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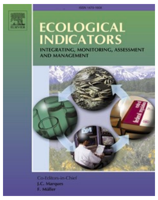

Water balance partitioning for ecosystem service assessment. A case study in the Amazon

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ABSTRACT

Rainforests ensure fundamental water-related ecosystem services that are currently threatened by land-use change, in particular deforestation. Quantitative assessments of water-related ecosystem services have traditionally focused on the benefits linked to direct water availability for humans. Under this perspective, forests have been considered as water consumers, due to high interception and transpiration rates that reduce water flows available to downstream human activities. In contrast, their role as water suppliers through transpiration from tree canopies has often been neglected. Integrating this second perspective into assessments of water-related ecosystem services from forests and other land covers is key to providing a comprehensive support to decision-making processes on land-use change. In addition, specific indicators are necessary to incorporate the contribution of the different water balance components into ecosystem service assessment.

In this paper, we investigate the use of water balance partitioning for the assessment of water-related ecosystem services. We use three water balance models (two existing ones and one developed in this study) and compare, via model simulations, water balance partitioning and water-related ecosystem services of a forested and a deforested area of the Brazilian State of Rondônia. Then, we propose a set of indicators that, based on the outputs of the models, provide a multidimensional characterization of different land-use types. Regardless of the model used, the values of these indicators for the selected case study consistently point out the key role of vegetation in regulating the water cycle. Forests act as effective indirect water suppliers for human activities and are key players in moisture recycling, thanks to high evapotranspiration rates (about 68% of total precipitation). Deforested areas, instead, act as direct suppliers of water flows for human activities due to higher drainage rates (about 50% of total precipitation).

The proposed methodology helps highlight the importance of comprehensive water-related ecosystem services assessments. Moreover, the indicators quantitatively support the impact assessment of land-use change on the different processes involved in the water cycle and on human activities relying, directly or indirectly, on these processes.

1. Introduction

Forests play a key role in guaranteeing fundamental ecosystem services (ES) such as food provisioning, biodiversity conservation, climate and freshwater regulation, and mitigation of natural disasters (Brandon, 2014). In particular, tropical forests provide the majority of these ES (Díaz et al., 2005; Vitousek and Sanford, 1986) with an estimated economic value of 5,384 \$ ha^{-1} $year^{-1}$, almost twice that of temperate forests (Costanza et al., 2014). Several studies have highlighted the positive effects of forests on the water cycle, including the reduction of surface runoff, the support to groundwater recharge and maintenance of optimal soil moisture conditions (Bruijnzeel, 2004; Calder, 2003). Forests influence freshwater quality (removal of pollutants and trapping of sediments), quantity (total water yield), and timing (seasonal distribution of flows) by affecting key hydrological processes like evapotranspiration (ET) and canopy interception (Brauman et al., 2007; Carvalho-

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Santos et al., 2016).

Deforestation affects the above-mentioned processes and threatens the supply of water-related ES from forests. For instance, reduced canopy interception enhances surface runoff and erosion (e.g. Nepstad et al., 1994), while the inhibition of precipitation recycling decreases air moisture and rainfall (Spracklen et al., 2012; Spracklen and Garcia-Carreras, 2015). These issues have gained attention in recent years, principally because current deforestation rates have the potential to alter the water cycle on a range of geographical scales (Weng et al., 2019), causing increasing governance concerns (Ellison et al., 2017; Keys et al., 2019, 2017).

Although the key role of forests in regulating the water cycle and their influence on the availability of water resources have been widely recognised in the literature (Guimarães et al., 2017; Hackbart et al., 2017), their evaluation has historically been based on a 'demand-side' perspective, taking into account water demand for residential water consumption, hydropower generation, irrigation, flood prevention, and cultural services (Garcia-Prats et al., 2016; Martin-Ortega et al., 2013). From this perspective, forests appear to reduce the amount of water available to downstream human activities compared to other land-use types (Garcia-Prats et al., 2016; Kim et al., 2018). On the other hand, the so-called 'supply-side' perspective considers forests as responsible for the intensification of the water cycle at different spatial scales (Ellison et al., 2012; Sheil and Murdiyarso, 2009), since the water vapour they supply to the atmosphere substantially influences the rainfall regime (Keys et al., 2014; Sheil, 2018). In the Amazon, for instance, forest ET sustains more than 70% of the annual precipitation (Van Der Ent et al., 2010). Rainfall recycling contributes, in turn, to the maintenance of both forest ecosystems themselves (Keys et al., 2016) and rainfed agriculture (which accounts for 60–70% of global agricultural production; Wood et al., 2000).

According to Falkenmark and Rockström (2004), the key difference between demand- and supply-side perspectives is in the different water flows they focus on: the demand-side approach concentrates primarily on 'blue' water (flowing into rivers and aquifers), while the supply-side perspective focuses on 'green' water (flowing through the unsaturated zone of the soil, as well as evaporating from soils and tree canopies). Considering both the blue and green components is essential to comprehensively assess the contribution of different land-cover types to water-related ES (Albert et al., 2016; Van Oudenhoven et al., 2012), and to integrate existing ES assessment tools that do not account for the green water contribution (Peh et al., 2013; Sharp et al., 2014; Villa et al., 2014). A comprehensive assessment of water-related ES thus requires (i) quantitative methods, such as hydrological models, describing the relationship between land cover and key hydrological processes (Guswa et al., 2014), and (ii) the definition of the links between those processes and ES indicators (Martin-Ortega et al., 2013) to inform decision making in forest resources management (Figueira Branco et al., 2019; Layke et al., 2012).

Here we addressed the following questions: do estimates from different hydrological models coherently support the comparison between land covers in term of water balance? And do different land-cover types distinctively contribute to the water balance and to the provisioning of water-related ES, evaluated from both the green and the blue perspective? To answer these questions, we compared the outcomes of three models for water balance simulation applied to two areas of the Amazon region with different land cover (forested vs. deforested). Then, we used water balance partitioning (Hackbart et al., 2017; Kozak et al., 2011) to assess the impacts of deforestation on water fluxes. Finally, we investigated whether it is possible to summarise water balance partitioning in simple metrics allowing the comparison of different land-use types in terms of water-related ES. To this end, we defined a set of quantitative indicators accounting for both green and blue water flows and applied them to our case study.

2. Materials and methods

2.1. Case study

The intense deforestation of the Amazon rainforest started in the 1970s. Among the Amazonian regions, the Brazilian state of Rondônia is one of the most deforested: according to a study from the Brazilian National Institute for Space Research (INPE, 2008) this region has lost 22% of its original forest cover due to intensive agriculture, pasture, cattle ranching, mining, and urbanization (Leite et al., 2011; Pedlowski et al., 1997). For this reason, the Rondônia case study seems appropriate for assessing the impact of land cover change on the water balance. We selected two areas of about 12,000 km^2 each and characterized by similar meteorological conditions but two different land-cover types (Fig. A.1, Supplementary information): virgin tropical forest and pasture obtained through deforestation. We identified the land covers on the basis of the MOD12 2011 global land cover map (Friedl et al., 2010) and verified that no significant changes occurred during the considered period (2005–2015) through a high-resolution global map of 21st-century land-cover change (Hansen et al., 2013). The choice of geographical scale and time horizon selected for the analysis allows accounting for the spatiotemporal variation of the water balance in the Amazon basin (Marengo, 2006; Poveda and Mesa, 1997).

2.1.1. Meteorological conditions and vegetation

We used data from the ERA-Interim database (Dee et al., 2011) to characterize the meteorological conditions of the selected study areas (Fig. A.2, Supplementary information). The dataset covers the 2005–2015 period, which was the latest available when the study was performed. Rainfall shows the typical seasonal pattern of the Southern Amazonian region (Marengo, 2005), with a wet season from October to May and a dry season (with a cumulative rainfall below 100 mm/month; Nobre et al., 2016) from June to September. July is the driest month, with a minimum of about 25 mm/month, while the first months of the year are the wettest, attaining values up to 300 mm/month. Net radiation time series show strong seasonal fluctuations in counter phase with precipitation patterns. The same pattern emerges from temperature, which has an annual mean of about 25.8 °C, while relative humidity strongly decreases during the dry season. All the meteorological variables show parallel seasonal patterns in forest and pasture areas. In contrast, the Leaf Area Index (LAI) shows remarkable differences in the vegetation structures of the two land covers: forest has an annual mean of 5.9 $m^2_{leaf} / m^2_{ground}$, while pasture has a lower value, equal to 3 $m^2_{leaf} / m^2_{ground}$. The forest LAI remains rather stable over the year, while in pasture areas it shows a marked decrease in the central part of the year, since the shallower root system of grasses does not allow water uptake from deeper soil layers, with a consequent reduction in photosynthetic activity during the dry season (Huete et al., 2006; Myneni et al., 2007).

2.2. Water balance partitioning

The water balance is strictly related to ecosystem functions and related ecosystem services because it influences the abiotic and biotic processes taking place within ecosystems (Mercado-Bettín et al., 2019; Ponce Campos et al., 2013). For this reason, water-related ES assessments require water balance models able to describe the main processes driving the water cycle (Mastrorilli et al., 2018). The conceptualization of these processes has led to the definition of a large number of models, whose appropriateness depends on the specific case study and its spatiotemporal scale (Abdollahi et al., 2019; Wang and Pullar, 2005).

Water balance partitioning is the disaggregation of the water balance into its main components, i.e. input flows from precipitation (P) and output flows as evapotranspiration (ET), surface runoff (R), groundwater drainage (D) and change in soil water content (ΔW)

(Thornthwaite and Mather, 1957). A generic water balance can be written as (Sokolov and Chapman, 1974):

$$P = ET + R + D + \Delta W \tag{1}$$

In this work, we investigate the relationship between vegetation cover and water balance. We compare the outputs of three different water partitioning models: the Global Land Evaporation Amsterdam Model (GLEAM) (see section 2.3), the software HYDRUS 1-D (section 2.4) and the Soil-Vegetation-Water (SOVEWA) model, developed in this work as a tool with intermediate characteristics between the previous two (section 2.5). All three models simulate hydrological flows on a daily scale based on earth observation data but are based on different modelling assumptions and have different levels of flexibility for the user.

A comprehensive assessment of the influence of vegetation on the water balance requires an explicit description of how plant biomass dynamics and soil water dynamics interact. This is possible with HYDRUS-1D through the definition of several parameters, some of which are difficult to be determined. On the other side, GLEAM considers the effect of land cover on water flows, but does not explicitly describe plant biomass dynamics. To bridge this gap, we developed a simple dynamical model (SOVEWA) describing the coupled dynamics of water in the soil and in plant biomass by taking into account the main hydrological processes.

To obtain consistent and comparable outputs from the three models, we assumed that the infiltration process is strictly one-dimensional (i.e. that water flows only vertically), and that lateral flows between contiguous land parcels are negligible compared to vertical ones (De Ridder and Boonstra, 1994). This assumption, on which GLEAM is based, seems reasonable in our case, considering that the mean slope in the study area is $< 8\%$ and that draining conditions are satisfactory (Cochrane and Cochrane, 2006).

Through the calculation of the annual water balance from all the methodologies (obtained by summing up daily water flows), we verified that there is no carry over of water from one year to the next one (positive and negative water storage variations tend to balance), so water accumulation in the soil can be considered negligible ($\Delta W = 0$). Under the hypotheses cited above, the water balance can be simplified as

$$P = ET + R + D \tag{2}$$

where ET, in turn, can be partitioned into three distinct contributions: transpiration by plants (T), evaporation from the soil (E), and rainfall intercepted by the canopy and immediately evaporated back to the atmosphere (indicated in the following simply as interception, I):

$$ET = T + E + I \tag{3}$$

All terms are expressed as actual rather than potential flows.

2.3. Gleam

GLEAM (Martens et al., 2017; Miralles et al., 2011) is a set of algorithms using land cover and other satellite measures to evaluate the different components of evapotranspiration (transpiration, interception, evaporation from bare soil and water bodies, and snow sublimation), and satellite soil moisture data as a constraint on potential evaporation rates. The model is composed of four separate modules to estimate (i) potential evapotranspiration (ETp), based on temperature and net radiation data through Priestley-Taylor's equation (Priestley and Taylor, 1972); (ii) interception, with Gash's analytical model (Gash, 1979); (iii) evaporation; and (iv) actual ET, estimated from ETp through a multiplicative stress factor ranging from zero to one and accounting for root-zone and vegetation water content. GLEAM does not consider surface runoff, so the remaining fraction of precipitation is referred to as drainage. The estimates of daily ET flows for each land-cover type are then aggregated proportionally to the fraction of different land covers (i.e., bare soil, low vegetation, tall vegetation and open water) over a quasi-global grid (50° N – 50° S) at a spatial resolution of 0.25° × 0.25°. We downloaded the model outputs (version 3.0b) from the GLEAM SFTP server (www.gleam.eu).

2.4. HYDRUS-1D

Among the existing hydrological models (Devia et al., 2015; Sood and Smakhtin, 2015), we selected HYDRUS-1D (Šimůnek and Hopmans, 2009; Šimůnek and Van Genuchten, 2008). The freely accessible version of this software includes a finite-element model for the simulation of water, heat and solute movements through a mono-dimensional medium. The model is able to disaggregate ET into its distinct components, as well as to describe the dynamics of soil water content and water uptake by vegetation (Feddes et al., 1978).

The main modelling assumptions of HYDRUS-1D are the following. Vertical water movement into the soil is described via Richard's equation (Richards, 1931). Surface runoff includes both runoff from soil saturation and from excess of rainfall intensity. ETp is estimated with Penman-Monteith's equation (Kaelbling et al., 1996; Penman, 1956; Testa et al., 2011) and it is then partitioned into evaporation and transpiration via a Beer-Lambert's law (Ritchie, 1972) as a function of LAI. Interception is also expressed as a function of LAI, with land-cover dependent parameters (Van Dam et al., 1992; Von Hoyningen-Hüne, 1983). Actual evaporation is assumed to be equal to potential evaporation as long as the water in soil is above a certain threshold, while it becomes smaller otherwise. Finally, actual transpiration is calculated as the volume of water uptaken by plants according to Feddes' formula (Feddes et al., 1978). Settings and data used to run HYDRUS-1D simulations for our case study are described in section A.2 of the Supplementary information.

2.5. Sovewa

The SOVEWA model focuses on the regulation effect of water availability on plant growth, while it does not take into account the feedback of vegetation dynamics and evaporative flows on the atmospheric phase of the water cycle (Bonan, 2008; Pielke, 2001), which would have required also a model of atmospheric circulation.

The model describes the main water exchanges between soil, vegetation and atmosphere, and is based on the following assumptions. Rainfall (P) is the only input to the model; a fraction of P, increasing with the crown biomass (Thornley, 1996), is intercepted by vegetation before reaching the soil and evaporates back into the atmosphere. The remaining fraction infiltrates vertically into the soil until the saturated condition is reached, beyond which the excess of water is transformed into surface runoff. The water infiltrated into the soil can either evaporate, drain into the aquifer, or be uptaken by vegetation. Evaporation from the soil is assumed to be a function of the plant's ability to intercept light and of the soil water content (Thornley, 1996), while drainage depends on the soil properties. The water uptaken by the vegetation supports plant photosynthesis and, consequently, the storage of water into biomass through plant growth (Kruger and Volin, 2006). Water losses from the vegetation compartment are associated with the loss of dead biomass and with water transpiration through plant stomata (Gardner, 1978).

The model encompasses two state variables, both expressed in $\mathrm{kg}_{\mathrm{H_2O}}/\mathrm{m}^2$ (Thornley, 1996): water stored in the soil (S) and water accumulated in the vegetation biomass (B). The dynamics of these two variables are described by the following system of ordinary differential equations:

$$\dot{S} = \begin{cases} P - I(B) - E(S,B) - D(S) - U(S,B) & S < S_{sat} \\ -E(S,B) - D(S) - U(S,B) & S \geqslant S_{sat} \end{cases} \tag{4}$$

$$\dot{B} = \eta U(S,B) - \rho B \tag{5}$$

Eq. (4) describes the water balance of the soil, where: rainfall (P) is the only input to the compartment; I is the water intercepted by the vegetation, and $P - I$ is the amount of water that reaches the soil and infiltrates vertically, provided that the soil is not saturated ($S < S_{\text{sat}}$); E is the water that evaporates from the soil; D is the water draining into the aquifer; and U is the water uptaken by the vegetation. As mentioned before, when the water content of the soil reaches saturation (S_{sat}), infiltration is inhibited and a surface runoff (R) is generated:

$$R = \begin{cases} 0, & S < S_{sat} \\ P - I & S \geqslant S_{sat} \end{cases} \tag{6}$$

Eq. (5) describes the water balance of the vegetation. The first term represents the gross water gain through photosynthesis, which is assumed to be proportional to water uptake by roots (U) through a parameter (η) expressing the uptake efficiency of vegetation. The remaining fraction of water uptaken by the vegetation is lost through transpiration [$T = (1 - \eta)U$]. The second, negative term represents water losses through plant respiration and biomass death (litter production), which is assumed to be proportional to water content in plant biomass (B) through parameter ρ (d^{-1}). A more detailed description of the model formulation and parametrization, along with details about its calibration, is provided in section A.3 (Supplementary information).

2.6. From water balance partitioning to ecosystem services

The different components of the water balance, estimated with the methods described above, can be used to assess the contribution of different water flows to ecosystem services. We identified possible ES indicators based on the categories introduced by the Millennium Ecosystem Assessment (MEA, 2005), explicitly considering both blue and green water flows (Table 1). The first indicator summarizes the importance of green water flows in the water cycle: the ratio ET/P represents the fraction of rainfall contributing to evapotranspiration. This contribution can be further disaggregated into 'productive' water flows, represented by the fraction of rainfall sustaining plant transpiration (T/P) and hence supporting primary production, and 'non-productive' water flows, represented by the fraction of rainfall contributing to evaporation and interception [$(E + I)/P$] and predominantly characterized by a regulating role. Moreover, the fraction of rainfall intercepted by the canopy (I/P) provides a proxy for soil erosion prevention and flood mitigation. Finally, the last indicator focuses on blue water flows: the ratio $(D + R)/P$, i.e. the fraction of rainfall contributing to drainage and surface runoff, is associated with direct benefits to downstream human activities such as irrigated agriculture and hydropower production. Similar indicators have been used in a study by Castelli et al., (2017) to assess water-related ecosystem services in a Bolivian rural–urban landscape, but without considering those related to green water flows.

Table 1
Indicators of water-related ecosystem services.

Hydrological process	Water-related ES indicator	Description	ES categories
Evapotranspiration	ET/P	Sum of 'productive' and 'non-productive' green water components. It is a proxy of local moisture recycling capacity (Keys et al., 2016)	Provisioning, regulating, cultural, supporting
Evaporation and interception	$(E + I)/P$	Refers to 'non-productive' green water flows	Regulating
Interception	I/P	Proxy for the prevention of soil erosion and flood mitigation	Regulating
Transpiration	T/P	'Productive' green water flow that contributes to primary production. It includes both direct uses, i.e. food from rainfed agriculture and wood, and indirect ones, i.e. biodiversity and resilience enhancement through vegetation growth	Provisioning, regulating, supporting
Drainage and runoff	$(D + R)/P$	Blue water component used in human water uses like hydropower and direct human use through withdrawals from surface and groundwater bodies	Provisioning, regulating, cultural, supporting

3. Results

3.1. Water balance partitioning

The results of partitioning the annual water balance of forest and pasture in the Amazon basin are summarized in Fig. 1. The outputs of the three models consistently point out the important role of vegetation in influencing the annual water balance. In the forest, transpiration and interception represent together about 65% (from 64% to 69%, depending on the model) of the total annual water balance. In the pasture, this share drops down to 42% (31–48%). In particular, transpiration in the forest represents about 50% of total rainfall according to all three models; interception contributes on average 14% to the water balance of the forest, while it is below 4% for pasture. Results obtained with SOVEWA show the largest difference between the two land-cover types: the sum of transpiration and interception in the forest is more than double (64%) than the one in the pasture (31%). The difference between forest and pasture is less marked, but still clear in the results obtained from the other two models (+50% in the forest according to GLEAM and + 35% according to HYDRUS-1D).

Focusing on the ET process and its components (transpiration, interception and evaporation), total annual ET in the forest ranges between ca. 1300 and 1450 mm year^{-1} and is systematically higher than in the pasture (Table 2). However, the relative magnitude of the difference between the two land-cover types depends on the model used, ranging between + 10% (HYDRUS-1D) and + 79% (SOVEWA) in favour of the forest. ET estimates show significant spatiotemporal variation within the same land-cover type, with coefficients of variation between 3 and 10% within the same land cover. Nevertheless, this variation is considerably lower than the difference between the two land covers.

Transpiration (T) from vegetation contributes more than 70% to the overall ET, representing the largest ET component in both forest (ranging between 73 and 80%, depending on the model) and pasture areas (71–74%). Interception (I) also plays an important role in the forest, with all models indicating a share of about 20% on total ET. Evaporation from the soil (E), instead, contributes to a lesser extent (ca. 3%) to ET in the forest. In contrast, all three models show an opposite relative importance of these two contributions in the pasture: interception represents, on average, only 7% of total ET, while evaporation accounts for about 21%. Considering the total direct contribution of vegetation to ET, namely the sum of plant transpiration and interception, results point out that in the forest ca. 95–98% of the annual ET flow is regulated by vegetation. This share remains high yet markedly lower in pasture, ranging between 76% and 82%.

3.2. Water-related ecosystem service indicators

The results of water balance partitioning can be used to assess water-

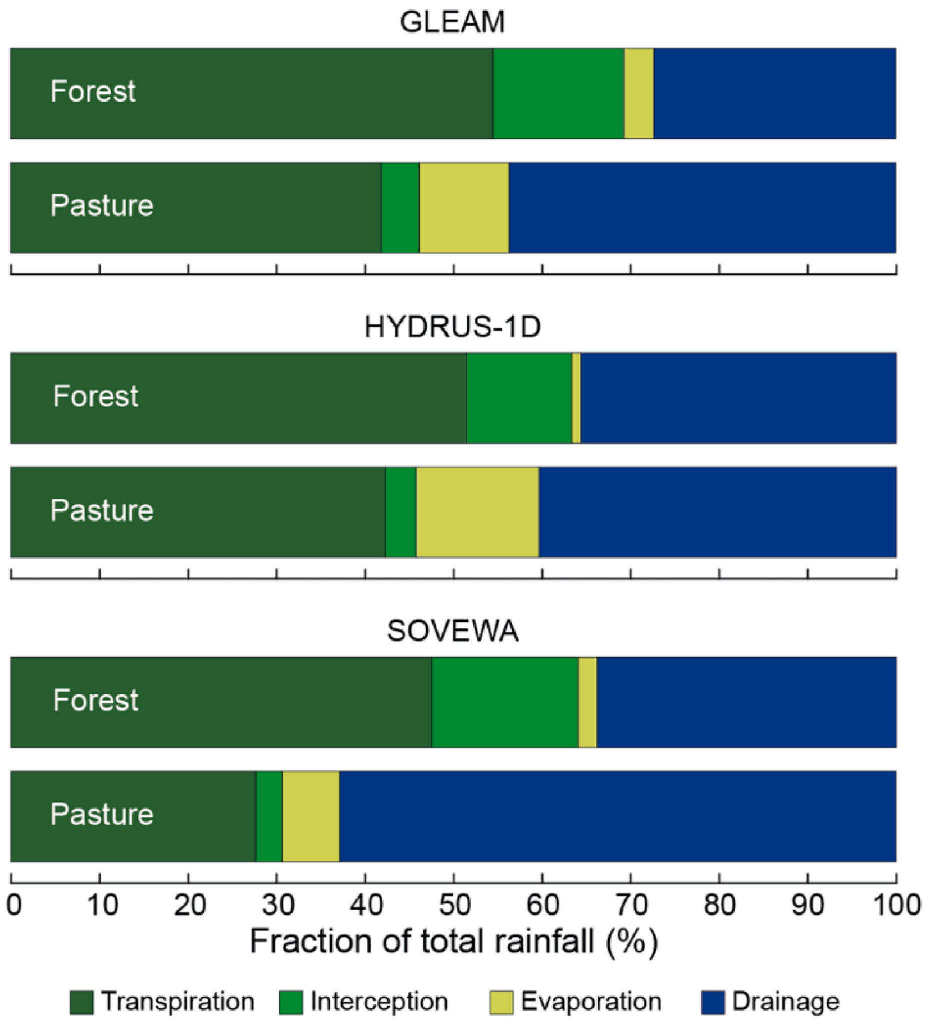

Fig. 1. Annual water balance partitioning in a forest and a pasture area of the Amazon (state of Rondônia) calculated with GLEAM, HYDRUS-1D and SOVEWA models. All terms are averaged over the period 2005–2015 and are expressed as a fraction of total rainfall. Surface runoff is not shown because it is zero according to all three models.

Table 2
Annual evapotranspiration partitioning in a forest and a pasture area of the Amazon (state of Rondônia) calculated with GLEAM, HYDRUS-1D and SOVEWA models. Reported values are mean ± SD over time (2005–2015) and space (four 0.25°×0.25° cells for each land-cover type).

Land cover	Model	Hydrological flow (mm year^{-1})			
		ET	*T*	*I*	*E*
Forest	GLEAM	1309 ± 39	984 ± 26	264 ± 20	61 ± 4
	HYDRUS-1D	1407 ± 46	1124 ± 47	261 ± 19	23 ± 4
	SOVEWA	1449 ± 142	1052 ± 2	351 ± 3	46 ± 1
Pasture	GLEAM	1000 ± 39	740 ± 31	77 ± 20	182 ± 18
	HYDRUS-1D	1284 ± 51	907 ± 56	75 ± 10	302 ± 58
	SOVEWA	809 ± 51	600 ± 1	67 ± 0	142 ± 1

related ES indicators, as described in Section 2.6. Fig. 2 shows the estimates of selected ES indicators (see Table 1) for forest and pasture. Looking at the first two indicators, the total blue component [$(D+R)/P$] and the total green component (ET/P), it clearly emerges that the forest generates more green water flows than the pasture, hence contributing more (68 vs. 50% on average) to rainfall recycling. On the other hand, pasture generates more blue water flows than forest, providing a higher contribution (50% vs. 32% on average) to direct human uses.

Focusing specifically on green water flows, the forest contributes more than pasture to flows associated with primary productivity (T/P) and with soil protection via canopy interception (I/P), while no remarkable difference between land-cover types emerges with respect to non-productive green water flows, associated with regulating ES [$(E+I)/P$].

4. Discussion

Quantitative assessments of ecosystem services are essential to support decision making in land planning and forest management (Feld et al., 2007; Figueira Branco et al., 2019). In this work, we first compared the performances of three models in reproducing the partitioning of the water balance in two areas of the Amazon region characterized by different land cover (forest vs. pasture). Then, we used the results of water balance partitioning to assess water-related ES of forest and pasture with a set of quantitative indicators.

The three models consistently point out the important role of vegetation cover in water balance partitioning. From a qualitative viewpoint, the results show, in accordance with existing experimental evidence (Wang-Erlandsson et al., 2014), that forests are characterized by higher transpiration and interception rates, while pasture is characterized by higher evaporation rates from the soil. From a quantitative viewpoint, our estimates indicate that tropical forest contributes to more than 60% of total water outflows and more than 95% of ET via transpiration and

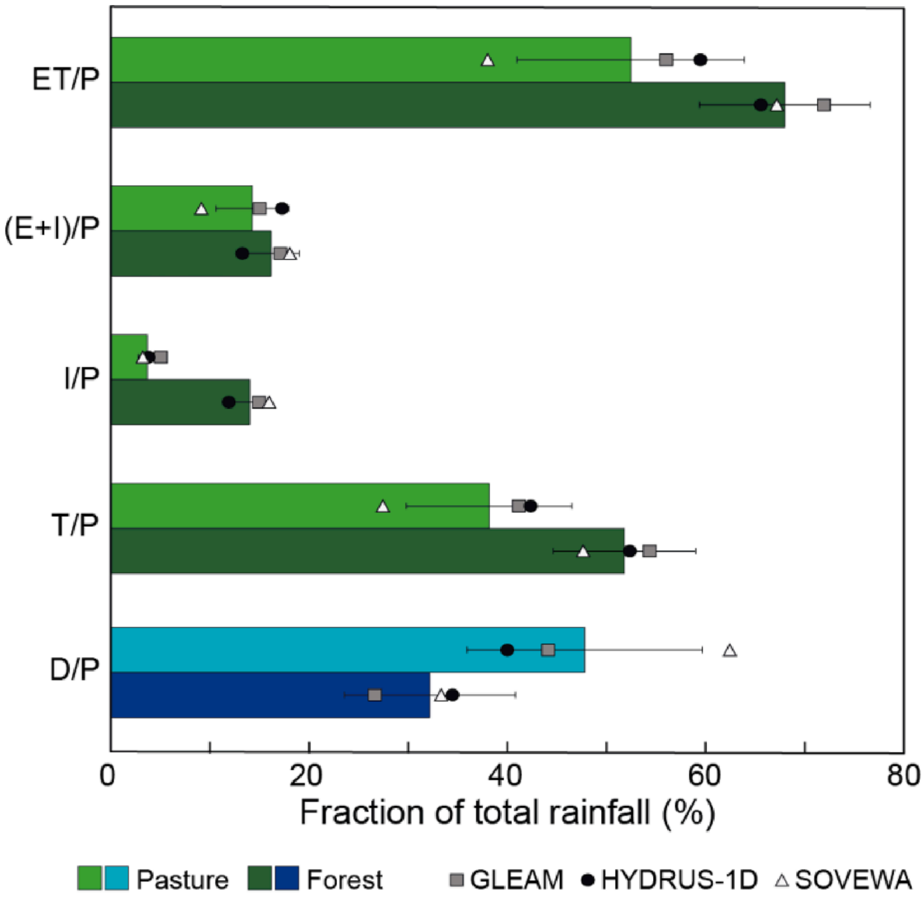

Fig. 2. Water-related ecosystem service indicators for a forest and a pasture area of the Amazon (state of Rondônia). All indicators (see Table 1 for details) are expressed as a percentage of total rainfall. Reported values are mean (bars) ± SD (whiskers) calculated with all the three models (GLEAM, HYDRUS-1D and SOVEWA), over time (2005–2015) and space (four 0.25°×0.25° cells for each land-cover type). Average values calculated with GLEAM, HYDRUS-1D and SOVEWA models are also shown for each indicator. Numeric values are reported in Table A.3 (section A.4. Supplementary information).

interception, while in deforested areas converted to pasture these contributions drop below 46% and 82%, respectively. These patterns are also in accordance with current knowledge about the contribution of forests to ET and rainfall interception (Wang-Erlandsson et al.; 2014). In particular, ET estimates obtained with all three models (1309–1449 mm year^{-1}) fall in the middle of the range (1095–1679 mm year^{-1}) reported in the literature (Marengo, 2005; Wang-Erlandsson et al., 2014; Zeng, 1999).

Although there are significant differences in the basic assumptions on which the three models are based, their results are substantially coherent. In particular, despite the high level of simplification of the processes described, SOVEWA is able to reproduce in a satisfactory way the outputs of more sophisticated models such as GLEAM and HYDRUS-1D, at least as regards the water balance of forests. There is, instead, a larger discrepancy between SOVEWA and the other two models with respect to the water balance of pasture. This is likely due to the rapid biomass dynamics of pasture vegetation, which is not fully captured by SOVEWA. This causes a possible underestimation of transpiration flows, and a consequent overestimation of water drainage. Greater accuracy, to the partial detriment of the simplicity of the model, could be achieved by integrating additional processes, such as energy balance, irrigation, litter accumulation and forest floor interception (Falkenmark and Rockström, 2004; Van Der Ent et al., 2014). Another possible reason of discrepancy among the results of the three models is the choice of the dataset used to run the simulations. While for HYDRUS-1D and SOVEWA we used a single, self-consistent dataset (the ERA-Interim reanalysis), GLEAM bases its simulations on a broader dataset, including but not limited to the ERA-Interim database (Martens et al., 2017).

Due to the spatiotemporal variability of evapotranspiration processes, analyses at the mesoscale are considered more suitable to investigate the complex interactions between vegetation dynamics and the water cycle compared to studies conducted at the large geographic scale (D'Almeida et al., 2007). Hydrological models with different spatial (local, mesoscale or global) or temporal (daily, seasonal, annual or multiannual) resolution can thus provide significantly different results (D'Almeida et al., 2007; van der Ent et al., 2012). In addition, feedbacks from the vegetation on the atmospheric component of the water cycle are important to consider, especially when deforestation processes encompass a broad geographic scale. In fact, current deforestation rates have the potential to significantly alter the timing and magnitude of ET (Spracklen et al., 2012; Von Randow et al., 2008). In particular, deforestation levels in the Amazon region are deemed to be close to the tipping point beyond which the hydrological cycle would be altered so as to bring about a transition from forest to savannah (Lovejoy and Nobre, 2018; Vieira et al., 2008). Preserving the extent and integrity of the Amazon forests is increasingly crucial to ensure the regular functioning of the local and global water cycles.

The results of water balance partitioning provide a basis to derive quantitative indicators for the characterization of different vegetation covers in terms of water-related ES. We focused, in particular, on those related to green water flows, which have often been neglected in ES assessments. In light of the information provided by these indicators, tropical forests are confirmed as important green water suppliers compared to deforested areas (Ellison et al., 2012), with higher ET rates than pasture, both in absolute terms and in terms of the different components of the water balance. ET from forests is an important moisture source for precipitation, even at the local scale, and loss of forest cover can alter rainfall patterns (Ellison et al., 2012). This is in contrast with the traditional (demand-side) view, according to which forests are seen as water sinks reducing downstream water availability to human activities (Andréassian, 2004). On the other hand, the values of the drainage indicator are in line with the traditional demand-side view.

Notice, however, that we did not consider the fact that tree cover loss can promote soil degradation and, consequently, the infiltration capacity of the soil (Ellison et al., 2017): this may affect the ability of pasture to recharge groundwater reserves, which is particularly important during the dry season.

From the supply-side perspective, instead, forests are seen as major contributors to “productive” green water flows, sustaining higher levels of primary production even during the dry season thanks to their deeper root system compared to pastures (Nepstad et al., 1994), with clear benefits also in terms of improved carbon storage in the soil. Moreover, forests can more effectively contribute to protecting soils from erosion, thanks to their higher rainfall interception capacity (Balthazar et al., 2015). On the other hand, the transition to pasture increases evaporation from the soil (Miralles et al., 2011), thus reducing the availability of water for the production of plant biomass. Finally, forests are crucial in determining microclimate and rainfall patterns, especially through moisture recycling both at the mesoscale and at the large scale (Eltahir and Bras, 1994; Sheil and Murdiyarso, 2009).

From a methodological viewpoint, the choice of the selected indicators has been based on the ES categories introduced in the MEA. Other, more recent, classifications exist, such as the Economics of Ecosystems and Biodiversity classification (TEEB, 2010) and the Common International Classification of Ecosystem Services (CICES, Haines-Young and Potschin, 2018). This latter is based on the same approach as the MEA classification but does not include supporting services, as they are viewed as ecosystem functions rather than services. Nevertheless, the MAE classification has become a standard reference that is still widely used in the scientific literature. In any case, all these classifications organize ES into a hierarchical framework: in our study we considered only the highest (i.e. broadest) categories, because we wanted to keep the focus on the process of developing ES indicators based on the fluxes defining the water balance.

The proposed indicators can be effectively used to compare the effect of land-use change on the delivery of water-related ES services but cannot be used to compare areas with different meteorology. Nevertheless, we believe that the proposed approach represents a promising starting point for the integration of the demand-side and supply-side perspectives in the assessment of water-related ES. In addition, it allows quantifying the impacts of land use change on water resource availability. The methodology is conceived to work at a small scale, but the proposed indicators can also be applied at broader spatial scales. This study can thus help understand the relationships that link hydrological and vegetation dynamics with ecosystem services, paving the way for a deeper understanding of the contribution of ecosystem services to human well-being (Grizzetti et al., 2016; Rieb et al., 2017).

CRediT authorship contribution statement

Enrico Casagrande: Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing - original draft. **Francesca Recanati:** Conceptualization, Methodology, Writing - original draft. **Maria Cristina Rulli:** Writing - review & editing, Supervision. **Daniele Bevacqua:** Methodology, Writing - review & editing, Supervision. **Paco Melià:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.107155.

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