

## Methodological and Ideological Options

Tropical Forests, Tipping Points, and the Social Cost of Deforestation<sup>☆</sup>Sergio L. Franklin Jr.<sup>a,\*</sup>, Robert S. Pindyck<sup>b</sup><sup>a</sup> Superintendência de Seguros Privados, Av. Presidente Vargas 730, Rio de Janeiro, RJ 20071-900, Brazil<sup>b</sup> Sloan School of Management, Massachusetts Institute of Technology, 100 Main Street, Cambridge, MA 02139, United States

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## ABSTRACT

Recent work has suggested that tropical forest and savanna represent alternative stable states, which are subject to drastic switches at tipping points, in response to changes in rainfall patterns and other drivers. Deforestation cost studies have ignored the likelihood and possible economic impact of a forest-savanna critical transition, therefore underestimating the true social cost of deforestation. We explore the implications of a forest-savanna critical transition and propose an alternative framework for calculating the economic value of a standing tropical forest. Our framework is based on an average cost method, as opposed to currently used marginal cost methods, for the design of optimal land-use policy or payments for ecosystem services. We apply this framework to the calculation of the social cost of deforestation of the Amazon rainforest.

## 1. Introduction

A number of studies have assessed the economic benefits of a standing tropical forest by estimating the foregone economic benefits resulting from deforestation. The present value of the foregone economic benefits due to one hectare of deforestation has been compared to the present value of future economic benefits of alternative land uses (e.g., crops and cattle ranching) in order to determine the socially optimal land-use policy. To our knowledge, no studies have accounted for the likelihood and possible economic impact of a large-scale forest dieback.

Ecosystems are exposed to gradual changes in climate, nutrient loading, habitat fragmentation or biotic exploitation, and they are usually assumed to respond in a smooth way. However, studies of forests, lakes, coral reefs, oceans, and arid lands have shown that smooth change can be interrupted by sudden drastic switches to a contrasting state (Scheffer et al., 2001).

A tipping point can be defined as a situation in which an ecosystem experiences a drastic shift to a new state causing significant changes to its biodiversity and ecosystem services. Under certain environmental conditions, the ecosystem can have two or more alternative stable states, separated by an unstable equilibrium. Tropical forests and

savannas represent alternative stable states, which are subject to drastic switches at tipping points in response to changes in rainfall patterns and other drivers (Lobo Sternberg, 2001; Warman and Moles, 2009; Staver et al., 2015).

We develop a new framework for calculating the marginal economic value of a standing tropical forest, and explore the implications of forest-savanna critical transitions on the design of optimal land-use policy and payments for ecosystem services. We show that marginal cost methods are not appropriate for the design of optimal land-use policy, or for the design of payments for ecosystem services, and propose the use of an average incremental cost method, with the increment properly defined. We also develop a definition of the average incremental social cost of deforestation that, to some extent, follows the approach used in Pindyck (2016) to measure an average social cost of carbon.

In the next section we discuss the social cost of deforestation of the Amazon as measured by existing marginal cost models. Section 3 explains the nature of the forest-savanna tipping point, and provides evidence that the Amazon rainfall patterns are maintained, in part, by the forest itself. Section 4 proposes a new framework for calculating the marginal social cost of deforestation, taking into account changes in forest resilience. Section 5 introduces the average incremental cost

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method and shows how, with the increment properly defined, it can be used for the design of optimal land-use policy and payments for ecosystem services. Section 6 concludes.

## 2. The Social Cost of Deforestation as Measured by Existing Marginal Cost Models

Other studies have tried to estimate the social cost of Amazon deforestation by applying the concept of total economic value (TEV) to assess the economic benefits of a standing tropical forest and the foregone economic benefits resulting from deforestation (Torrás, 2000; Andersen et al., 2002; Margulis, 2004). The total economic value of a natural resource is the sum of its direct use, indirect use, option, and existence values,<sup>1</sup>

$$TEV = \text{Direct use value} + \text{Indirect use value} + \text{Option value} + \text{Existence value}, \quad (1)$$

where:

- The direct use value of a standing tropical forest stems from sustainable harvesting of timber and non-timber products, such as nuts, fruits and latex, and from ecotourism.
- The indirect use value depends on the ecological functions performed by the forest, such as water recycling, soil and watershed protection, fire prevention, and carbon storage. Estimates of the indirect use values linked to water recycling, erosion control and watershed protection are rarely made, due to the lack of evidence of the ecological impact of a few hectares of deforestation. Estimates of the indirect use value linked to carbon storage are based on the estimates of net carbon emissions per hectare cleared, and cost of additional ton of carbon released into the atmosphere (i.e., marginal cost of carbon).
- The option value refers to uncertain benefits that can be realized at some point in the future, and reflects the willingness to preserve an option for the potential future use of the forest. Most studies estimate only the option value of biodiversity protection, based on the prospects of forest biodiversity yielding new drugs, and their future medicinal benefits.
- The existence value is unrelated to both current and optional use, and arises because people are willing to pay for the existence of an environmental asset without ever directly using it. The existence value includes the value that society is willing to pay to secure the survival and well being of other species.

The Amazon rainforest, shown in Fig. 1, covers around 530 million hectares of land (Soares-Filho et al., 2006),<sup>2</sup> and includes territory belonging to nine nations. Brazil holds about 60% of the forest area, followed by Peru with 13%, Colombia with 10%, and Venezuela, Ecuador, Bolivia, Guyana, Suriname and French Guiana with smaller amounts.

The range of ecosystem services and benefits provided by the Amazon rainforest can be classified as private, local/regional public, and global. Private benefits are always local and include, for example, the profits derived from timber and non-timber products that can be harvested from the forest. Local and regional public benefits include water recycling, nutrient recycling, fire control, erosion control and watershed protection. Global benefits include, for example, carbon storage and biodiversity protection.

Over the last few decades the Amazon forest has experienced rapid land use change, with 15% of the original area deforested by 2003 (Soares-Filho et al., 2006). Among the nine nations with forest territory, only Brazil generates and shares spatially detailed information on



Fig. 1. Map of the Amazon rainforest.

annual forest extent and change. In particular, the size of the Brazilian Amazon forest has decreased year by year and is now approaching 80% of its original area (INPE, 2015). Although Brazil has substantially reduced deforestation rates, these rates are increasing in other Amazon countries (Hansen et al., 2013).

Table 1 shows estimates for the present value of the foregone economic benefits from one hectare of Amazon deforestation. These are marginal values in that they represent the change in value for a small change in the forest area, at current deforestation levels. The numbers in this table are derived from estimates from four deforestation cost studies of the Brazilian Amazon, Andersen et al. (2002), Margulis (2004), Soares-Filho et al. (2017a) and Soares-Filho et al. (2017b). In order to make these estimates comparable and accessible, the collected values were updated to 2017 US\$ values (i.e., adjusted for inflation), and converted into present values using a common discount rate, 2.5%, based on survey results in Pindyck (2016). In addition to the sources for each estimate, Table 1 also shows the method used for each calculation.

The present value of the foregone economic benefits from one hectare of deforestation,  $PV_{O_t}$ , has been incorrectly interpreted as the marginal economic value of a standing tropical forest, and it has been compared to the present value of future economic benefits of alternative land uses (e.g., crops and cattle ranching),  $AU_t$ . Deforestation cost studies have shown that, at current deforestation levels, the foregone economic benefits due to deforestation are much lower than the future economic benefits of alternative land uses. Some have argued that Amazon ecosystems are subject to non-linearities — i.e., sudden dramatic increases in the magnitude of damage once the forest area is reduced below some critical threshold — so that additional deforestation can result in rapid increases in the marginal economic value.<sup>3</sup>

Something is missing from these marginal economic value calculations. The greatest non-linearity in the total economic value of a tropical forest occurs at the deforestation threshold that triggers the forest-savanna critical transition, but no existing cost studies account for the likelihood and possible impact of a catastrophic shift to the savanna state. In fact, when the first economic impact of forest degradation appears, the forest ecosystem may have already started the self-propagating transition to the savanna state, which will almost certainly be irreversible. We turn to that next.

<sup>3</sup> See, for example, Torrás (2000) and Andersen et al. (2002). According to Strand (2017), losses of rainforest likely lead to less rainfall and increased forest fire risk, which in turn increase marginal forest value by making primary forest loss avoidance more valuable.

<sup>1</sup> See, for example, Pearce (1993).

<sup>2</sup> One hectare is equal to 10,000 square meters, or roughly 2.47 acres.

**Table 1**

Present value of the foregone economic benefits due to one hectare of deforestation (in US\$ per hectare).

	Present value (in 2017 dollars)	Sources and comments
<b>Direct use value</b>		
Timber products	1,368	Average of Andersen et al. (2002), Margulis (2004) and Soares-Filho et al. (2017a).
Non-timber products	200	Soares-Filho et al. (2017b). Brazil nuts only.
Ecotourism	288	Average of Andersen et al. (2002) and Margulis (2004).
Total	1,856	
<b>Indirect use value<sup>a</sup></b>		
Carbon storage	1,118	Average of Andersen et al. (2002) and Margulis (2004).
Water recycling	0	Andersen et al. (2002).
Nutrient recycling	0	Andersen et al. (2002).
Protection against fires	711	Andersen et al. (2002).
Watershed protection	0	Andersen et al. (2002).
Total	1,829	
<b>Option value</b>		
Biodiversity protection	39	Andersen et al. (2002). (Margulis (2004) provided an estimate for the average economic value.)
Total	39	
<b>Existence value</b>		
Existence value	65	Andersen et al. (2002). (Margulis (2004) provided an estimate for the average economic value.)
Total	65	
<b>Grand total (PV<sub>0</sub>)</b>	<b>3,789</b>	

<sup>a</sup> Most studies say that one hectare of deforestation, at the current deforestation level, will have almost no impact on the ecological functions of water recycling, nutrient recycling and watershed protection.

### 3. The Forest-Savanna Tipping Point

Recent studies have extensively investigated the tree cover distribution of tropical forests and savannas in Africa, Australia and South America. Hirota et al. (2011) analyzed the relationship between the distribution of tree cover and mean annual precipitation, and found that the frequency distribution of tree cover in the tropics has three distinct modes, corresponding to tropical forest, savanna, and treeless states. Additionally, tree cover does not increase gradually with rainfall, but is constrained by ranges which could be identified as treeless (0 to 5%), savanna (around 20%) or tropical forest (around 80%). The rarity of places with 5–10% or 50–60% tree cover suggests that these situations are unstable because of the positive feedbacks among tree cover, precipitation, fire and drought.

Precipitation is a major driver of past and recent shifts in the extension of tropical forests and savannas (Bowman et al., 2010; Mayle et al., 2007). Staver et al. (2011) used datasets on tree cover, rainfall, fire frequency, and soil categories to show that with intermediate rainfall levels having mild seasonality, both forests and savannas are common, and only fire feedbacks can explain the bimodality in tree cover.<sup>4</sup> In particular, they found that a large part of the Amazon forest supports biome bistability, i.e., although it is currently in the forest state, a sufficiently severe perturbation can induce a self-propagating shift to an open savanna. Hilker et al. (2014) showed that the vegetation canopy of the Amazon rainforest is highly sensitive to changes in precipitation patterns, and the reduction in rainfall since 2000 has diminished vegetation greenness across large parts of Amazonia. In much of the eastern and southeastern part of the Amazon basin (and bordering subtropical grassland), the rainfall reduction has been as high as 25%.

Evidence is accumulating that the Amazon rainfall patterns are

maintained in part by the forest itself, through contributions of water vapor to the atmosphere (Coe et al., 2009), and the precipitation patterns are bound to change with severe changes in forest cover (Malhi et al., 2007). According to Fearnside (1997), approximately half of the precipitation in the Amazon forest is derived from water that recycles through evapotranspiration. The Andes Mountains function as a six-kilometer high barrier that blocks the water vapor above the forest, and air currents carry the moisture across the Amazon region and towards the southeast and center of the South American continent. As such, the Amazon forest not only keeps the air moist for its own purposes, but also exports water vapor via aerial rivers, which carry the water that will produce the abundant rainfall that irrigates distant regions (Nobre, 2014). According to the biotic pump theory (Makarieva and Gorshkov, 2007), abundant tree transpiration, together with very strong condensation in the formation of clouds and rainfall leads to a reduction in atmospheric pressure over the forest, and draws moist air over the oceans inland.

A number of vegetation-climate models have suggested that Amazon ecosystems may cross a tipping point if deforestation exceeds about 40% of the original forest area, after which large areas of forest will experience a self-propagating transition to the savanna state (which can take several decades to a century to fully reach the new equilibrium). For example, Sampaio et al. (2007) assessed the climate impacts of converting the Amazon rainforest into pastures or soybean croplands, and found an accelerating decrease of rainfall for increasing deforestation for both classes of land use conversion, while the reduction in precipitation was more evident when deforestation exceeded 40% of the original forest cover. Nepstad et al. (2008) suggested that the economic, ecological and climatic systems of Amazonia may be interacting to move the forest towards a near-term tipping point, and predicted a large-scale substitution of the Amazon forest by savanna-like vegetation by the end of the twenty-first century. Nobre and Borma (2009) found that tipping points for the Amazon forest may exist for total deforested area greater than 40% and for global warming greater than 3–4 °C. Lawrence and Vandecar (2015) suggested that tropical forest clearing beyond 30–50% may constitute a threshold for

<sup>4</sup> Fire spread depends on a continuous grass layer, so that the lower is the tree cover, the higher is the fire spread, which causes further forest dieback and further reduction in tree cover.

Amazonia, beyond which reduced rainfall would trigger a significant decline in ecosystem structure and function.<sup>5</sup>

The Amazon forest covers a wide region subject to different stresses and conditions: the northeastern Amazonia, with somewhat drier conditions and growing anthropogenic impacts; the northwestern Amazonia, with little direct anthropogenic impact and relatively intact ground cover; and the southern Amazonia, subjected to strong land use change drivers. The most significantly at-risk domains are the southern and eastern Amazonia. Nobre et al. (2016) showed that after crossing the tipping point (and reaching a new equilibrium state), the fraction of remaining forest area would be in the range of 30–40%, mostly located in the northwestern Amazon, close to the Andes Mountains.

The risk of a large-scale forest dieback should therefore be a major concern of policy makers, and provides an argument in favor of stringent reductions in deforestation.

#### 4. The Social Cost of Deforestation Accounting for Changes in Forest Resilience

The existence of forest-savanna tipping points implies that changes in forest resilience affect the marginal economic value of a standing forest, and must be accounted for when calculating that marginal value. *Forest resilience* is the capacity of a forest to respond to a perturbation or disturbance by resisting damage and returning to its original condition. Such perturbation or disturbance can include stochastic events such as fire, drought and flooding, and human activities such as deforestation. There are large uncertainties about the effect of deforestation on the amount of in-forest precipitation, and the effect of forest precipitation on the ecosystem resilience. However, most scientists agree that deforestation reduces forest precipitation, and the greater the deforestation, the less resilient the forest will be.

One can think of forest resilience as a multidimensional function that depends on a number of ecosystem-wide variables. All other things held constant, forest resilience is a function of rainfall patterns. Because the Amazon rainfall patterns are in large part maintained by the forest itself, forest resilience can be represented as a function of the proportion of deforested area at any time.

##### 4.1. Analytical Framework

Let  $A$  denote the Amazon's original forest area, which at time  $t$  is the sum of the forest area,  $F_t$ , and the deforested area,  $D_t$ , and let  $d_t$  denote the proportion of total area that is deforested. Forest resilience can be expressed as  $R_t = f(d_t)$ , where  $f(0) = \alpha$ ,  $0 < \alpha \leq 1$ , and  $f(h) = 0$ , with  $h$  the deforestation threshold that triggers a large-scale forest-savanna transition. Assume that  $f(d)$  is monotonically decreasing and strictly concave in the interval  $[0, h)$ ,  $f(d) = 0$  for  $d \in [h, 1]$ , and once the deforestation threshold is reached, system dynamics change irreversibly and the ecosystem never gets back to the forest state.<sup>6</sup> The functional form of the forest resilience function can depend on a number of ecosystem-wide variables, such as precipitation volume and seasonality, soil characteristics, and temperature. Its concavity can be inferred from the positive feedbacks among tree cover, precipitation, fire and drought.

<sup>5</sup> In addition, Davidson et al. (2012) showed that the changes in rainfall and discharge associated with deforestation already observed in the southern and eastern Amazon demonstrate potential for significant vegetation shifts and further feedbacks to climate and discharge, and Pires and Costa (2013) showed that while inner forest regions remain inside a rainforest bioclimatic envelope, outer forest regions may cross the forest-savanna bioclimatic threshold even at low deforestation levels.

<sup>6</sup> In fact, to get the ecosystem back to the forest state, it would be necessary to reduce the size of the deforested area far below the deforestation threshold, due to the hysteresis effect. By “irreversibly”, we mean it would be extremely costly to get the ecosystem back to the original state of tropical forest.

The total forest area is divided into a number of grid cells, of one hectare each, centered around the latitude and longitude coordinates  $x$  and  $y$ . Let  $V_\psi(S_t)$  denote the economic value of a one-hectare grid cell at time  $t$ , which is a function of a vector of state variables,  $S_t(x, y)$ . The subscript  $\psi$  indicates whether the grid cell is in forest state ( $\psi = F$ ), savanna state ( $\psi = S$ ), or treeless state ( $\psi = O$ ), so that  $V_F(S_t)$ ,  $V_S(S_t)$  and  $V_O(S_t)$  denote the economic value of a one-hectare grid cell in each state.

The marginal economic value of a standing forest,  $V_F(S_t)$ , is the marginal social cost of deforestation, i.e., the total cost to society of an additional hectare of deforested area. Let  $MSCD(S_t)$  denote the marginal social cost of deforestation, so that  $MSCD(S_t) = V_F(S_t)$ , where  $S_t(x, y) = [E_t(x, y), N_t(x, y), R_t]$  is a vector of state variables. Here  $E_t(x, y)$  and  $N_t(x, y)$  denote the set of hectare-wide economic and nature state variables, identified by the grid coordinates  $(x, y)$ , and  $R_t$  is a measure of forest resilience (i.e., an ecosystem-wide state variable):

- $E_t(x, y)$  includes a number of economic state variables, such as price of timber and non-timber products, price of energy, price of carbon, logistics and extractive costs;
- $N_t(x, y)$  includes nature state variables, such as vegetation type, average tree cover, soil characteristics, temperature, day length hours, evapotranspiration rate, biodiversity; and
- $R_t$  is the measure of forest resilience, expressed as a function of the proportion of deforested area,  $R_t = f(d_t)$ . The forest-savanna tipping point is characterized when the forest resilience reaches zero, and that happens when the proportion of deforested area,  $d_t$ , reaches the deforestation threshold  $h$ .

For simplicity, assume that the economic state variables do not depend on the geographic location of the grid cell, and the vector of nature state variables can only take two values:  $N_t = N_F$  if the ecosystem is in the forest state, and  $N_t = N_S$  if the ecosystem is in the savanna state.<sup>7</sup> Suppose the ecosystem is currently in the forest state (i.e.,  $\psi = F$ ) so that the total economic value of the forest area is  $TEV_t = \bar{V}_F F_t$ , where  $\bar{V}_F$  is the average economic value of a representative hectare of forest, and  $F_t$  is the size of forest area at time  $t$ . Suppose that at time  $t^*$  forest resilience is zero, so one additional hectare of deforestation makes the ecosystem cross the forest-savanna tipping point.

Let  $G^*$  denote the forest area that undergoes the self-propagating transition to the savanna state. Prior to crossing the tipping point, its total economic value is  $TEV_{t^*} = \bar{V}_F G^*$ . After crossing the forest-savanna tipping point, the total economic value of  $G^*$  changes to the value of an equivalent savanna area (at time  $t^* + \tau$ ),  $TEV_{t^*+\tau} = \bar{V}_S G^*$ , where  $\tau$  is the time period until reaching the new equilibrium state. To estimate the foregone economic benefits from such a large-scale forest dieback (of  $G^*$ ), we cannot use marginal values because they do not capture the ecosystem non-linearities. We must instead use estimates for the average economic values of forest,  $\bar{V}_F$ , and savanna,  $\bar{V}_S$ .<sup>8</sup> Thus, the total (undiscounted) loss resulting from the forest-savanna transition is  $(\bar{V}_F - \bar{V}_S)G^*$ . We assume that the state transition occurs at a constant

<sup>7</sup>  $E_t$  and  $N_t$  can be interpreted as the geographic averages of the economic and nature state variables, respectively. In a more general case, the Amazon forest area could be split into a number of domains, subject to different stresses and conditions, and each domain (e.g., northwestern, northeastern and southern) could be split into a number of areas with similar economic and nature state variables.

<sup>8</sup> Marginal and average economic values can be quite different. A number of deforestation cost studies have suggested that one hectare of Amazon deforestation, at the current deforestation level, will have almost no impact on the ecological functions of water recycling, nutrient recycling and watershed protection (e.g., Andersen et al., 2002). Additionally, a number of authors have argued that Amazon ecosystems are subject to non-linearities so that additional deforestation can result in rapid increases in the marginal value (e.g., Torras, 2000 and Strand, 2017).

rate, so that the loss rate due to the state transition is  $LR = (\overline{V}_F - \overline{V}_S)G^*/\tau$  (which does not depend on time). Over the interval  $dt$ , the loss resulting from the forest-savanna transition is  $LR \cdot dt$ .

The marginal social cost of deforestation must be calculated for two different regimes. In the pre-threshold regime (i.e.,  $R_t > 0$ ):

$$\begin{aligned} MSCD &= V_F(E_t, N_F, R_t) \\ &= \text{Change in } TEV \text{ due to an additional hectare of deforestation,} \end{aligned} \quad (2)$$

which is a function of the economic and nature state variables, and the forest resilience, at time  $t$ . At the threshold (i.e.  $R_t^* = 0$ ):

$$\begin{aligned} MSCD &= V_F(E_t^*, N_F, 0) = PV_{O_t^*} + \int_0^\tau e^{-rt} \frac{(\overline{V}_F - \overline{V}_S)G^*}{\tau} dt \\ &= PV_{O_t^*} + \left(\frac{1}{r\tau}\right) [\overline{V}_F - \overline{V}_S] G^* (1 - e^{-r\tau}), \end{aligned} \quad (3)$$

where  $PV_{O_t^*}$  is the present value of the foregone economic benefits due to one hectare of deforestation at time  $t^*$ ,  $r$  is the discount rate,  $\tau$  is the time until  $G^*$  reaches the savanna state, and  $\overline{V}_F - \overline{V}_S$  is the present value of the foregone economic benefits from each hectare of forest that undergoes the state transition.

#### 4.2. Economic Impact of a Forest-Savanna Transition

Existing marginal cost methods have incorrectly interpreted the present value of the foregone economic benefits from one hectare of deforestation,  $PV_O$ , as the marginal economic value of a standing tropical forest,  $V_F$ . However, Eqs. (2) and (3) show that when we take into account the existence of forest-savanna tipping points,  $V_F \neq PV_O$ .

In order to estimate the economic loss from a large-scale forest dieback, it is necessary to estimate the change in average economic value of a representative hectare of forest that undergoes the forest-savanna transition,  $\Delta \overline{V}_{F,S} = [\overline{V}_F - \overline{V}_S]$ . We use the concept of total economic value (*TEV*) to assess the foregone economic benefits resulting from deforestation. For the marginal values, we assess the foregone economic benefits from a single hectare of deforestation (shown in Table 1). For the average values, we need to assess the foregone economic benefits resulting from a much larger deforestation and divide that value by the number of hectares deforested.

We assume that the average direct use values of forest are the same as the marginal values shown in Table 1. The characteristic tree cover of savanna is approximately 25% of the characteristic tree cover of forest (Hirota et al., 2011). Usually, the lower the tree cover, the lower the potential revenues from harvesting, and the higher the transportation costs. For savanna, we assume that the characteristic tree cover is not dense enough to justify accessing it for harvesting (i.e., the average direct use values linked to timber and non-timber products are zero), and the average direct use value linked to ecotourism is 25% of the estimated value for forest.

The average indirect use value from carbon storage is the product of the average carbon stock per hectare of forest/savanna and the average social cost of carbon. For forest, the quantity of carbon present in the biomass was that adopted by the Amazon Fund, of 100 tons of carbon per hectare (tC/ha), which corresponds to the equivalent of 367 tons of carbon dioxide per hectare (tCO<sub>2</sub>/ha).<sup>9</sup> For savanna, the average carbon stock was assumed to be 25% of the average carbon stock of forest, that is 25 tC/ha. For the average social cost of carbon, we use US\$80/tCO<sub>2</sub>, as suggested in Pindyck (2016).<sup>10</sup>

The indirect use values linked to water resources can be consolidated into a single economic benefit, water resource values,

<sup>9</sup> See, for example, AmazonFund (2010). This is a conservative measurement when compared to data in the literature (between 130 tC/ha and 320 tC/ha).

<sup>10</sup> There is in fact a large range of possible values, but the US\$80/tCO<sub>2</sub> estimate is based on a limited sample of high confidence data.

including the regulation of water flows, precipitation and river discharge. These ecosystem services provide a series of economic benefits to the region, in large measure related to agricultural outputs and electric power generation, mostly in the vicinity of the forest, but also in distant areas by cycling atmospheric water in the form of aerial rivers to the southeast and center of South America (Fearnside, 2003).<sup>11</sup> For forest, the average indirect use values linked to water resources were drawn from the average estimates in De Groot et al. (2012). We assume that the forest-savanna transition will reduce evapotranspiration by 75%, so that the average indirect use values after the state transition are 25% of the values for forest. For the Brazilian economy, this is consistent with the assumption that 30% of the total gross domestic output of the agribusiness sector, and 50% of total potential hydroelectric energy production are dependent on the Amazon forest.<sup>12</sup>

The average option value was obtained from the values indicated in Fearnside (1997) and Margulis (2004), after adjusting them for inflation. Because large expanses of the Amazon forest still need proper biological inventories (Oliveira et al., 2017), we considered the high value scenario of biodiversity maintenance in Fearnside (1997). We used information in De Groot et al. (2012) to calculate the ratio between the median values of the gene pool protection/conservation service provided by tropical forests and woodlands. This ratio was multiplied by the estimate for the average option value of forest, in order to find the estimate for the average option value of savanna, and the change in average economic value of a representative hectare of forest that undergoes the state transition.

Table 2 summarizes the estimates for the change in average economic value of a representative hectare of forest that undergoes the forest-savanna transition. These are average values in the sense that they represent the change in value for a large change in the forest area, and capture ecosystem non-linearities not considered in marginal cost calculations. The numbers in this table are derived from estimates provided by Fearnside (1997), Andersen et al. (2002), Margulis (2004), AmazonFund (2010), Soares-Filho et al. (2017a) and Soares-Filho et al. (2017b), the social cost of carbon in Pindyck (2016), averages of ecosystem service values summarized in De Groot et al. (2012), and our calculations. All of these estimates were updated to 2017 US\$ values and converted into present values using a 2.5% discount rate.

#### 4.3. The Marginal Cost Model

In what follows, we make two simplifying assumptions. First, we ignore the opportunity cost of depletion, and assume that the change in total economic value resulting from an additional deforestation equals the present value of the foregone economic benefits “taking into account the likelihood and possible impact of a forest-savanna transition.” Second, we assume that the economic and nature state variables remain roughly constant until the ecosystem crosses the forest-savanna tipping

<sup>11</sup> Under the influence of the Hadley circulation system ([https://en.wikipedia.org/wiki/Hadley\\_cell](https://en.wikipedia.org/wiki/Hadley_cell)), the south-central portion of South America should tend towards aridity, similar to the aridity found at the same latitude in other parts of the globe, such as in the Atacama desert, on the west side of the Andes, in the Namib and Kalahari deserts in Africa, and in the deserts in Australia. The aerial rivers produced by the Amazon rainforest explain the green area located in the east side of Andes, the quadrangle bounded by Cuiabá to the north, São Paulo to the east, Buenos Aires to the south, and the Andes to the west, which is responsible for 70% of the continent's gross domestic product (Nobre, 2014).

<sup>12</sup> Fearnside (1997) analyzed scenarios where 5%, 10% and 20% of Brazil's harvest are dependent on the Amazon forest. The Brazilian hydropower potential is estimated at 260 GW, 40% of which is located in the Amazon river basin.

**Table 2**

The change in average economic value of a representative hectare of forest that undergoes the forest-savanna transition (in US\$ per hectare).

	$\Delta \overline{V}_{F,S} = [\overline{V}_F - \overline{V}_S]$ (in 2017 dollars)	Sources and comments
<b>Direct use value</b>		
Timber products	1,368	Andersen et al. (2002), Margulis (2004), Soares-Filho et al. (2017a) and authors' calculations.
Non-timber products	200	Soares-Filho et al. (2017b) and authors' calculations. Brazil nuts only.
Ecotourism	216	Andersen et al. (2002), Margulis (2004) and authors' calculations.
Total	1,784	
<b>Indirect use value</b>		
Carbon storage	22,000	AmazonFund (2010), Pindyck (2016) and authors' calculations.
Water resource values	13,066	De Groot et al. (2012) and authors' calculations.
Total	35,066	
<b>Option value</b>		
Biodiversity protection	1,344	Fearnside (1997), Margulis (2004), De Groot et al. (2012) and authors' calculations.
Total	1,344	
<b>Existence value</b>		
Existence value	1,636	Margulis (2004). (Andersen et al. (2002) provided an estimate for the marginal economic value.)
Total	1,636	
<b>Grand total</b> ( $[\overline{V}_F - \overline{V}_S]$ )	39,830	

point, i.e., there is no significant changes to the prices of timber and non-timber products, average tree cover, biodiversity, etc.<sup>13</sup>

Uncertainty over the deforestation threshold that triggers the forest-savanna transition,  $H$ , can be described by a probability distribution,  $f_H(h)$ . We model the deforestation threshold by a normal distribution, i.e.,  $H \sim N(\mu, \sigma)$ . The range of studies suggesting that the Amazon forest may cross a tipping point if deforestation exceeds 40% suggests that  $\mu = 40\%$ . The fact that the Amazon rainforest has experienced severe droughts in the last few years suggests that the 30–50% interval proposed by Lawrence and Vandecar (2015) may represent a 90% confidence interval for the deforestation threshold. Thus, if deforestation reaches 30%, the probability of crossing the tipping point will be 5%. We assume that the forest ecosystem takes 60 years to undergo the state transition, after which the remaining forest area, mostly located in the northwestern Amazon (close to the Andes Mountains), will be 35% of the area at the tipping point.

Policymakers do not know the precise location of the deforestation threshold that will trigger the forest-savanna transition. The probability that an additional hectare of deforestation will bring the ecosystem to the forest-savanna tipping point is represented by  $P(d < H < d + \delta | H > d)$ , where  $\delta$  denotes the change in the proportion

<sup>13</sup> According to Hirota et al. (2011), the characteristic tree cover of forest (around 80%) and of savanna (around 20%) remain remarkably constant over a wide range of rainfall levels, so that instead of a direct relationship between precipitation and tree cover, we expect to see a shifting probability of the ecosystem being in either forest or savanna state. As a result, we do not expect to see much change in the direct use values linked to timber and non-timber products and ecotourism, and in the indirect use value linked to carbon storage. However, some use values (e.g., the option value of biodiversity) may significantly increase as the size of forest area decreases.

of deforested area due to an additional hectare of deforestation.

The marginal social cost of deforestation of the Amazon rainforest,  $MSCD$ , is the expected value of the change in  $TEV$  due to an additional hectare of deforestation. From Eqs. (2) and (3), it can be shown that

$$MSCD = PV_O + \left(\frac{1}{r\tau}\right)[\overline{V}_F - \overline{V}_S]A(1-d)(1-f)(1-e^{-r\tau}) \times P(d < H < d + \delta | H > d), \quad (4)$$

where  $A$ ,  $r$  and  $\tau$  respectively denote the original size of the Amazon forest, the long-term discount rate and the time period to fully reach the savanna state,  $f$  denotes the fraction of remaining forest area at the new equilibrium state,  $\delta = 1/A$  denotes the change in the proportion of deforested area due to an additional hectare of deforestation, and estimates for  $PV_O$  and  $[\overline{V}_F - \overline{V}_S]$  are shown on Tables 1 and 2.<sup>14</sup>

Fig. 2 shows, from the perspective of the Amazon region, how the marginal social cost of deforestation varies with the proportion of deforested area, ignoring and then taking into account a tipping point. First, ignoring the tipping point (as current cost studies do), the present value of the foregone economic benefits from one hectare of deforestation remains constant until the ecosystem reaches the forest-savanna tipping point, at which point the foregone economic benefits jump to US\$5 trillion. In this case we might estimate a marginal social cost of deforestation that is always lower than the marginal economic benefits of alternative land uses, so that the forest is continually converted into agricultural land, until there is a sudden transition to the savanna state, causing dramatic losses to all Amazon countries (and to the whole world). On the other hand, taking into account the existence of a forest-savanna tipping point, we can observe rapid increases in damages once the forest area is reduced below some critical point, which may function as an early warning to stop deforestation. Thus, accounting for the tipping point can significantly affect future policy should the amount of deforestation keeps increasing over time.<sup>15</sup> In this figure, the probability distribution of the deforestation threshold is modeled as a normal distribution with  $\mu = 40\%$ , such that [30%,50%] represents a 90% confidence interval (i.e.,  $\sigma \approx 6\%$ ).

Now take the perspective of an individual country, Brazil, where 60% of the Amazon forest is located. Let  $d_{B,t}$  denote the proportion of deforested area of the Brazilian Amazon, and  $d_{O,t}$  denote the proportion of deforested area of the other Amazon countries, so that  $d_t = .6d_{B,t} + .4d_{O,t}$ . If  $H$  denotes the (unknown) deforestation threshold of the Amazon forest, then for any given values of  $H$  and  $d_{O,t}$ , the deforestation threshold of the Brazilian Amazon that triggers the forest-savanna transition,  $H_B$ , is such that  $H_B = (H - .4d_{O,t})/.6$ . Thus,  $H_B$  is a linear transformation of the random variable  $H$ , so that  $H_B \sim N(\mu_B, \sigma_B)$ ,  $\mu_B = (1/.6)\mu - (.4/.6)d_{O,t}$  and  $\sigma_B = (1/.6)\sigma$ . The probability that an additional hectare of deforestation will bring the ecosystem to the forest-savanna tipping point is  $P(d_B < H_B < d_B + \delta_B | H_B > d_B)$ , where  $\delta_B$  denotes the change in the proportion of deforested area of the Brazilian Amazon from an additional hectare of deforestation.

The marginal social cost of deforestation observed by Brazil,  $MSCD_B$ , is the expected value of the change in  $TEV$  of the Brazilian

<sup>14</sup> To keep the notation simple, the index  $t$  has been omitted when no confusion arises. Take  $PV_O = \text{US}\$3,789$ ,  $[\overline{V}_F - \overline{V}_S] = \text{US}\$39,830$ ,  $A = 620$  million hectares,  $f = 35\%$ ,  $\tau = 60$  years, and  $r = 2.5\%$ .

<sup>15</sup> Using the 2005 deforestation rates, it was estimated that the proportion of deforested area would reach nearly 40% by 2026 (Wallace, 2007). The rate of deforestation of the Brazilian Amazon fell approximately 80% in the period 2005–2014 (INPE, 2015), but increased again in 2015–2016, when it reached the highest level since 2008 (INPE, 2016). In 2016, Brazil joined the Paris Agreement, and committed to zero deforestation by 2030. The other Amazon countries (which hold about 40% of the forest area) did not make any commitment to stop deforestation. As the ecosystem approaches a tipping point, it becomes increasingly fragile, in the sense that a small perturbation, such as a dry year or some small scale deforestation, may invoke a critical transition to the other state.

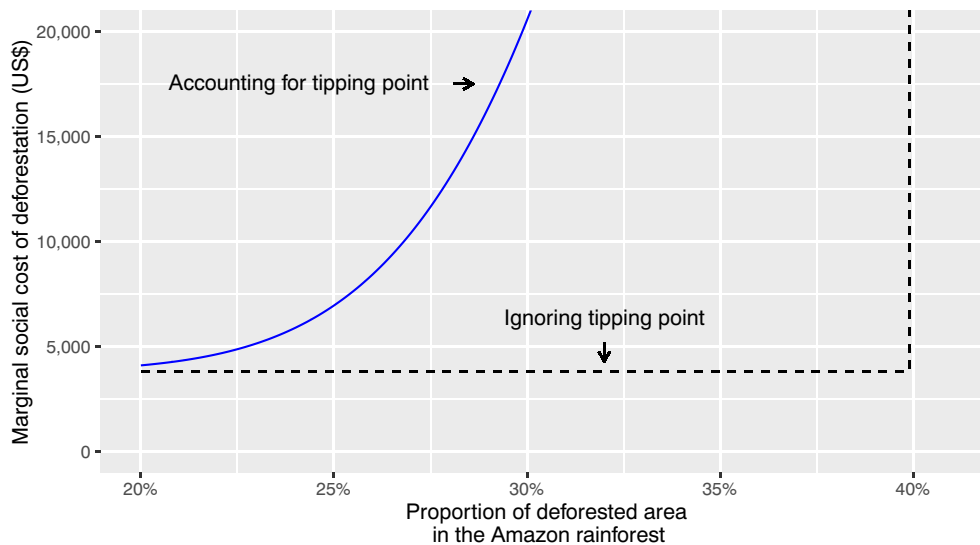


Fig. 2. Marginal social cost of deforestation observed by the Amazon region.

Amazon due to an additional hectare of deforestation. From Eqs. (2) and (3), it can be shown that

$$MSCD_B = PV_O + \left(\frac{1}{r\tau}\right)[\bar{V}_F - \bar{V}_S]A_B(1 - d_B)(1 - f_B)(1 - e^{-r\tau}) \times P(d_B < H_B < d_B + \delta_B | H_B > d_B), \tag{5}$$

where  $A_B$ ,  $r$  and  $\tau$  respectively denote the original size of the Brazilian Amazon forest, the discount rate, and the time to fully reach the savanna state,  $f_B$  denotes the fraction of remaining forest area at the new equilibrium state,  $\delta_B = 1/A_B$  denotes the change in proportion of deforested area of the Brazilian Amazon from an additional hectare of deforestation, and estimates for  $PV_O$  and  $[\bar{V}_F - \bar{V}_S]$  are in Tables 1 and 2.<sup>16</sup>

Fig. 3 shows, from the Brazilian perspective, how the marginal social cost of deforestation varies with the proportion of deforested area, when the other Amazon countries convert 20% and 40% of their forest areas to alternative land uses. The existence of a forest-savanna tipping point implies that each Amazon country observes a marginal social cost of deforestation that depends on the land-use policy adopted by the others. This gives rise to a coordination problem in which all parties can realize mutual gains, but only by making mutually consistent decisions. (Even if all Amazon countries decide to cooperate, it will be very difficult to monitor compliance because only Brazil generates and shares spatially detailed information on annual forest extent and change.) Here again, the probability distribution of the deforestation threshold is modeled as a normal distribution with  $\mu = 40\%$ , such that [30%,50%] represents a 90% confidence interval (i.e.,  $\sigma \approx 6\%$ ).

The marginal social cost of deforestation is not well-suited to the design of optimal land-use policy. First and most importantly, the marginal social cost derived above is conditional on the ecosystem not having crossed the forest-savanna tipping point. However, when the proportion of deforested area is  $d_{t_0}$ , we cannot know whether the ecosystem will cross the tipping point in the future. Additionally, individual countries do not devise optimal land-use policies for each hectare of forest. Instead, they analyze alternative land uses of much larger areas. As shown in the next section, an incremental cost measure is thus better suited for the design of land-use policy.

<sup>16</sup> To keep the notation simple, the index  $t$  has been omitted when no confusion arises. Take  $PV_O = \text{US}\$3,789$ ,  $[\bar{V}_F - \bar{V}_S] = \text{US}\$39,830$ ,  $A_B = 372$  million hectares,  $f_B = 35\%$ ,  $\tau = 60$  years, and  $r = 2.5\%$ .

### 5. The Average Incremental Social Cost of Deforestation

We propose an average incremental cost measure as an alternative measure of the social cost of deforestation. In general, the incremental cost of a product or service is the increase in total cost following the introduction of an additional increment of production. That increment can take several forms: one additional unit of the product or service (in which case the incremental cost is the marginal cost), the entire output over some period, the output for a group of products or services, etc. In our case, the increment is the size of an additional area that is deforested. The average incremental social cost of deforestation is the change in total economic value due to that incremental deforestation,  $\Delta TEV$ , divided by the change in the forest area,  $\Delta F$ , i.e.,  $AISCD = \Delta TEV / \Delta F$ . How large that increment should be depends on whether the cost study will be used for the design of optimal land-use policy or payments for ecosystem services.

If the objective of the cost study is the design of optimal land-use policy, it is important to understand how the average social cost of deforestation changes as the planned/target deforestation level changes. To see this, take the perspective of an individual country, say Brazil, and let  $\Delta F = (d_B - d_{B,t_0})A_B$  denote the size of an additional area of the Brazilian Amazon that is deforested. The average incremental social cost of deforestation for Brazil at time  $t_0$ ,  $AISCD_B$ , is given by  $E\left[\frac{\Delta TEV}{\Delta F} | H_B > d_{B,t_0}\right] = \frac{1}{\Delta F} E[\Delta TEV | H_B > d_{B,t_0}]$ . From Eqs. (2) and (3), it can be shown that

$$AISCD_B = PV_O + \left(\frac{1}{r\tau}\right)[\bar{V}_F - \bar{V}_S] \left(\frac{1 - d_B}{d_B - d_{B,t_0}}\right) (1 - f_B)(1 - e^{-r\tau}) \times P(H_B < d_B | H_B > d_{B,t_0}), \tag{6}$$

where  $d_{B,t_0}$  denotes the proportion of deforested area of the Brazilian Amazon at time  $t_0$ ,  $r$  and  $\tau$  denote the discount rate and time to fully reach the savanna state,  $f_B$  denotes the fraction of remaining forest area at the new equilibrium state, and estimates for  $PV_O$  and  $[\bar{V}_F - \bar{V}_S]$  are in Tables 1 and 2.<sup>17</sup> Again, each Amazon country observes an average incremental social cost of deforestation that depends on the land-use policies adopted by the others. Therefore, prior to designing its own policy, each country should carefully assess the planned land-use

<sup>17</sup> To keep the notation simple, the index  $t$  has been omitted when no confusion arises. Take  $PV_O = \text{US}\$3,789$ ,  $[\bar{V}_F - \bar{V}_S] = \text{US}\$39,830$ ,  $d_{B,t_0} = 20\%$ ,  $f_B = 35\%$ ,  $\tau = 60$  years, and  $r = 2.5\%$ .

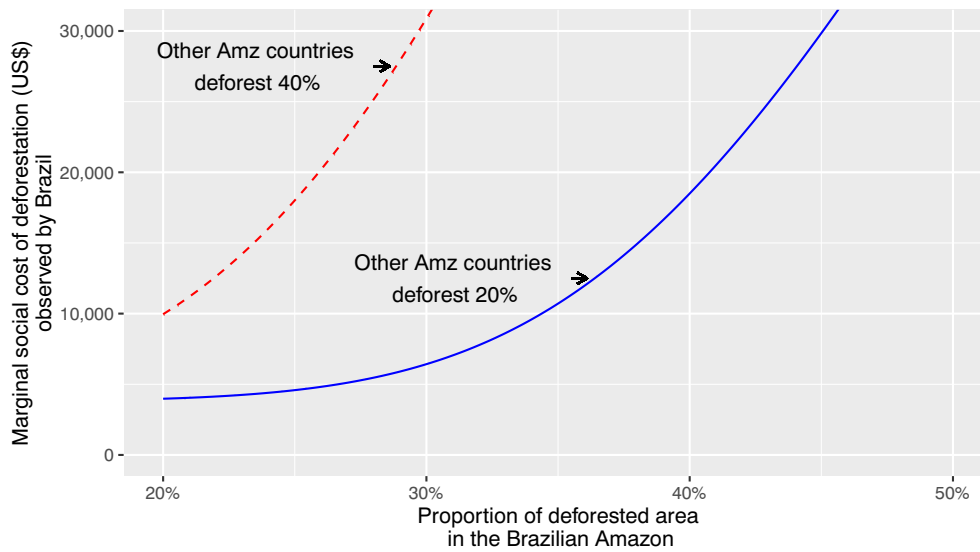


Fig. 3. Marginal social cost of deforestation observed by Brazil.

policies of the other Amazon countries, and then compare the average incremental social cost of deforestation with the future economic benefits of alternative land uses.

Most of the ecosystem services and benefits provided by the Amazon forest are public. Some are regional public (such as the ecological functions of climate regulation, water recycling, erosion control), and some are global public (such as carbon storage and biodiversity protection). The global benefits can be seen as positive externalities enjoyed by the rest of the world as a result of the Amazon countries' efforts to preserve the rainforest. Payments for global ecosystem services would seek to overcome the current free rider problem and attempt to compensate the Amazon countries so as to correct the market failure through economic reward of forest conservation.

Escalating global demands for new agricultural land should create incentives for alternative land uses. It seems reasonable for the international community to provide appropriate incentives, in the form of payments for ecosystem services, to ensure the continued provision of global ecosystem services and benefits such as carbon storage, biodiversity protection and existence value. To see this, imagine a situation where global demands for new agricultural land keeps increasing over time, so that the potential benefits from alternative land uses are always higher than the local and regional benefits from a standing tropical forest. Then, in the absence of appropriate incentives, one should expect that the forest area will keep being converted into agricultural land until the ecosystem crosses the forest-savanna tipping point.

Thus, if the objective of the cost study is the design of payments for ecosystem services, the choice of increment should be the additional deforested area that will bring the ecosystem to the forest-savanna tipping point, i.e.,  $\Delta F = (H - d_{t_0})A$ , where  $H$  is the (unknown) deforestation threshold,  $d_{t_0}$  is the proportion of deforested area at time  $t_0$ , and  $A$  is the original size of the Amazon forest. Assuming a constant deforestation rate,  $dr$ , the time until reaching the tipping point is the random variable  $T = (H - d_{t_0})/dr$ . Using the assumptions set forth on Section 4.3, it can be shown that the average incremental social cost of deforestation is

$$\begin{aligned}
 AISCD_{tip} &= E \left[ \frac{\Delta TEV}{\Delta F} \middle| H > d_{t_0} \right] \\
 &\approx PV_0 + \int_{d_{t_0}}^1 e^{-r \frac{y-d_{t_0}}{dr}} \left[ \frac{\left(\frac{1}{r}\right) [\bar{V}_F - \bar{V}_S] (1-y)(1-f)(1-e^{-rT})}{(y-d_{t_0})} \right] f_{H|H > d_{t_0}}(y) dy,
 \end{aligned}
 \tag{7}$$

where  $f_{H|H > d_{t_0}}(y) = \frac{d}{dy} P(H \leq y, H > d_{t_0}) / P(H > d_{t_0})$ , and  $H \sim N(\mu, \sigma)$ .

There are large uncertainties about future deforestation rates in the Amazon region because these rates often change according to changes in national environmental policies. From Eq. (7), the average incremental social cost of deforestation can be calculated for a number of deforestation scenarios:

- If Brazil keeps its commitment to the Paris Climate Agreement, and other Amazon countries also make similar commitments, the Amazon deforestation rate will tend to zero, and  $AISCD_{tip}$  will tend to  $MSCD$ . However, economic incentives for more deforestation will still exist, and the market will be operating imperfectly.
- If the future deforestation rate is constant and equal to the average rate in 2011–2015 (i.e.,  $dr = 0.13\%$  per year), the Amazon deforestation will reach 30% in 80 years, and  $AISCD_{tip}$  will be approximately US\$9,000 /ha.
- If the future deforestation rate is constant and equal to the average rate in 2001–2005 (i.e.,  $dr = 0.87\%$  per year), the Amazon deforestation will reach 30% in 12 years, and  $AISCD_{tip}$  will be approximately US\$35,000 /ha.
- If the potential economic benefits of alternative land uses are higher than the local and regional benefits from a standing tropical forest, and all Amazon countries respond unconstrainedly to economic incentives, they will deforest as much as they can in the first year (until reaching the tipping point), and  $AISCD_{tip}$  will be approximately US\$52,000 /ha.

The latter scenario seems to be the most appropriate for the design of payments for ecosystem services so as to correct the market failure and provide economic reward for forest conservation. Thus, in what follows, assume that the Amazon countries respond unconstrainedly to economic incentives. Let  $AISCD_{glb}$  denote the average incremental social cost of deforestation due to the loss of global ecosystem services and benefits (such as carbon storage and biodiversity protection). A risk-neutral global party may be willing to pay up to that value to ensure the continued provision of such services/benefits, because this is how much it expects to lose on average, per hectare of deforested area. Similarly, let  $AISCD_{lo/re}$  denote the average incremental social cost of deforestation due to the loss of the local and regional ecosystem services and benefits. The Amazon countries may be willing to pay up to that value to ensure the continued provision of such services/benefits, because this is how much they expect to lose on average, per hectare of deforested area.



**Table 3**

Sensitivity analysis of the average incremental social cost of deforestation due to the loss of global and local/regional ecosystem services and benefits (in US\$ per hectare).

	$P(H \in \mu \pm 10\%) = 90\%$ (i.e., $\sigma \approx 6\%$ )	$P(H \in \mu \pm 10\%) = 80\%$ (i.e., $\sigma \approx 8\%$ )
<b><math>AISCD_{gbl}</math></b>		
$\mu = 40\%$	31,662	38,491
$\mu = 45\%$	21,779	24,340
<b><math>AISCD_{lo/re}</math></b>		
$\mu = 40\%$	20,663	24,722
$\mu = 45\%$	14,787	16,310

Both  $AISCD_{gbl}$  and  $AISCD_{lo/re}$  can be found by solving Eq. (7) for the respective ranges of ecosystem services and benefits. Table 3 shows a sensitivity analysis of  $AISCD_{gbl}$  and  $AISCD_{lo/re}$  with respect to the probability distribution parameters of the deforestation threshold,  $\mu$  and  $\sigma$ . The results show that  $US\$14,787 \leq AISCD_{lo/re} \leq US\$24,722$ , and  $US\$21,779 \leq AISCD_{gbl} \leq US\$38,491$ . In fact,  $AISCD_{gbl}$  should be interpreted as a ceiling price. The international community may be willing to pay any amount equal to or below this ceiling price, which is enough to make the value of the local and regional ecosystem services/benefits provided by the Amazon rainforest match the potential economic benefits of alternative land uses.

Existing cost studies have compared the present value of the foregone economic benefits due to one hectare of deforestation,  $PV_O$  (equal to US\$3,789, as shown in Table 1), with the present value of future economic benefits of alternative land uses,  $AU$  (in the range between US\$10,000 and US\$35,000),<sup>18</sup> and they have found that, at the current deforestation level, the foregone economic benefits due to deforestation are much lower than the potential economic benefits of alternative land uses. The framework proposed in this paper shows that when tipping points are taken into account, the social cost of deforestation can be much higher than the foregone economic benefits due to one hectare of deforestation, and payments for ecosystem services may be necessary to ensure the continued provision of global ecosystem services and benefits.

In fact, the present value of future economic benefits of alternative land uses,  $AU$ , should be compared to how much each party expects to lose on average if the forest area is converted into agricultural land:

- If  $AU \leq AISCD_{lo/re}$ , payments for global ecosystem services are not necessary, because the Amazon countries will find it is in their best interest to protect the rainforest so as to ensure the continued provision of the local and regional ecosystem services/benefits.
- If  $AISCD_{lo/re} < AU \leq AISCD_{tip}$ , the international community may be willing to pay any amount equal or below  $AISCD_{gbl}$  which is enough to make the value of the local and regional ecosystem services/benefits match the future economic benefits of alternative land uses.
- If  $AU > AISCD_{tip}$ , one should expect the Amazon deforestation to proceed up to the point where the ecosystem non-linearities, now captured by the proposed framework, make it economically efficient to protect the rainforest.

We argue that payments for the global ecosystem services provided by the rainforest can provide the financial support needed for a novel sustainable development paradigm, where the Amazon forest is seen as a global public good of biological assets and biomimetic designs, such as in Nobre et al. (2016), and for which local research capacity, high-performance computing infrastructure and human capital are essential elements. Fig. 4 illustrates the relationships among distinct pieces of the

average social cost of deforestation, future economic benefits of alternative land uses, and payments for global ecosystem services, for the case when  $AISCD_{lo/re} < AU \leq AISCD_{tip}$ .

## 6. Concluding Remarks

If it were certain that the worst outcomes from deforestation could be addressed successfully in the future, either through natural regeneration or reforestation, so that the forest-savanna tipping point would never be reached, then we could rely on current marginal cost calculations that ignore forest resilience. However, if plausible scenarios exist in which the forest ecosystem undergoes a transition, the marginal economic value of a standing forest can be much higher than the present value of the foregone economic benefits from one hectare of deforestation.

Existing cost studies tell us nothing about the likelihood and possible economic impact of a large-scale forest dieback, which should be a major policy concern. Ignoring the existence of forest-savanna tipping points means underestimating the social cost of deforestation, favoring the adoption of alternative land uses, and facing the risk of an unexpected shift to the savanna state, which will result in dramatic losses of ecosystem services and benefits.

This paper proposes an alternative framework for calculating the economic value of a standing tropical forest, and explores the implications of a forest-savanna critical transition for the design of optimal land-use policy and payments. The economic value of a one-hectare grid cell of forest is modeled as a function of a number of hectare-wide (economic and nature) state variables and one ecosystem-wide state variable, forest resilience. This framework allowed us to disentangle the impact of deforestation on the hectare-wide state variables from that on the ecosystem-wide state variable. The marginal economic value of a standing tropical forest is then measured by the change in total economic value from an additional hectare of deforestation “taking into account the likelihood and possible economic impact of a large-scale forest-savanna transition.” We applied this framework to the estimation of the social cost of deforestation of the Amazon rainforest.

We have shown advantages to using an average incremental cost method for the design of optimal land-use policy and payments for ecosystem services. For land-use policy, the increment should be the size of an additional area that is deforested. For the design of payments for ecosystem services, the increment should be the additional deforested area that will bring the ecosystem to the forest-savanna tipping point (i.e., a random variable). Current marginal cost models do not provide an advance warning of an approaching tipping point, and Amazon countries must take into account the risk of a large-scale forest dieback. Additionally, the social cost of deforestation observed by one Amazon country depends on the land-use policies of other countries, and payments for ecosystem services may be necessary to ensure the continued provision of global ecosystem services and benefits such as carbon storage and biodiversity protection. The average incremental social cost of deforestation is a single number that provides relatively long-term guidance for the design of payments for ecosystem services. That number can be used by all Amazon countries, and it is not expected to change much over time, while the marginal social cost of deforestation faced by an individual country may change from year to year.

Future research can address the assumptions of this paper and the uncertainties related to forest resilience and the forest-savanna transition. Resilience is highly site- and scale-specific, and is difficult to quantify.<sup>19</sup> It can depend on a number of ecosystem-wide variables, most importantly on precipitation volume, but also on environmental

<sup>18</sup> See, for example, Andersen (1997), Andersen et al. (2002) and Margulis (2004).

<sup>19</sup> For a recent research on the quantification of ecological resilience see, for example, Mitra et al. (2015).

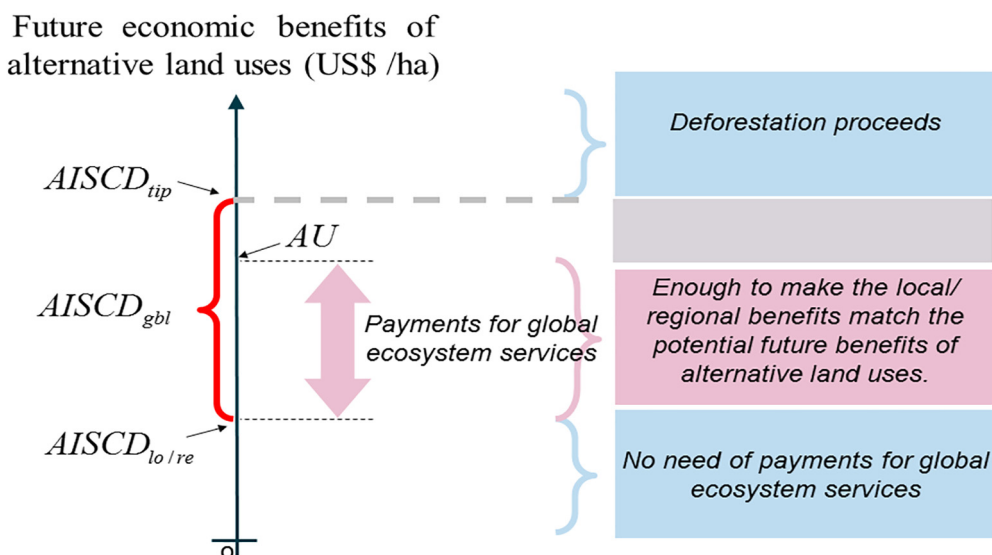


Fig. 4. Relationships among average incremental social cost of deforestation (AISC), future economic benefits of alternative land uses (AU), and payments for ecosystem services.

conditions such as climate and soil. The exact forest-savanna tipping point is unknown. Hirota et al. (2011) suggest that deforestation to the unstable threshold of 60% tree cover might induce a self-propagating shift to an open savanna over a range of rainfall levels. Nobre and Borma (2009) suggest that tipping points for the Amazon forest may exist for total deforested area greater than 40% and for temperature increase greater than 3–4 °C. We treated forest resilience as a function of the proportion of deforested area, and modeled the uncertainty over the threshold by a normal distribution. (We ignored any possible effect of global warming on the threshold.) The impact of forest resilience on the economic value of a standing forest is also largely unknown. Additionally, the interdependence of land-use policies across countries (that results from the existence of a tipping point) leads to coordination problems that we largely ignored.

A final caveat: Our focus has been the appropriate method for calculating the social cost of deforestation. For that purpose, most of the data employed in the calculations were drawn from other studies, some of which related to other tropical forests besides or in addition to the Amazon rainforest. A more robust cost study would require a thorough assessment of the input data used in this model. There is, for example, considerable uncertainty as to what the “true” average social cost of carbon (SCC) is, and estimates range from as low as US\$15/tCO<sub>2</sub> to well over US\$200/tCO<sub>2</sub> (see, e.g., Pindyck, 2013a and Pindyck, 2013b). We used a value of US\$80 as our “base case,” but also ran the model with an SCC of US\$40 to determine how sensitive our results are to the SCC. We found that the sensitivity is quite limited. For example, with 30% deforestation and accounting for tipping, the marginal social cost of deforestation is about US\$20,000 if the SCC is US\$80 per metric ton, but falls to US\$17,000 if the SCC is US\$40 per metric ton. Thus our general conclusions seem robust to the specific choice of the SCC number.

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