and more research is needed to elucidate key functional mechanisms. Using a simplified eco-hydrological scheme, in this work we analyzed how land-use decisions modify the partition of some essential regulatory ES by altering basic relationships between biomass stocks and water flows. A comprehensive meta-analysis and review was conducted based on global, regional and local data from peer-reviewed publications. We analyzed five datasets comprising 1348 studies and 3948 records on precipitation (PPT), aboveground biomass (AGB), AGB change, evapotranspiration (ET), water yield (WY), WY change, runoff (R) and infiltration (I). The conceptual framework was focused on ES that are associated with the ecological functions (e.g., intermediate ES) of ET, WY, R and I. ES included soil protection, carbon sequestration, local climate regulation, water-flow regulation and water recharge. To address the problem of data normality, the analysis included both parametric and non-parametric regression analysis. Results demonstrate that PPT is a first-order biophysical factor that controls ES release at the broader scales. At decreasing scales, ES are partitioned as result of PPT interactions with other biophysical and anthropogenic factors. At intermediate scales, land-use change interacts with PPT modifying ES partition as it the case of afforestation in dry regions, where ET and climate regulation may be enhanced at the expense of R and water-flow regulation. At smaller scales, site-specific conditions such as topography interact with PPT

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and AGB displaying different ES partition formats. The probable implications of future land-use and climate change on some key ES production and partition are discussed.

1. Introduction

Despite the vast research effort over the past decades, our knowledge about the functional foundations of ecosystem service (ES) provision is still limited (Bennett et al., 2015). More research is needed to elucidate essential functional mechanisms that are behind the issue across space and time. A better understanding of those mechanisms is the way to choose among sustainable land-use/land-cover options (Power, 2010). Beyond the need of elucidating the functional basis of ES provision, our premise was that such provision must be driven by the needs of concrete beneficiaries in the real world, which must benefit from regulatory processes like those related to local climate regulation (rainfall and temperature), water flows regulation (flood control, streams and water bodies maintenance) and water provision from surface (freshwater supply) and subsurface sources (underground water recharge, purified water supply).

Ecological theory indicates that humans modify essential ecosystem functions, and resulting ES provision, by altering the biomass stock and the water flow (Viglizzo et al., 2012). For a long time ecologists have assumed that, the provision of several ES is closely associated with the availability of biomass and water in ecosystems (Costanza et al., 1998). Therefore, ES would be affected if one or both resources are modified by land-use/land-cover change (Kremen, 2005). But to what extent land use decisions exert a control on the delivery of ES? Here we address this question relying on existing studies across scales and site conditions.

We relied on a simple conceptual scheme that associates the above-ground biomass with key eco-hydrological flows. It describes functional attributes of biomass in ecosystems, and the functional partition of water through a cascade that begins with rainfall and continues with water taking different routes throughout the ecosystem (Fig. 1). In this work, the ES partition is the fragmentation and distribution of ES into aerial, surface and subsurface ecosystem components securing human benefits and wellbeing at different spatial and temporal scales.

How does the notion of ES partition deal with the concept of ES bundles? Raudsepp-Hearne et al. (2010) developed a framework for analyzing the provision of ES bundles (set of services that appear together repeatedly) across landscapes. They show that tradeoffs may occur at the landscape scale, where management may exceptionally produce desirable or undesirable sets of ecosystem services. In our research, the study ES subjected to partition may or may not be part of ES bundles. In our case, the study regulatory ES may eventually be part of ES bundles, and the tradeoffs among single regulatory ES (e.g. climate regulation vs. surface flow regulation) may be part of tradeoffs among ES bundles, for example, climate regulation, biomass and food production on the one hand, vs. flow regulation, water bodies and stream maintenance on the other hand.

We associate the biomass accumulation and the water fluxes with the provision of essential regulatory services. Our scheme clearly prioritizes the effect of biomass stock on water partition through the ecosystem, but what about the reverse effect? Despite the overall effect of precipitation on plant carbon in ecosystems still remains controversial (Wang et al., 2015), it should be noted that plant carbon accumulation and exchange are very sensitive to the precipitation regime (Weltzin et al., 2003), including both the amount of precipitation and its temporal distribution (Chen et al., 2009).

As Fig. 1 shows, key ES analyzed in this work are (i) soil protection (the retention of soil material within ecosystem boundaries, (ii) carbon sequestration, (iii) local rainfall regulation, iv) local thermal regulation, v) surface flow regulation by runoff control, vi) groundwater recharge by infiltration and (vii) water purification as water infiltrates across soil layers.

Regarding soil protection, scientific evidence (Brauman et al., 2007) demonstrates that vegetation reduces the erosive impact of rain and wind because tree roots hold the soil together and avoid the washing away and the blasting of soil particles. Without vegetation, lands may lose large amounts of sediments (Sekercioglu, 2010). Terrestrial sequestration means using plants to capture CO_2 from the atmosphere by means of photosynthesis and then storing it as carbon in plant tissues as well as in the soil. Plants retain and use the carbon to live and grow, and when plants die, part of the carbon is stored in the soil (Don et al., 2011). It should be noted that terrestrial sequestration does not store CO_2 as a gas but stores the carbon portion of the CO_2. When lands are de-vegetated, the soil carbon combines with the oxygen and reenters the atmosphere as CO_2 gas (IPCC, 2006). Afforestation and reforestation by humans are good examples of terrestrial sequestration practices (Lal, 2008). Plants play a major role in climate regulation at the global scale (IPCC, 2007), but they also play a role in precipitation and temperature regulation at the local scale through evapotranspiration. The water cycle is completed when water vapor is released back into the atmosphere through both land evaporation and plants transpiration (Hoffman et al., 2003; Wright, 2005). Plants act as heat and humidity pumps transferring heat and releasing water vapor that form clouds and later come back as rain. Because of the physical principle of evaporative thermo-regulation, vegetation has the potential to moderate the effects of local temperature (Sodhi et al., 2007). Water flow regulation, which comprises both water recharging by infiltration and surface runoff, is one of the most vital services of ecosystems, particularly when provided by forests, rivers and wetlands. Vegetation in particular strongly modulates the intensity and timing of flows, and potentially reduces the impact of floods (Bradshaw et al., 2007).

The influence of plant cover is greater than that of any other biotic factor protecting soil against erosion (Geist and Lambin, 2004). Plant cover is effective in preventing erosion to the extent that it absorbs the kinetic energy of raindrops and winds, covers a large proportion of the soil during periods of the year when rainfall and wind is most aggressive, slows down runoff and sediment flow, and keeps the soil surface porous (Lal, 2009). Evidence from SE Asia confirms that plant cover density reduced surface erosion by more than an order of magnitude compared to lands with no ground cover (Sidle et al., 2006).

The hydrological scheme focuses, in this work, on the balance between the precipitation input (PPT), and the partition of water among evapotranspiration (ET), water yield (WY), surface runoff (R) and infiltration (I). ET comprises direct evaporation from soil and water transpired by plants. Foliage-intercepted water was set aside in this analysis. WY is partitioned between R and I. The picture should ideally be completed by subsurface flows entering and leaving the ecosystem (Yaseef et al., 2010), but such routes are not generally measured. A simple balance equation was used here:

$$\mathrm{PPT} = \mathrm{ET} + \mathrm{R} + \mathrm{I}.$$

In this study, ET, WY, R and I are considered ecological functions, or intermediate ES, that lead to the provision of some important regulatory ES. Thus, (i) ET is associated with climate regulation, which comprises the local regulation of precipitation and temperature, (ii) R is associated with water flow regulation (e.g., stream and water body maintenance), and (iii) I with water recharge and water purification.

It is not difficult to find links between biomass stock and water partition. Some studies (Lean and Warrilow, 1989; Pielke and Avissar,

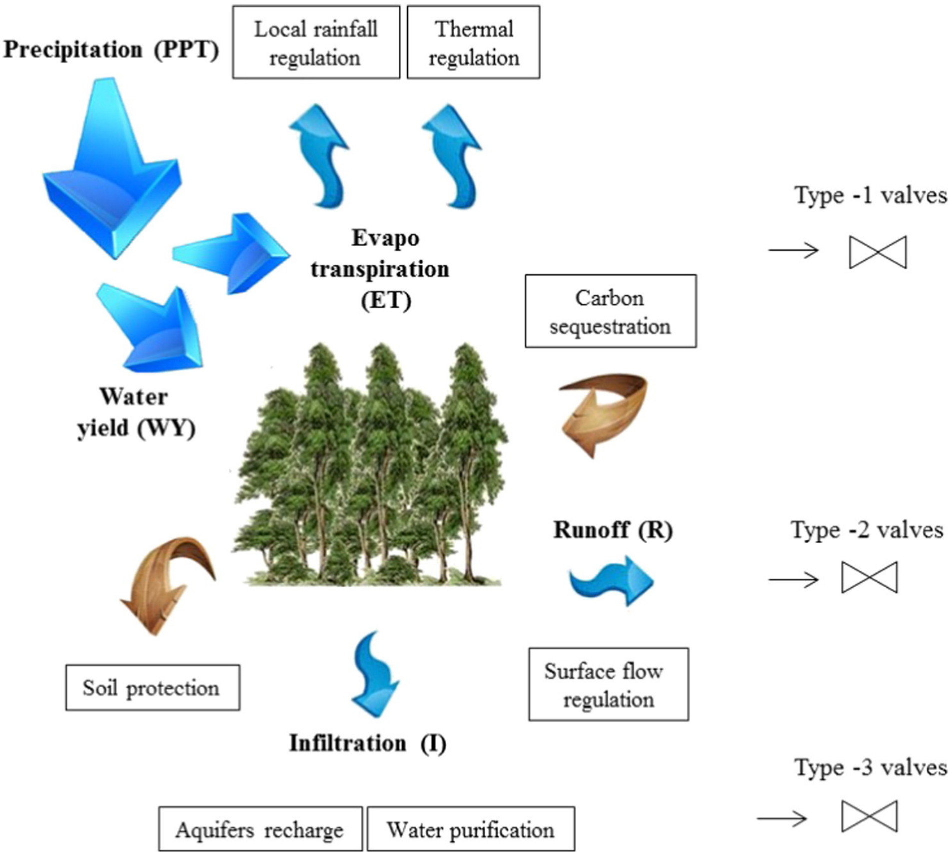

Fig. 1. Conceptual framework used for analyzing the relationships between plant biomass, water pathways (highlighted) and the related provision of regulating ecosystem services (in boxes). On the right side, location of different types of "valve" (see text for explanation).

1990; Dickinson and Kennedy, 1992) have demonstrated that changes in the biomass canopy alter ET by affecting the water that evaporates from plants and the soil. For example, forests often evaporate more water and transmit more heat to the atmosphere as latent heat than grassland/savannas or annual crops. Latent heat cools the local environment. Likewise, more water vapor in the atmosphere increases the probability of cloud formation and convective rainfalls. On the other hand, as Ilstedt et al. (2007) showed in a review of global data, humans can modify water-flows regulation (altering the balance between R and I) by increasing or reducing biomass stocks in ecosystems. Thus, by causing land-use/land-cover changes, humans could modulate the partition of various ES.

However, it should be noted that the control of ES partitioning is neither simplistic nor static. On the contrary, it looks complex and dynamic. Any attempt to maximize the ES provision in one direction may cause a decline in another direction (Bennett et al., 2009). As a result, unexpected tradeoffs may rise when humans try to simultaneously enhance the provision of multiple ES (Raudsepp-Hearne et al., 2010). A positive ES in a given circumstance can become negative (dis-service) in a different one. For example, the ET pathway may compete for water with the runoff one in humid areas, but excessive ET in dry areas can deplete useful runoff (Viglizzo et al., 2014) and transport undesirable salts to the ground (Jobbágy et al., 2008, Amdan et al., 2013). Likewise, runoff water that feed and maintain the function of streams and wetlands in a flat terrain can trigger disturbing flows and landslides in a sloped one (Sidle et al., 2006).

Following the scheme proposed by Jobbágy et al. (2012), we applied the notion of water-routing "valves" that can get increasingly opened or closed by modifying land use/land cover patterns (see location of "valves" in Fig. 1). "Type-1 valves" operate on the partition of precipitation into evapotranspiration and water reaching the ground (WY). "Type-2 valves" control the partition of effective precipitation into water flowing over the surface (R) or infiltrating into the soil (I). "Type-3 valves" regulate the fraction of infiltrated water that is released as vapor to the atmosphere through transpiration and surface evaporation (major components of ET), or reaches deep soil layers or groundwater as deep drainage. To complete the analysis of water-partition routes we need to explore the effect of drivers that operate at different scales (Bailey, 1998): (i) the precipitation at the macroscale, (ii) the aboveground biomass (AGB) stock at the mesoscale and (iii) site conditions such as soil type, vegetation density and topography at the microscale. Our hypothesis was that the partition ES is not static, but variable because it is sensitive to changes that humans can cause on land-cover patterns. However, beyond its sensitivity, the important issue is how humans can handle land cover in order to secure the provision of essential regulatory ES. To test our hypothesis, we analyzed ES partition following land use changes under three different conditions (i) wet and dry climate; (ii) high and low AGB and (iii) flat and steep terrains.

2. Methods

We conducted a comprehensive meta-analysis of data provided by peer-reviewed publications. The analysis comprised 1348 studies that involved 3948 records on precipitation (PPT), aboveground biomass (AGB), AGB change (AGBC), evapotranspiration (ET), water yield (WY), water-yield change (WYC), runoff (R), infiltration (I), terrain type (T) and soil type (ST).

2.1. Dataset building and geographic scope of the study

A collection of five datasets was built based on different sources of global, regional and local data. Units and expressions for analyzed variables are the following: PPT in mm $year^{-1}$, AGB in ton DM (dry matter) ha^{-1}, ET in mm $year^{-1}$, WY in mm $year^{-1}$, (ii), R in mm $year^{-1}$, and I in mm $hour^{-1}$; T in degree (°) of slopes and ST in % sand. Variables were analyzed under wet and dry conditions, low and high AGB, low- and high-sloped T. Reviews and meta-analysis articles were used for dataset building:

Dataset 1: Data included 713 geo-referenced cases from different sites throughout the world. It was organized to study three climatic regions (dry, sub-humid and humid, respectively receiving <500 mm $year^{-1}$, 500–1000 mm $year^{-1}$ and >1000 mm $year^{-1}$) and a range of plant-cover patterns that differ in their tree/shrub/grass relations. Driving factors included PPT, AGB, ET, and WY. Supporting literature for ET data was Sterling et al. (2012), which comprised different methods for ET data calculation (modeling, satellite data, Penman-Monteith equations, soil water balance, eddy covariance, micrometeorological measurements, etc.). WY values were estimated by means of the difference between PPT and ET. AGB was estimated from ET following the procedure described by Viglizzo et al. (2014).

Dataset 2: a collection of 131 cases was built to analyze PPT, AGB, ET, WY, and WYC in response to AGBC The set contains data from Africa (Kenya, Madagascar and South Africa), Asia (Japan), North America (USA), Oceania (Australia). Supporting authors were Hibbert (1967); Bosch and Hewlett (1982); Marvin (1996) and Brown et al. (2005). Data were based on paired catchment studies, which have been divided into four broad experiment categories: afforestation, deforestation, regrowth, and forest conversion. Regression was used to analyze annual discharges from control and treated catchments. Changes in WY were assumed to be due to vegetation change (Brown et al., 2005).

Dataset 3: Data was provided by 77 case studies from Asia (China, Algeria, Israel, and Tunisia), N and S America (Canada and Ecuador), Europe (France, Germany, Greece, Hungary, Italy, Portugal, Romania, Servia and Spain). Data was used for analyzing relationships between AGB and R under high and low terrain slope. Maetens et al. (2012) provided the largest compiled database on plot runoff under natural rainfall conditions in Europe and other Mediterranean countries. The database was originally used to investigate the effect of land-use change on annual runoff and sedimentation.

Dataset 4: comprised 128 cases in SE Asia from Brunei, Indonesia, Malaysia, Philippines, and Thailand (Sidle et al., 2006). Studies supplied data on vegetation cover, management practices, slope and R. The same relationship across low and high-sloped terrains was also evaluated through a 50 study-case source picked up from sites compiled in dataset 3. Supporting authors were Sidle et al. (2006), who have addressed a broad set of forest land uses, soil and site characteristics, monsoon storms and management schemes to study surface and landslide erosion in Southeast Asia.

Dataset 5: 299 cases were considered to analyze the relationship between AGB and I under low and high PPT. Data were supplied by studies done in five continents (Africa, America, Europe and Oceania), and 12 countries (Burkina Faso, Cameroon, Ethiopia, Zambia, Zimbabwe, Canada, Ecuador, Puerto Rico, USA, Germany, Spain and Australia). Part of the recharge data was obtained from a compilation by Scanlon et al. (2006) and part of the infiltration data were provided by Ilstedt et al. (2007) and Thompson et al. (2010). Recharge/infiltration values in these sources were estimated using a variety of techniques, including physical, chemical, isotopic and modeling techniques, with the chloride mass balance being the most extensively used one.

The global map in Fig. 2 deploys the data point locations of the five datasets.

Based on AGB data from IPCC (2006) and ET data from Sterling et al. (2012), a set of nine algorithms were generated to estimate AGB for different vegetation types and climatic regions. Relying on theoretical and empirical evidence (Bradford and Hsiao, 1982; Steduto et al., 2007; Steduto et al., 2009), we assumed that AGB and ET maintain a significant positive correlation. In order to avoid a spurious circular analysis, and considering that the estimated AGB values are dependent from ET, AGB was only associated with figures obtained from independent sources of P and WY data. More details on this procedure can be found in Viglizzo et al. (2014).

As mentioned above, the conceptual framework focuses on AGB stocks, water pathways and the balance between water inputs (PPT) and outputs (ET, R and I). Regulating ES considered in this framework were soil protection, carbon sequestration, local-climate regulation, water-flow regulation and water recharge (Costanza et al., 1997). They depend on functional relations between available water and plant biomass (Jackson et al., 2005, Jobbágy et al., 2012). AGB was an extensively studied factor primarily determined by water availability (IPCC, 2006), which is the result of the balance between the water input and the water output.

2.2. Cross-scale approach

Because ecosystems are spatial systems that are inserted or nested into upper systems, each hierarchical level subsumes the environment,

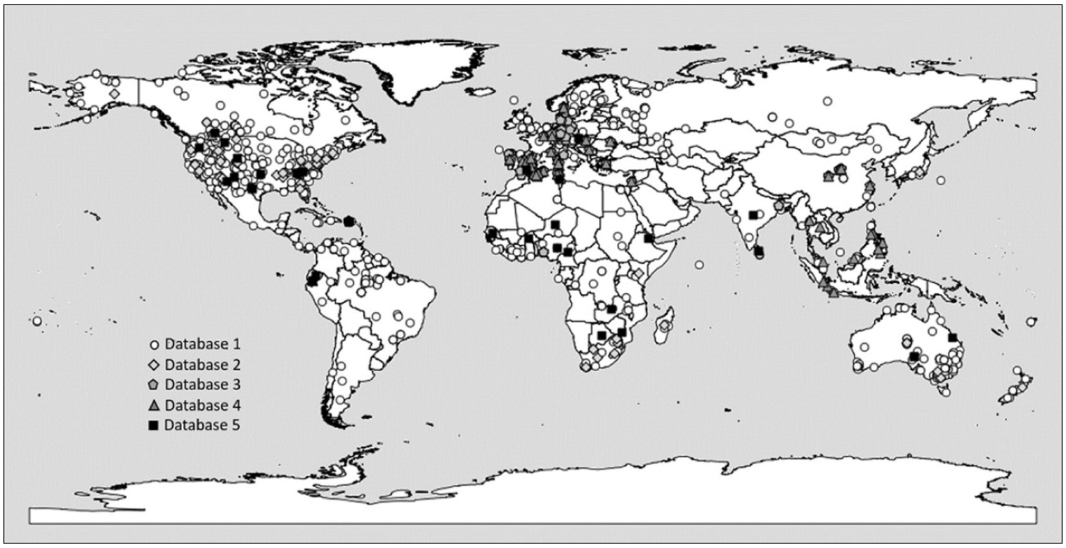

Fig. 2. Worldwide distribution of data from five datasets comprising 1348 study cases.

and controls the behavior, of the system at the level below it (Bailey, 1996). For example, precipitation controls runoff in a watershed, which in turn interacts with slopes to produce stream channels (Warren, 1979). The macroclimate is a source of energy and water that exerts a high-hierarchy control that regulates the distribution of ecosystems over the Earth. As climate changes so do ecosystems (Bailey, 1998) as well as their ecological functions. Latitude, continental position, and altitude are primary factors that strongly modulate the macroclimate pattern, which is organized in temperature and moisture gradients (Trewartha et al., 1967). Given that PPT represents the top hierarchical driver in this study, we divided our global dataset into dry (< 500 mm year^{-1}), sub-humid (500–1000 mm year^{-1}) and humid climatic regions (> 1000 mm year^{-1}). Other factors such as AGB and terrain relief emerge at decreasing hierarchical levels.

In order to undertake different aspects of the study problem and facilitate its understanding, we introduced the notions of macro-, meso- and micro-scale. In quantitative geographical terms, the macro-scale comprises spatial dimensions between 10,000 and 1,000,000 km^2, the meso-scale between 1 and 10,000 km^2, and the micro-scale up to 1 km^2. The macro-scale is usually a large-scale unit used to describe and measure the dynamics of factors such as climate and weather. Within this conceptual framework, PPT is a macro-scale physical factor that has a strong influence, for example, on biophysical attributes that are located at a meso-scale such as AGB or biomass stocks (Rockström et al., 2007). The reverse effect of AGB on rainfall is generally local and small (Bailey, 1998). At the micro-scale, local physiographic factors such as the slope, in interaction with vegetation and the condition of the soil, can strongly affect the pattern and intensity of water flows. The first topographic factor influencing water flows is steepness in hill and mountain slopes (Sidle et al., 2006).

2.3. Meta-analysis

The statistical analysis was based on linear and nonlinear (polynomial, logarithmic and exponential) regression models that were chosen to find best-fitting equations.

In a first step, assuming that data samples are normally distributed, we applied a parametric regression analysis. Given that utilized data sources were highly heterogeneous, the normality of residuals was tested in a second step in order to assess the confidence intervals surrounding parameters and predictions. In doing that we applied non-parametric regression analysis, which was used to compare an empirical distribution function with that of a sample distributed according to a normal distribution of the same mean and variance. The Shapiro-Wilk test (Shapiro and Wilk, 1965) was chosen to test normality because it is considered best suited to handle samples of <5000 observations.

The normality test demonstrated that data in our five datasets did not follow a normal distribution. To measure the magnitude of statistical anomalies, we decided to display in our tables both the parametric and non-parametric determination coefficients. A non-parametric method, the so-called Lowess regression analysis (Locally weighted regression and smoothing scatter plots), which was introduced by Cleveland (1979), was applied in order to create smooth curves through scattergrams.

As non-parametric analysis does not release statistical parameters for the regression as parametric analysis does, we decided to test the correlation between parametric and non-parametric values of R^2. Given that a very high correlation coefficient ($R = 0.935$) between both R^2 was obtained, we decided to proceed relying on parameters provided by the conventional parametric models. Therefore, parameters such as standard error, intercept, regression coefficient b, standard error, and F Fishers's test were incorporated to the analysis.

3. Results and discussion

3.1. Across scales: from global to regional

3.1.1. Precipitation, carbon sequestration and soil protection

Here we assumed that PPT is a high-hierarchy global factor that may exert a downward control on hydrological and biophysical processes at lower hierarchical levels. The statistics of this analysis displayed in Table 1 suggest that PPT drives AGB at the world scale, regulating ES provision related to AGB stocks. Despite differences between datasets 1 and 2, the relation tends to weaken when the analysis throughout the whole PPT range is projected to regional scales (climate regions). The R^2 values of regression models differ both in the slope sign and in the statistical significance. We can infer that PPT is a powerful factor that drives the partition of carbon sequestration and soil protection at the global scale. The dominant driving role of PPT on AGB stocks at the global scale can be visualized in Fig. 3.

The scientific evidence shows PPT plays a major role on carbon (C) sequestration and soil protection: while carbon uptake by plants mitigates climate change at the global scale, soil protection by plant cover prevents erosion from water and wind. The higher the PPT and the biomass stock, the greater the C stored and warming mitigation (IPCC, 2006). The opposite occurs when land is de-vegetated. Deforestation is one the largest source of human-induced C emission (Berthron et al., 2009), especially in tropics and subtropics regions (Don et al., 2011). It should be noted, however, that other factors such as plant composition, soil type, land-use history and technology also influence the balance between C uptake and C emission in ecosystems (Lagamière et al. (2010). On the other hand, the positive effect of plant-biomass cover on soil protection was recognized since many centuries ago. During the last five decades, well-known literature reviews (Hibbert, 1967; Bosch and Hewlett, 1982; Zhang et al., 1999; Best et al., 2003; Andréassian, 2004; Lal, 2009; Scheffler et al., 2011) demonstrated that de-vegetated plots are more vulnerable than the vegetated ones to water and wind erosion, uncontrolled runoff, sediments release and landslides. Plant roots hold soil particles together avoiding the washing away and the blasting of soil particles (Brauman et al., 2007).

3.1.2. Precipitation and climate regulation

High-precipitation areas, particularly those having high biomass stocks and high productivity rates, release ES that are related to the ET function. It has been extensively demonstrated that plant-cover change affects carbon cycle, warming and climate at the global scale (Falkowski et al., 2000). But it has also been recognized that plants affect PPT and temperature at the regional and local scale when water vapor is released back into the atmosphere through evaporation from land and transpiration by plants (Hoffman et al., 2003; Wright, 2005). Vegetation

Table 1
Relationships between precipitation (mm year^{-1}) and aboveground biomass (ton DM ha^{-1}) across a range from humid to dry climatic regions. Data from datasets 1 and 2.

			Precipitation vs. aboveground biomass				
Dataset	PPT range (mm year^{-1})	Number of cases	Best fitting function	PR R^2	NPR R^2	NPR SE	PR P value
1	All PPT range	713	Q	0.3683	0.376	576.11	<0.0001
	0–500	220	L(+)	0.0003	0.000	48.70	0.7830
	500–1000	214	Lg	0.0542	0.049	62.27	<0.0001
	1000–3500	279	Q	0.1567	0.186	81.86	<0.0001
2	All range	131	Lg	0.2159	0.200	561.30	<0.0001
	0–1000	35	Lg	0.4956	0.574	52.19	<0.0001
	1000–2000	73	Q	0.1007	0.282	67.33	<0.0010
	2000–3000	23	L(+)	0.0502	0.050	90.62	0.2670

References: PPT: precipitation; L(+): lineal b positive; Q: quadratic; Lg: logarithmic; PR: parametric regression; NPR: non parametric regression; (R^2) determination coefficient; (SE) square error.

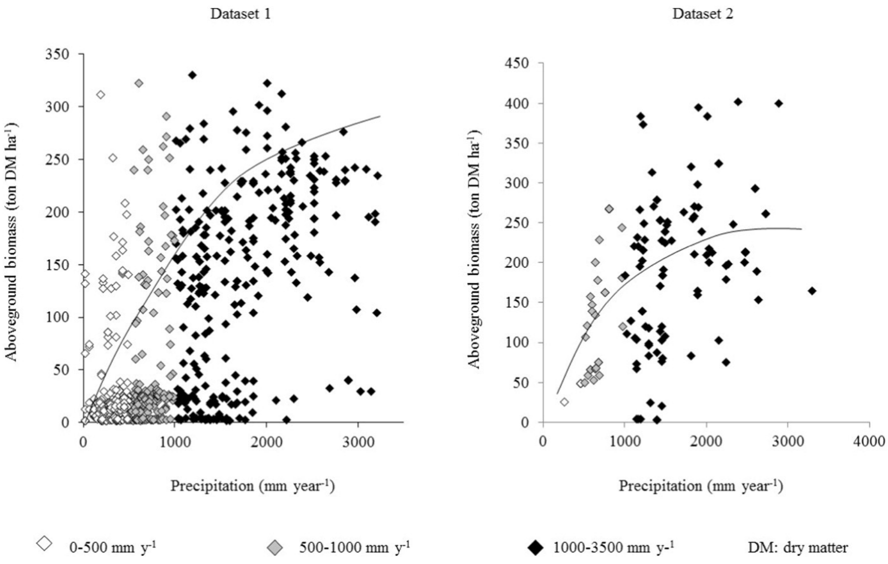

Fig. 3. Relationship between precipitation and aboveground biomass across three climatic regions. Data from data sets 1 and 2, and statistics in Table 1.

acts as heat and humidity pumps that transfer heat and release water vapor that later comes back as rain. Direct measurements above forested and deforested land in Amazonia show that evapotranspiration declined and temperature increased when forests were converted to pasture (Gash and Nobre, 1997; Dubreuil et al., 2012). Satellite data, on the other hand, revealed a continued release of water vapor into the atmosphere in forests but not in deforested areas, especially during dry periods (Saleska et al., 2007). However, the principles described above were neither confirmed nor always supported by results from modeling studies and observational evidence. Because deforestation has occasional coincided with natural variations of climate, the attribution of climate-regulation services is viewed with caution and skepticism by some ecologists. In fact, topography, plant-cover fragmentation, vegetation discontinuities and small clearing are common sources of confusion. Given that small-deforested patches at the local scale have coincided with less warming and more rainfall, some climate scientists (Saad et al., 2010; Lawrence and Vandecar, 2015) believe that PPT may suffer an abrupt decline once a critical deforestation threshold is surpassed.

Beyond uncertainty, high-precipitation areas with high biomass stocks show high ET rate provide more climate-regulation services than dry, low biomass areas. This can be appreciated in Table 2. Setting aside the whole precipitation range, only the sample size explains the highly significant relationships despite the relatively low R^2 values in climatic regions of dataset 1. All regression models were highly significant in results from dataset 2, except in regions of >2000 mm $year^{-1}$.

Table 2
Relationships between precipitation (mm $year^{-1}$) and evapotranspiration (mm $year^{-1}$) across a range from humid to dry climatic regions. Data from datasets 1 and 2.

			Precipitation vs. evapotranspiration				
Dataset	PPT range (mm $year^{-1}$)	Number of cases	Best fitting function	PR R^2	NPR R^2	NPR SE	PR P value
1	All PPT range	713	Q	0.4058	0.406	565.92	<0.0001
	0–500	220	L(+)	0.0734	0.041	329.43	<0.01
	500–1000	214	Lg	0.1107	0.045	243.52	<0.0001
	1000–3500	279	Q	0.1811	0.172	398.66	<0.0001
2	All PPT range	131	Lg	0.2985	0.217	223.89	<0.0001
	0–1000	35	Lg	0.5644	0.450	89.55	<0.0001
	1000–2000	73	Q	0.2282	0.161	212.06	<0.0001
	2000–3000	23	L(+)	0.0407	0.041	284.28	0.289

References: PPT: precipitation; L(+): lineal b positive; Q: quadratic; Lg: logarithmic; PR: parametric regression; NPR: non parametric regression; (R^2) determination coefficient; (SE) square error.

Although the relationships were not linear (Fig. 4), it can be concluded that PPT is not only a first-order determinant of biomass stock, but also of ET and its related-ES release.

3.1.3. Precipitation and water yield

WY represents the difference between PPT and ET. In practical terms, WY is the amount of PPT water reaching the ground, which later flows over the surface and partitions into runoff and infiltration. Part of the infiltrated water is capture by plant roots and released back to the atmosphere as water vapor, and part runs away from roots to soil layers eventually reaching groundwater aquifers through a so-called deep-drainage process (Jobbágy et al., 2012).

The analysis of WY throughout the overall PPT range and the three study climatic regions reveals a positive and highly significant relation between PPT and WY both in datasets 1 and 2 analysis (Table 3). As Fig. 4 shows, positive values of WY reveal PPT surplus, but as it was demonstrated by Viglizzo et al. (2014), negative WY values may indicate that vegetation captures water from sources other than rainfall (generally soil water resources) to sustain the ET demand of plant biomass. This can be easily appreciated in the analysis of dataset 1 in Fig. 5. But given that dataset 2 did not provide negative WY figures, this effect cannot be equally perceived. However, the projection of the linear trend below 500 mm $year^{-1}$ indicates that negative values are inevitable when PPT is not sufficient to compensate for ET water losses.

This is a common phenomenon in forests of riparian zones in dry regions, where the ET demand of woody vegetation can only be sustained if a high water inflow, out of PPT, is supplied (Bosch and Hewlett, 1982). Given that dataset 2 did not provide negative WY figures, this effect cannot be equally perceived. However, the projection of the linear trend below 500 mm $year^{-1}$ indicates that negative values are inevitable when PPT is not sufficient to compensate for ET water losses. This functional response may become especially critical in dry regions where water normally is the most important constraining resource to sustain an active ET. Thus, in regions where rainfall is insufficient to maintain active all water pathways, some services such as climate regulation are released at the expense of other services that can be drastically cut, as it happens with the groundwater provision or the maintenance of water streams and water bodies.

3.1.4. Aboveground biomass and water yield

Beyond precipitation, the relationships between biomass and water yield deserves attention because it represents a downward movement across scales.

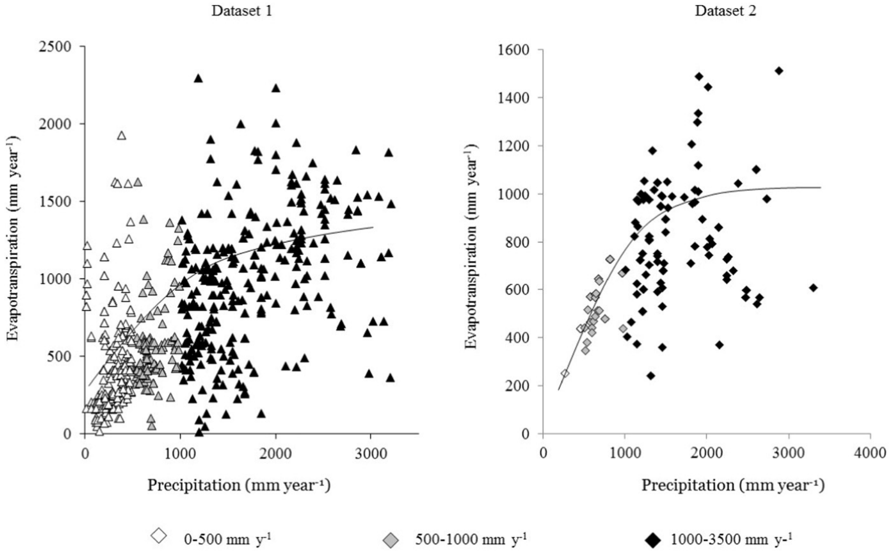

Fig. 4. Relationship between precipitation and evapotranspiration across three climatic regions. Data from datasets 1 and 2 and statistics in Table 2.

Table 3
Relationships between precipitation (mm year^{-1}) and water yield (mm year^{-1}) across a range from humid to dry climatic regions from two different dataset sources.

Dataset	PPT range (mm year^{-1})	Number of cases	Precipitation vs. water yield				
			Best fitting function	PR R^2	NPR R^2	NPR SE	PR P value
1	All PPT range	713	L(+)	0.6629	0.665	328.27	<0.0001
	0–500	220	L(+)	0.0591	0.082	329.66	<0.01
	500–1000	214	L(+)	0.0619	0.039	246.19	<0.01
	1000–3500	279	L(+)	0.5016	0.510	393.55	<0.0001
2	All PPT range	131	L(+)	0.8382	0.837	223.90	<0.0001
	0–1000	35	Lg	0.3430	0.378	88.49	<0.0001
	1000–2000	73	Q	0.3052	0.208	210.57	<0.0001
	2000–3000	23	L(+)	0.3486	0.298	279.34	<0.01

References: PPT: precipitation; L(+): lineal b positive; Q: quadratic; Lg: logarithmic; PR: parametric regression; NPR: non parametric regression; (R^2) determination coefficient; (SE) square error.

Table 4 depicts results from a regression analysis that aimed at assessing the relationships between AGB and WY throughout the global precipitation range and three climatic regions. The value of slope b was negative in all cases when the rough relationship between AGB and WY was assessed (dataset 1). WY tends to decline as AGB increases in the three climatic regions. The more water is lost as ET, the less water reaches the soil-surface as WY. It should be noted that regression models were highly significant in all cases because of the high number of analyzed cases, independently of the value of determination coefficients (R^2).

However, as Viglizzo et al. (2014) have demonstrated in a previous work, the negative value of the slope can be influenced by the vegetation type. The negative relationship between AGB and WY was very high in the case of grasslands/savannas, intermediate in shrublands and low in forests. In the case of grasslands/savannas, the strong fall in WY in all climatic regions occurred in response to small increments of AGB, suggesting that grasses have a high actual ET per unit of AGB. Despite both biomes, show greater AGB, the response decreases in the case of shrubs and trees. This contrasting behavior suggests that trees and shrubs can maintain more biomass (woody material in particular) than grasses per unit transpired water.

Our results and the scientific evidence demonstrate that WY can be associated both with service as well as dis-service provision in

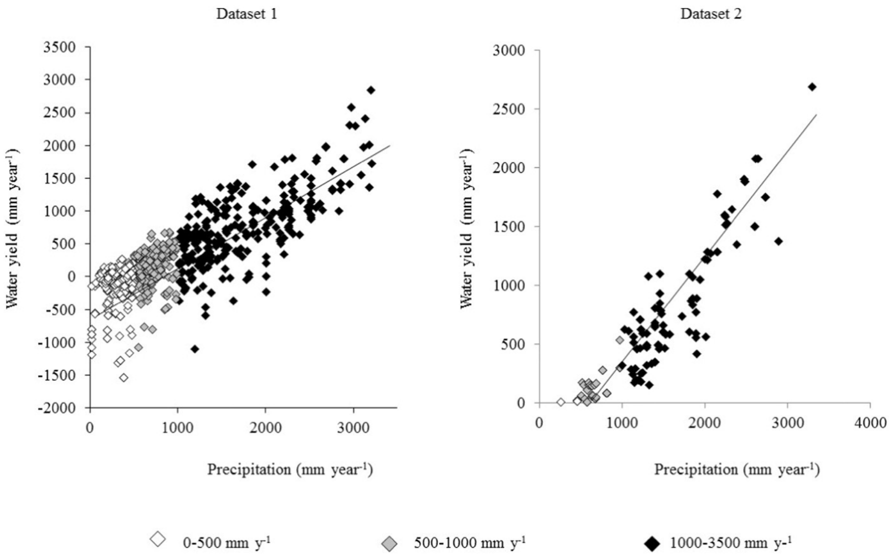

Fig. 5. Relationship between precipitation and water yield across three climatic regions. Data from datasets 1 and 2, and statistics in Table 3.

Table 4
Relationships between aboveground biomass (ton DM ha^{-1}) and water yield (mm $year^{-1}$), and the respective changes in both variables, throughout a range of climatic regions using datasets 1 and 2.

	Dataset	AGB	No. of cases	Best fitting function	PR R^2	NPR R^2	NPR SE	PR P value
AGB vs. water yield	1	All PPT range	713	Q	0.0620	0.043	554.39	<0.0001
		Dry	220	L(−)	0.1389	0.199	307.77	<0.0001
		Sub-humid	214	L(−)	0.1665	0.203	223.66	<0.0001
		Humid	278	L(−)	0.0347	0.200	224.33	<0.0001
Change in AGB vs. change in water yield	2	All PPT range	129	L(−)	0.1228	0.243	131.16	<0.0001
		Dry	35	L(+)	0.0082	0.008	107.03	0.606
		Sub-humid	71	L(−)	0.0236	0.112	132.93	<0.01
		Humid	23	Q	0.5993	0.524	122.68	<0.0001

References: PPT: precipitation; AGB: aboveground biomass; L(+): lineal b positive; L(−): lineal b negative; Q: quadratic; DM: dry matter; PR: parametric regression; NPR: non parametric regression; (R^2) determination coefficient; (SE) square error.

ecosystems. Among other reasons, the evidence shows that trees are commonly planted under the argument that forests provide several ecosystem services like carbon sequestration, climate regulation, soil protection, water-flow control, and improved water supply. There is a widespread public perception that forests also promotes infiltration and groundwater recharge during the wet season, later acting as 'biophysical sponges' that gradually release water during the dry period (Malmer et al., 2010). There are no rigorous studies that showed an improvement of flows after tree plantation on dry regions and degraded tropical land. On the contrary, a number of studies have shown that afforestation has drastically reduced stream flows in tropical dry areas (Kaimowitz, 2005). Combining >600 observations from field research and modeling, Jackson et al. (2005) have documented substantial losses in water yield (and increased soil salinization and acidification) after tree plantation. Such study demonstrated that plantations globally decreased stream flows by 227 mm per year causing that streams became completely dries for at least one year. This conflict between tree-biomass production and water yield is cause of increasing concern because today water is a precious resource in many tropical and dry regions (Rockström et al., 2007). One consequence of this is that various ecosystem services associated with biomass production can be offset by dis-services that come from water scarcity.

How can humans modify the tradeoffs between plant biomass and water? Water flows tend to speed up when humans increase AGB density in ecosystems. This is the effect that meta-analysis of dataset 2 in Fig. 6 shows. This is line with early paired catchment studies that have been widely used for determining the magnitude of water yield changes resulting from changes in vegetation density. A number of well-known review articles have summarized the results of those studies (Hibbert, 1967; Bosch and Hewlett, 1982; Hornbeck et al., 1993; Stednick, 1996; Sahin and Hall, 1996). For example, the meta-analysis of Sahin and Hall (1996) that comprised data from 145 experiments has shown that a 10% reduction in the cover of deciduous hardwood rendered a 17–19 mm increase in yield. However, they also showed that not all tree species have similar response: WY increased by 20–25 mm in response to 10% reduction in cover of conifer-type forests, whereas that for eucalyptus type forest increased by only 6 mm. Beyond the high statistical significance of all-data regression model, our results in Fig. 6 and Table 4 show that relations may vary in different climatic regions. The effect seems to be negligible in dry areas, but may be quite significant in the humid ones. This suggests that a meaningful interaction between WY change and precipitation can be expected in high-rainfall regions, and that humans have the capacity of manipulating such relation.

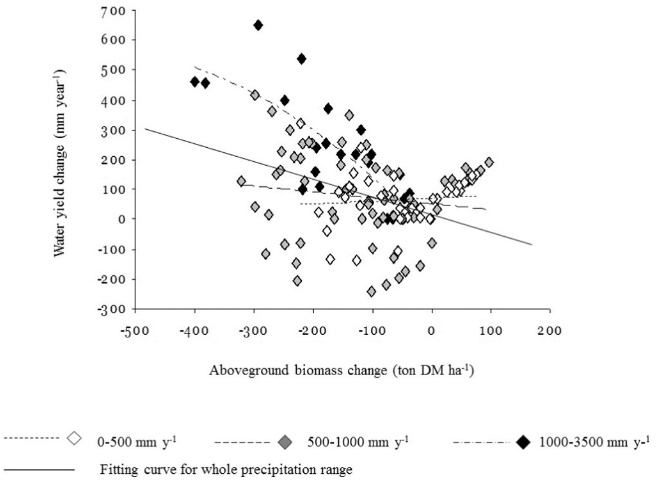

Fig. 6. Relationship between aboveground biomass change and water yield change throughout three climatic regions. Data from dataset 2 and statistics in Table 4.

3.2. Across scales: from regional to local

As the analysis moves downward across scales, the provision of regulating ES such as runoff and sedimentation control and groundwater recharge seems to be modulated by factors other than PPT and AGB.

3.2.1. Aboveground biomass and runoff

Services and dis-services represent opposite faces of the same coin (Zhang et al., 2007). Healthy ecosystems regulate water flows and stabilize streams and water bodies within predictable limits. On the other hand, damaged ecosystems may result in uncontrolled and destructive runoff that causes overflow of rivers and streams, floods, sediments load and landslides on sloped terrains (van Wilgen et al., 1998). One critical challenge is to ensure the provision of controlled runoff services minimizing or avoiding dis-services that are destructive to humans and nature.

Some review articles were unable to be conclusive regarding the AGB-runoff relation. Numerous quantitative studies have been done throughout the world during the last 60 years using different methods such as runoff plots, rainfall simulations and paired experimental plots. Beyond the lack of conclusive results (Andréassian, 2004), some significant differences in annual runoff were found by McMahon et al. (1992) when they compared different forest types on catchments in temperate regions. Given that forests were evergreen or deciduous, Peel et al. (2001) summarized statistics demonstrating that the spatial distribution of evergreen and deciduous vegetation was the primary cause of the differences observed by McMahon et al. (1992). Comparing catchments with similar precipitation, in other study Peel et al. (2002) found that the variability of annual runoff was explained both by the percentage of forest and by the type of forests covering the catchments.

Our results in Table 5 show a negative linear relationship, not always significant, between AGB and runoff. Taking into account the whole AGB data range, and despite its low R^2, the regression model was significant at $P < 0.01$. But determination coefficients tend to decrease when AGB data were split into two categories of factors: slope and precipitation. Although regression models are not equally significant in all cases, regression coefficients (b) in Fig. 7 show that AGB density is inversely

Table 5
Lineal relationships between aboveground biomass (ton DM ha^{-1}) and runoff (mm $year^{-1}$) under different terrain slope and precipitation regime. Data from dataset 3.

Dataset	Factor	Number of cases	Aboveground biomass vs. runoff				
			Best fitting function	PR R^2	NPR R^2	NPR SE	PR P value
3	All AGB range	77	L(−)	0.0934	0.187	46.44	<0.01
	Slope < 15°	34	L(−)	0.0616	0.060	125.49	0.157
	Slope > 15°	43	L(−)	0.0978	0.089	46.28	<0.05
	P < 500 mm $year^{-1}$	34	L(−)	0.1651	0.164	18.45	<0.05
	P > 500 mm $year^{-1}$	43	L(−)	0.1352	0.195	58.60	<0.01

References: AGB: aboveground biomass; L(−): lineal b negative, DM: dry matter; PR: parametric regression; NPR: non parametric regression; (R^2) determination coefficient; (SE) square error.

related with annual runoff under varying slope and different precipitation regimes. Given the difference among coefficients, we can infer that interactions are possible between slope and AGB on the one hand, and slope and precipitation on the other hand. Interactions may occur if we take into account that more AGB seems to be necessary to alleviate the negative impacts of runoff under high slope (>15°) and high precipitation (>500 mm $year^{-1}$) than in the opposite case. Our results confirm the conclusions of previous reviews by Sidle et al. (2006) and Maetens et al. (2012), who have demonstrated that AGB attenuates the negative impact that steep slopes and high precipitation have on annual runoff.

3.2.2. Precipitation, aboveground biomass and groundwater recharge

The increasing demand on finite and increasingly stressed freshwater sources gives estimations on groundwater recharge high scientific significance, especially in semiarid and arid regions, (Scanlon et al., 2006). Groundwater recharge involves a deep drainage function associated with the provision of two ecosystem services: water filtration/water cleaning, and freshwater supply from underground aquifers (Costanza et al., 2007; Havstad et al., 2007). The public in general and part of the ecological community have believed since long time ago that there is a strong link between AGB and groundwater recharge. Given that AGB tends to slow down surface flows, it has been assumed that AGB favors the infiltration of water into the soil. However, caution is required because such relation is neither direct nor simple.

In our analysis, we did not find any significant relation between precipitation and infiltration in wet regions, in contrast to the existence of a positive and significant relation in arid-semiarid regions (Table 6). Based on figures from Scanlon et al. (2006) and Thompson et al. (2010) compiled in dataset 4 and 5, we found highly significant positive correlations between rainfall and infiltration in arid-semiarid regions where precipitation is lower than 500 mm $year^{-1}$. On the contrary, data from Thompson et al. (2010) and Ilstedt et al. (2007) allowed us finding that such correlations become close to zero in subhumid–humid where precipitation ranged between 850 and 4100 mm $year^{-1}$.

Despite of the argument of a direct relationship between vegetation and infiltration, such relation remains insufficiently measured and clarified by means of sound studies (McCarthy and Enquist, 2007). So, a relevant eco-hydrological question remained unanswered: how does vegetation influence groundwater recharge across a wide range of climate regimes? As it happens with precipitation, AGB correlates well with infiltration in dry, but not in wet areas (Table 6). Thompson et al. (2010) undertook the meta-analysis of field data to examine the biomass-infiltration relation in different vegetation and soil types across a climatic gradient that ranges from extreme arid deserts to humid tropics. They found that the enhancement of infiltration capacity in the presence of vegetation is well documented in arid ecosystems, but vegetation is not well correlated with infiltration in humid climates. Reanalyzing data from these authors and Scanlon et al. (2006), in Table 6 we show a positive correlation between AGB and infiltration in dry areas. But what it is a positive and highly significant relation in the case of Thompson et al. (2010) data, such relation remains positive but not significant in the case of Scanlon et al. (2006) data. In wet areas, such positive relation becomes neutral with data from Thompson et al. (2010) but becomes negative when data from Ilstedt et al. (2007) were analyzed.

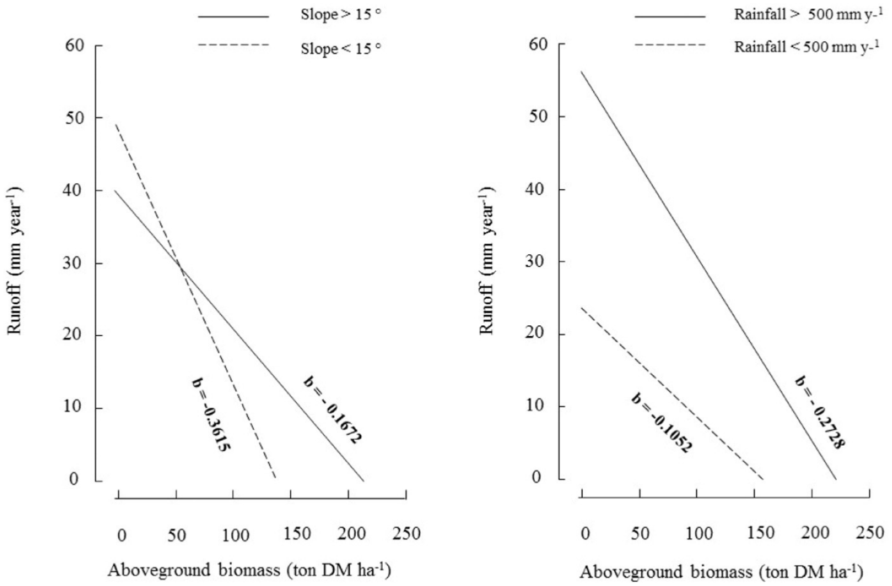

Fig. 7. Diagrams showing the regression coefficient b of relationships between aboveground biomass and annual runoff under high and low slope, and high and low rainfall conditions. Data from dataset 3 and 4, and statistics in Tables 5 and 6.

Table 6
Relationships between precipitation, AGB and the infiltration rate based on dataset 4 and 5.

	Dataset	Source	No. of cases	Best fitting function	PR R^2	NPR R^2	NPR SE	PR P value
PPT vs. infiltration rate	4/5	Scanlon et al. (2006)						
		<500 mm $year^{-1}$	29	L(+)	0.150	0.162	117.62	<0.05
		Thompson et al. (2010)						
		<500 mm $year^{-1}$	46	L(+)	0.363	0.296	73.68	<0.01
		500–4100 mm $year^{-1}$	194	L(0)	0.009	0.002	1217.8	>0.05
		Ilstedt et al. (2007)						
		850–2500 mm $year^{-1}$	28	L(0)	0.005	0.002	567.23	>0.05
AGB vs. infiltration rate	4/5	Scanlon et al. (2006)						
		<500 mm $year^{-1}$	29	L(+)	0.014	0.000	4.17	>0.05
		Thompson et al. (2010)						
		<500 mm $year^{-1}$	46	L(+)	0.324	0.181	7.41	<0.01
		500–4100 mm $year^{-1}$	194	L(0)	0.000	0.002	111.78	>0.05
		Ilstedt et al. (2007)						
		850–2500 mm $year^{-1}$	28	L(−)	0.005	0.224	6.89	>0.05

References: AGB: aboveground biomass; PPT: precipitation; L(+): lineal b positive; L(−): lineal b negative, L(0): lineal b zero; PR: parametric regression; NPR: non parametric regression; (R^2) determination coefficient; (SE) square error.

According to those authors, the physical characteristics of the soil may be a dominant driver of infiltration in wet regions. They considered that soil water saturation - and eventually the weak capacity of plants to enhance infiltration - under humid conditions can explain the low infiltration rates recorded in wet areas. Other studies have demonstrated that some pathways in the water cycle, such as that of infiltration, are not directly influenced by plant activity (Bracken and Croke, 2007; Mayor et al., 2008). Spaeth et al. [1996] argued that a complex suite of biological and physical processes might affect infiltration at the rooting zone. Again, data from Thompson et al. (2010) was used in this work to build Table 7, which shows that soil type can be a powerful driver of infiltration. No correlation was found between infiltration and sand below 50% sand in soil, but such correlation becomes positive and highly significant ($R^2 = 0.886$) in soils having >50% sand. Thus, factors other than the biotic ones may drive water recharge in dry areas. It should be noted that sandy soils tend to predominate in arid and semiarid regions (Kadry, 1975) where infiltration rates tend to be higher than those of the humid ones.

Despite it was frequently mentioned by literature on ecosystem services, it is not clear the effect of vegetation on water purification. Infiltration into groundwater may result in improved water quality (Brauman et al., 2007), but not always was this process considered as an ecosystem service. On the other hand, the purification effect on water was well demonstrated in the case of wetlands, particularly in the case of riparian vegetation. Many works show cases that provide empirical evidence that confirms such effect: wetlands are efficient at removing nutrients from water by means of mechanisms, like gaseous N removal, N and P uptake by riparian plants and sediments deposition (Verhoeven et al., 2006). Water-resource managers worldwide are considering the potential role of riparian zones and floodplain wetlands for improving stream-water quality.

Table 7
Relationships between precipitation and % sand in soil and the infiltration rate based on dataset 5.

			% sand vs. infiltration rate				
Dataset	Source	No. of cases	Best fitting function	PR R^2	NPR R^2	NPR SE	PR P value
5	Thompson et al. (2010)						
	Sand (0–50%)	56	L(0)	0.006	0.006	55.84	0.566
	Sand (50–100%)	21	L(+)	0.886	0.824	75.59	<0.0001

References: L(+): lineal b positive; L(0): lineal b zero; PR: parametric regression; NPR: non parametric regression; (R^2) determination coefficient; (SE) square error.

4. Discussion and conclusions

Our analysis suggests that the partition of ecosystem services in nature shows a strong scale-dependency. In fact, partitioning behaves as an emergent property that varies from small (several square meters) to large-scale areas (several square kilometers) and from one scale to the following. As it is shown in Fig. 8, the relationship (measured through R^2) between the analyzed parameters tends to be more robust at broader (e.g., the whole globe and broad climatic regions) than at smaller scales (e.g., basins, fields/plots). In other terms, the dominant effect of driving variables like rainfall or AGB on ecosystem service partition is visible at large but not necessarily at small scales. It is likely that variables other than those of rainfall and AGB emerge at reduced scales and modify the service share within the ecosystem. Results show decreasing values for R^2, and varying (positive, negative or neutral) relations at decreasing scales. Various studies have revealed similar trends in scale-oriented studies on water sedimentation (Bergkamp, 1998; Jiongxin and Yunxia, 2005; De Vente and Poesen, 2005; Restrepo et al., 2006).

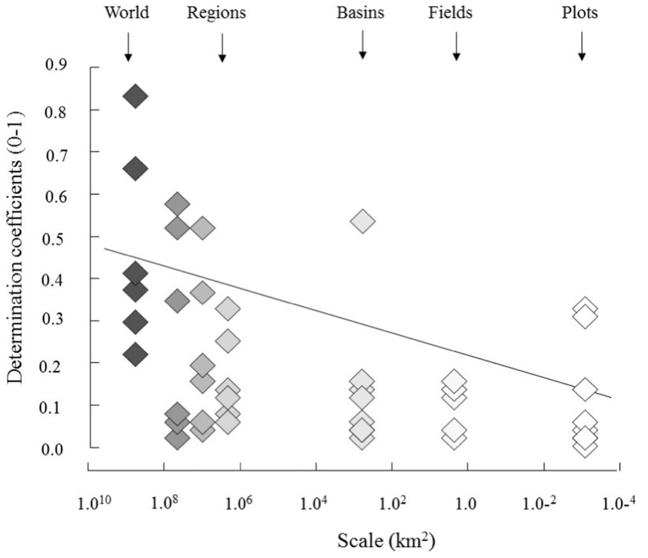

Fig. 8. The value of determination coefficients (R2) at decreasing geographic scale. R2 values were estimations from regression models in this work involving the relations between precipitation, aboveground biomass, evapotranspiration, water yield, runoff and infiltration.

The increasing power of regression models with increasing scales could be explained by two facts: (i) high correlations are obtained when the statistical variability of data is high. And such variability is larger at broader than at smaller scale due to the large diversity of environments found over at large scales; or (ii) interactions between large-scale driving factors and small-scale emerging factors may spread or disperse the effect of the first ones. However, another fact cannot be discarded, since some authors have suggested that the scale dependency of relations may be caused by (iii) complex non-linear relations that emerge when a critical threshold is surpassed after moving from one scale to the following (Lane et al., 1997; Osterkamp and Toy, 1997; Slaymaker, 2006). For example, the emergence of a topographic threshold at a small scale may spread the effect of large-scale, dominant driving factors.

Research outcomes indicate that precipitation and aboveground biomass are both dominant driving factors at broad geographical scales. Relying on our meta-analysis, in Fig. 9 we graphically deploy a hypothetical representation of ecosystem service partition throughout the high-low precipitation gradient and the high-low aboveground biomass gradient. In Fig. 10 we represent what may happen when the slope – a small scale factor – interferes on both gradients.

Ecosystem-service partition under high AGB density seems to be quite different in wet and dry areas. The activation of “type-1 valves” due to land-use decisions can drastically modify ES partition in the landscape: while evapotranspiration and runoff of forests in wet areas may release a well-balanced relation between the local climate regulation and the water-flow regulation (Fig. 9a), in dry areas both services may suffer imbalance (Fig. 9b).

In dry areas, “type-1 valves” open and enhance ET in forested lands, closing the water yield pathway, thus affecting both the water flow regulation (R) and the infiltration (I) of water to deep soil layers and aquifers. Occasionally, “type-1 valves” open the ET pathway that causes a depletion of underground water resource. In practice, “type-3 valves” privilege the partition of water to the ET pathway by closing the deep-infiltration one. The net effect is a decrease of underground water level, which on the other hand, may trigger an undesirable side effect (or negative ES provision): the accumulation of salts on the ground. Because of such imbalanced partition, various studies (Bosch and Hewlett, 1982; Zhang et al., 2004; Farley et al., 2005; Jackson et al., 2005; Scott et al., 2005; Calder, 2007; Van Dijk and Keenan, 2007) concluded that forests transpire more water and release less water to runoff and groundwater recharge than shallow-rooted plants such as crops, pastures or grasslands. Although the partition of water-related ES varies with vegetation type, the partition smooths in the case of pastures and grasslands/savannas, both under wet (Fig. 9c) and dry conditions (Fig. 9d).

The partition of regulatory ES, on the other hand, may be different in sloped terrains exposed to contrasting precipitation regimes and biomass stocks. The evidence from two review and meta-analysis articles (Sidle et al., 2006; Maetens et al., 2012) demonstrates that land-use that favors high AGB density (opening of type-2 valves) is quite effective to reduce runoff rate, as well as sedimentation and landslide risk, both in wet (Fig. 10a, c) and dry areas (Fig. 10b, d). However, if “type-2 valves” opens in high-precipitation areas under a land-use scheme that favors AGB removal (e.g., because of overgrazing) and reduces ET, a destructive runoff may trigger with the result of low soil protection, sedimentation and landslide risk. Such undesirable effect is smoothed in dry areas.

Land-use decisions may activate “type-3 valves” in different ways. “Type-3 valve” regulates the fraction of infiltrated water that is released as vapor to the atmosphere through ET, or reaches deep soil layers or groundwater because of deep drainage. In densely forested dry areas, “type-3 valves” favors underground water depletion because they enhance the ET pathway. But they may open to infiltration and deep drainage in conditions where vegetation is sparse and sandy soils

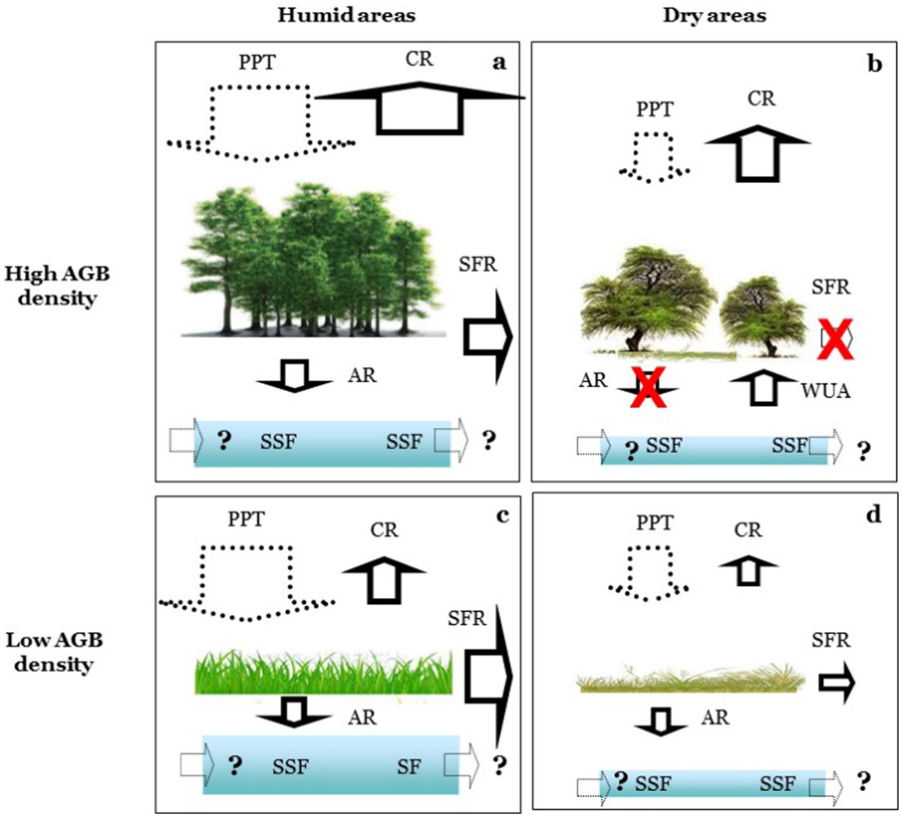

Fig. 9. Hypothetical representation of regulatory ES related to water pathways in humid and dry areas sustaining high and low stocks of aboveground biomass. Arrows of different size represent the relative importance of ES provision. Horizontal bands on the bottom represent groundwater level height. References: (PPT) annual precipitation; (CR) climate regulation (local rainfall and temperature regulation); (SFR) surface flow regulation; (AR) underground aquifer recharge; (WUA) water uptake from aquifer; (SSF) unknown subsurface water flow.

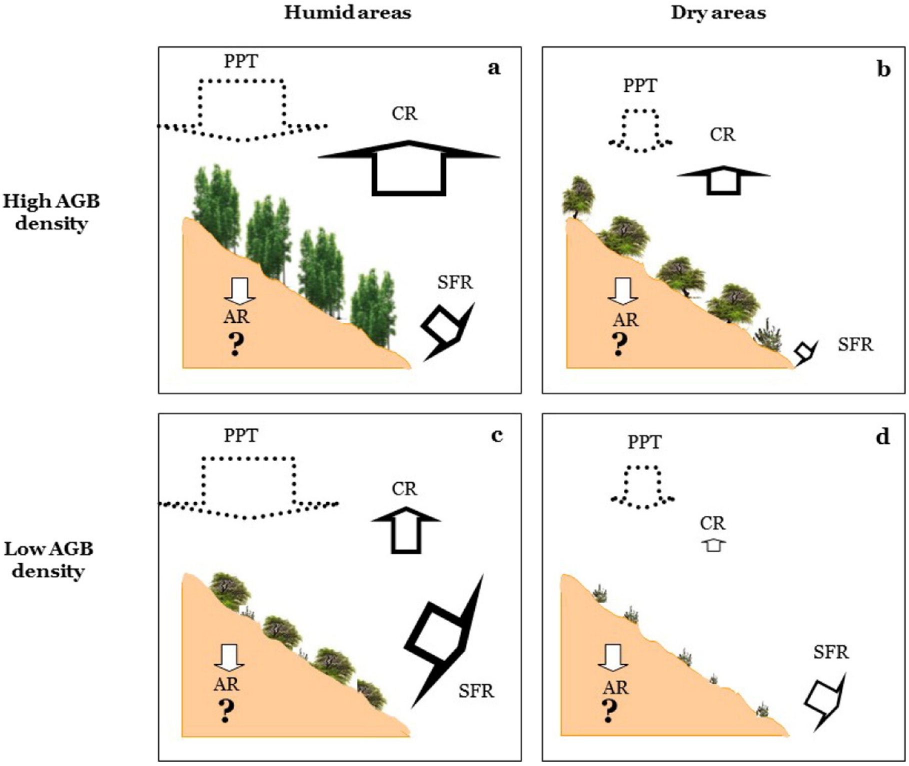

Fig. 10. Hypothetical representation of regulatory ES related to water pathways in sloped terrains of humid and dry areas sustaining high and low stocks of aboveground biomass. Arrows of different size represent the relative importance of ES provision. Arrows of different size show the relative magnitude of water pathways associated with ecosystem service or dis-service provision. References: (PPT) annual precipitation; (CR) climate regulation (local rainfall and temperature regulation); (SFR) surface flow regulation; (AR) underground aquifer recharge.

dominate the landscape. This pathway may be fully closed in water-saturated soils. In such cases, “type-3 valves” open to enforce the direct water evaporation pathway from soil.

The growing demand from agriculture and urban systems imposes increasing pressure on land and the provision of essential ES. The global climate change, on the other hand, is another pressing problem in the years to come. While some regions will remain unmodified, vast areas in the planet may become drier or wetter regarding the historical climate patterns (IPCC, 2014). Inevitably, we have to infer that climate change will affect the partition of ES provision. We can expect that future change in water, biomass and site conditions will modulate, across scales, new patterns of ecosystem service partition. Coming back to the driving factors that we analyzed (precipitation, biomass and relief), humans can handle only one: plant biomass. The three types of “valves” can be opened or closed by handling plant biomass change. The direct and indirect effects of plant biomass alteration across scales should be a target to be prioritized by science in the years ahead.

However, thinking that land-cover management is the main “valve” that humans can use to influence the provision of regulatory ecosystem services may be misleading. Beyond the impact of land-use/land-cover, it must be acknowledged a difference between “green and gray infrastructure”. People uncommonly think of forests, wetlands or other natural ecosystems as forms of infrastructure, but in practice, they are because of their role in regulating flows and preventing pollutants from entering into streams and water bodies that supply freshwater. Gray infrastructure, on the other hand, refers in general to a hard or traditional infrastructure that are made and engineered by humans for providing water management services. It may include gutters, storm sewers, tunnels, dams, pipes and mechanical devices collectively used for capturing and conveying water. The transition from a natural to an engineered landscape increases the impervious surface coverage. Such gray infrastructures alter or entirely eliminate native vegetation, upper soil layers, shallow depressions, and native drainage patterns that normally would intercept, evaporate, store, slowly convey, and infiltrate storm-water. These changes can increase flooding, degrade stream habitat, and pollute watercourses (Swartz and Belan, 2010). In terms of cost, investments in green infrastructure can be much less expensive than those in gray infrastructure. Authorities of New York City, for example, have evaluated two schemes to manage its storm-water flows: (i) the green one that emphasized stream buffer restoration and the creation of landscape elements to remove silt and pollution from surface runoff water, and (ii) the gray infrastructure involving tunnels and storm drains. The green infrastructure option presented a cost savings of more than US$ 1.5 billion (Talberth and Hanson, 2012). If green infrastructure can provide comparable benefits to gray infrastructure at reduced costs, budgets can be allocated to conservation, sustainable management, and/or restoration of natural ecosystems to achieve development goals (Talberth et al., 2012). Examples of public and private investments in green infrastructure already exist can be found in USA, Colombia and China.

Some questions that demand answering should be addressed by future investigations: Does the size and the density of deforested patches affect climate regulation? Are regulation services exposed to abrupt decline when certain deforestation thresholds are surpassed? What tradeoffs between different ES and between positive and negative services can be expected across scales? How do vegetation types (e.g., broad leaf vs. conifer, or evergreen vs. deciduous forests) regulate water flow and water recharge? These and other research issues will have to be undertaken as a pre-requisite to address sustainable options of land policy and land management.

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