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IMPORTANT NOTE

This report has been written to represent AMAZALERT deliverables D5.1,D5.2 and D5.3 together. As these three could only be written towards the end of the project, and since the information of D5.1 and D5.2 was meant to flow into D5.3, it seemed more appropriate to join these into one, coherent document. In its present form, D5.1 is best represented by sections 1,2,3 and 4; D5.2 is mostly represented by sections 5, 6 and 7.2; while D5.3 is represented by the whole document (as it would 'bring together' results), but focuses on section 7.1. Also he document follows the description and logic of the description of all tasks in WP5.

A blueprint for an early warning for critical transitions in Amazonia

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Summary

In this report we present the scientific background for an Early Warning system for critical transitions in Amazonia, explore the need and existing systems and finally propose an outline, or ‘ Blueprint’ for an Early Warning System (EWS). In sections 1-3, we review the issue and likelihood of climate change-induced or land-use change induced critical change in the Amazon, based on current literature and recent results from the AMAZALERT project. This literature recently tends to indicate lower risk of critical transitions than was assumed in earlier work, but the need to monitor potential change is an essential condition for this resilience of Amazonia.

To prepare for detecting warning signals, we investigate the potential pathways of change and their drivers, as well as different modes of warning. Change can be driven by long-term climate change, by land-use change or by extreme events in climate and weather. Transitions can be linear, non-linear or even strongly non-linear to discontinuous. The latter transition type is associated with critical transitions, or ‘ tipping points’ . Modes of warning include warning with long time lags, essentially projecting effects of climate change as a consequence of policy decisions, warning with shorter time lags, based on observing adverse trends in regional conditions, and warning on the basis of observing impacts already occurring. We investigated the possibilities for detecting change in each of these conditions.

The definition of thresholds is largely a matter of policy and society to decide on acceptable strength and occurrence of ecosystem services, but Science contributes to this by indicating the level of caution that needs to be taken in defining thresholds. If possible change is less reversible, the threshold should be defined in a more conservative way.

In sections 4-6, possibilities for monitoring critical change are discussed, followed by assessment of uncertainties and an inventory of existing monitoring systems in (mainly Brazilian) Amazonia. We systematically investigate the monitoring options of climate forcing and impact on the main services: carbon storage, water cycling and biodiversity. We also discuss options to monitor socio-economic processes as indicators of change. Novel and future possibilities for monitoring are given special attention.

Currently several monitoring systems are already active in Amazonia, but surprisingly most of these are focused on monitoring land cover change, biodiversity and biomass. The river discharges are well-monitored, and several fire detection and warning systems exist. Fewer observations are being carried out on regional weather and climate, and on essential conditions of soil water availability.

Finally, in sections 7 and 8 we discuss implementation options for an EWS in Amazonia. Stakeholder consultations overwhelmingly indicated that any EWS should be based on all the existing monitoring systems, and that it should be open-access and not ‘owned’ by one particular institution.
Based on this advice and, scientific background and practical possibilities, we then describe an outline system with general guidelines for implementation. We also, very preliminary, present a possible institutional setting for an EWS, based upon a small core unit of scientists operating and interpreting models and data streams, and keeping knowledge and analysis methods up to date.

1. Introduction. The importance of Amazonian ecosystem services and the likelihood of catastrophic degradation.

Amazonia harbours a multitude of ecosystem services, several well-defined, others less so, including services to human society and services to the long-term sustainability of life on planet Earth. Important and well-known services are, for example, the maintenance of rainfall recycling and transport into the South-American continent (Spracklen et al., 2012), storing and sequestering substantial carbon away from the atmosphere (Global Carbon Project, 2014; Gatti et al., 2014) and harbouring a large portion of global biodiversity. Many services can be derived from these basic, large-scale services of the Amazon Biome (Tejada-Pinell et al, 2014 (AMAZALERT D1.4). The existence of most of these services ultimately depends on integrity of abundant high biodiversity, high-biomass, forests in the region. These forests are under continued pressure of clearing for (mainly) agricultural use (Davidson et al., 2012; Aguiar et al., 2013). Several studies have suggested that remaining forests are also under threat from climate change, notably by rainfall reductions and temperature increase, enhanced by progressive CO_2 release to the atmosphere (White et al., 2000, Cox et al., 2000). Vulnerability of the forests is aggravated by progressive deforestation (Nobre and Borma, 2009). These studies also suggest that forest degradation in the region may occur in a highly non-linear fashion, with progressive decline occurring after certain thresholds in global climate or land-use change have been crossed (Nobre and Borma, 2009).

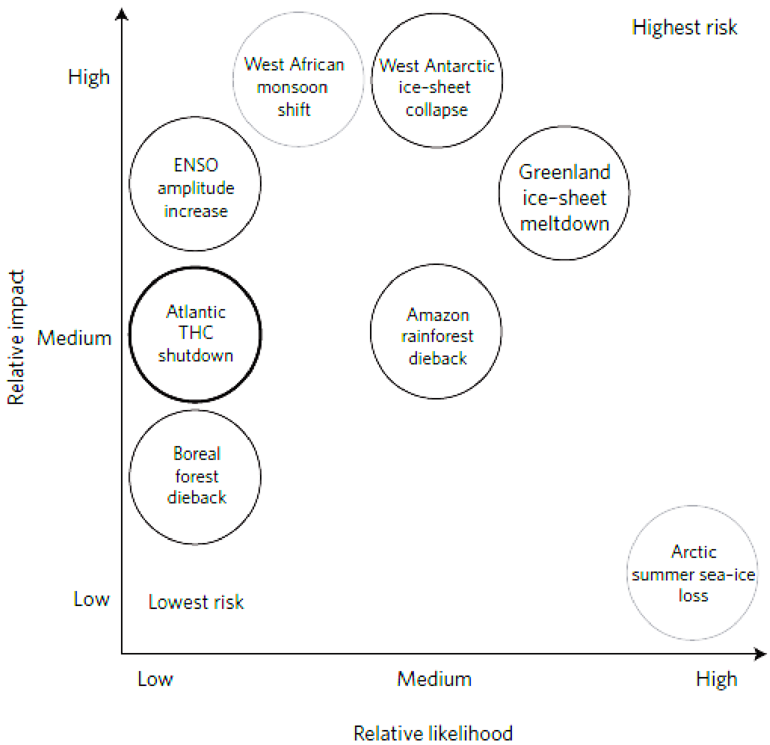


Figure 1 The relative importance of Amazon die-back risk compared to other global-scale threats to the Earth system (diagram from Lenton, 2011)

There is substantial confusion about the underlying nature and drivers of such decline (fig. 1). Broadly, global climate change, with changed temperature or moisture and heat input into the region and amplifying feedbacks in the system (associated with water recycling and fire) are possible drivers. Whether these lead to externally forced decline (as in Cox et al., 2000) or self-propelled decline caused by transitions across multiple stable states (e.g., Lenton et al, 2008; Oyama and Nobre, 2003; Lapola et al., 2009) is a matter of debate. It has been shown that relatively small changes in climate (temperature, dry season length can indeed lead to large changes in the modelled sustainable forest fraction in the Amazon (Good et al., 2011). That paper further shows that in the Cox et al. (2000) simulations, the Amazon carbon budget was extremely sensitive to climate while climate change was very large in those simulations; and that the simulated climate-induced die-back could be fully explained without accounting for vegetation feed-back Recent studies, however, suggest that Amazon dieback is not typical of current global coupled climate-vegetation models and highlight a large lack of understanding of key drivers of change, including the effects of temperature and CO2 concentrations (Huntingford et al., 2013; Good et al., 2013) and the effects of extreme droughts (Meir and Woodward, 2010). Kay et al. (2014) (AMAZALERT D3.4), state that "*The probability of climate-driven Amazon dieback occurring by the end of the century is significantly less than the probability of it not occurring. However, missing processes and biases (known and potential) in climate and earth system models are such that dieback is much harder to rule out than implied by these models alone. Further, the interactions between climate variability and change and land use change, particularly through fire, are likely to increase the probability of forest degradation"*. Nevertheless, pan-tropical analysis of vegetation patterns convincingly shows that rainforest and savanna may both exist under a narrow range of climate conditions as alternative stable states (Hirota et al., 2011; Staver et al., 2011), which does indicate an intrinsic risk for tipping points or critical transitions in response to relatively small variations in regional climate.

From a theoretical point of view it is plausible that alternative stable states do exist in the complex forest climate system of the Amazon. Extensive dense forests stimulate regional water cycling by evaporating moisture and are highly resistant to fire (fig 2). Logging and deforestation both decrease the local evapotranspiration and increase the risk of fire. While fire usually has a more local effect, even though it can be widespread, precipitation and water recycling is a regional phenomenon, and deforestation with reduced evaporation in one place can cause reduced rainfall patterns elsewhere (Avissar and Werth, 2005). As fire causes tree mortality and lack of precipitation hampers tree growth, it makes intuitive sense that two or more alternative stable states (or; attractors) can exist, with tipping points (or: critical transitions) between them: Extensive dense forest is a stable state but a state with low-density vegetation is also stable, as forest regrowth is hampered by lack of soil moisture and high fire frequency. If patches are isolated, seed dispersal may be a limiting factor as well (Van Nes et al, 2014). Global climate change may affect large-scale patterns of climate variability, which in turn modulate the flow of moisture into the Amazon Basin from the adjacent oceans. So climate change and land-use change can reinforce each other, leading to drying and degradation of the Amazon forests (Sampaio et al., 2007).

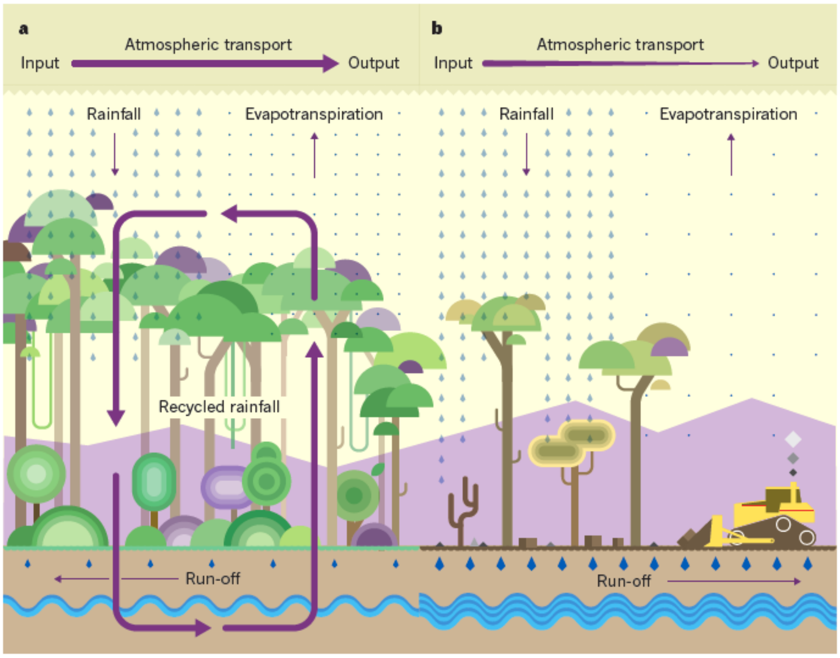


Figure 2 Pictorial representation of two stable states for the Amazonian water cycle. Picture of Aragao, 2012

The possibility of critical transitions occurring in ecosystems is usually illustrated using simple models, consisting of a set of only a few differential equations. Usually, in such equations rate constants are broad assumptions or empirical ratios, derived from observational data in steady-state systems (e.g. van Nes et al., 2014). Hirota et al. (2011) and Holmgren et al. (2013) illustrated the existence of multiple stable states in forest density using remote sensing data only, arguing that the spatial distribution of these states can be explained by rainfall and rainfall variability only. Meesters et al. (in prep) designed a simple one-dimensional surface-atmosphere exchange model which includes atmospheric feedback and large-scale oceanic moisture and heat transport. This model for Amazonia also shows strong non-linear sensitivity to global climate (oceanic moisture input), leading to accelerated drying, and predicts a critical transition to a stable state without evergreen broadleaf forest. Potential vegetation models, based upon a set of fixed conditions for evergreen forest and savanna, such as Oyama and Nobre (2003) and Lapola et al. (2009), also show the potential occurrence of multiple steady states in the Amazon in current climate.

More complex dynamic vegetation models, as well as coupled climate-vegetation earth system models, however, show less of such behaviour. A notable exception is the HADCM3/TRIFFID model, discussed above, that did show Amazon dieback and which was instrumental in triggering many subsequent studies (White et al., 2000; Cox et al., 2000). A reason for this difference could be that simple models are often also forced with extreme change, whereas complex models are usually forced with a range of (more realistic) climate or radiative forcing scenarios. Recent sensitivity studies of vegetation models (Huntingford et al. 2013; Galbraith et al., 2010; Kruijt et al., in press; Kruijt et al., in prep) show that in the models used to predict die-back, on one hand the very uncertain CO_2 fertilisation maximises the resilience of Amazon forests, while drought sensitivity is poorly represented and temperature increase almost always leads to overestimated climate sensitivity. While it is yet uncertain how the balance of these sensitivities will change when more data will come available, it appears that apparently, realistic climate change is not likely to lead to Amazon dieback very soon.

Because there is still substantial uncertainty, there is a clear need to increase the ability to forecast such decline and, where possible, to prevent it. For this, a set of tools: a system consisting of models, data and monitoring capability is needed to inform both policy makers and science on the best estimates of upcoming change in the Amazon. In a practical system that intends to inform on imminent degradation of the Amazon, 'down to earth' Early Warning such as observing whether trends in key drivers are crossing thresholds should be considered in the first place. However, since the relevant thresholds may be difficult to define and since this kind of warning signs may come too late, there should also be attention to signs that alert for approaching critical transitions. In a mathematical sense, these occur if the stable equilibrium as a function of external parameters has a discontinuity ('tipping point'), or at least a discontinuity in its rate of change. Especially tipping points need attention, as they correspond to strong hysteresis, which implies poor reversibility. The potential for such Early Warning (EW) has been explored before, mainly in a theoretical context, where it is shown mathematically that systems that contain critical transitions often show EW signs in variability statistics on approaching the transition (Lenton, 2011; Dakos et al., 2012; Scheffer et al., 2009).

In this study we treat these issues in a systematic way and evaluate the realism of such early warning, to provide the scientific base for an early warning system for critical change in the Amazon. We will first explore the phenomenon of critical change in the Amazon a little further. Then we will consider the various pathways of change and their detectability, methods to define thresholds and indicators, and categorise ways to monitor these indicators. Finally we will contemplate ways in which an EWS could be implemented, including communication and response to alerts.

2. Pathways and detection of transitions

2.1 Systematics and examples of critical change mechanisms in the Amazon

To design sensitive indicators of change it is important to understand the different forcing's and pathways of change. First, in the context of the Amazon, we propose to distinguish three main kinds of forcing:

1) Climate change, which is associated with global increases in CO_2 concentration and air temperature, but also with decreased inflow of atmospheric moisture into the Amazon basin from the Atlantic (Satyamurty et al., 2013; Pereira et al., 2012) This change is in itself highly uncertain, depending on emission scenarios but also varying among projections, and not necessarily gradual (IPCC, 2014). In this category, mitigation measures and lack of them, affecting climate change should also be considered as forcing factors. Emission scenarios linked to global and regional policies lead to distinctive climate change and hence to delayed impact on the Amazon. Conversely, every impact is linked to a specific set of mitigation policies in the past.
2) Land-use change, which is associated with economic activity in the region, but also by several other driving factors, from local to global (e.g. atlas of threats to the Amazon, Carneiro Filho and Braga de

Souza, 2009). On top of that, governance factors such as regional measures to mitigate deforestation but also settlement programmes can strongly affect deforestation, as has been demonstrated for the Brazilian Amazon (Aguiar et al., 2012). Forest cover decreases almost monotonously, with rare increases, but not necessarily continuously. Sudden increases or peaks in the rate of change can be caused by a multitude of socio-economic and political causes (Aguiar et al., 2012; Soares-Filho et al., 2006; Dalla-Nora et al., 2014). Therefore these drivers should be considered as forcing factors.

3) Extreme events, which are expected to increase in frequency. Extreme events are mainly associated with extremely dry and wet years, often linked to the ENSO phenomenon but also to the North-Atlantic circulation (Marengo et al., 2008), but it is not certain that these phenomena will be the main factors causing increase in extremes (IPCC, 2013). Extreme socio-economic events can also be important, causing migration, infrastructural change and strong change in land-use.

The next step is to understand which pathway and which functional cause-effect relationships a particular degradation impact will follow. This is important to assess the type of indicator signal that should be monitored and for the degree to and rate at which the degradation is reversible.
Two aspects to the potential transition pathways are linearity and hysteresis. Linearity here refers to the relationship of the equilibrium state of the impacted variable with the forcing variable; and hysteresis refers to the difference in the transition pathway between decline and (usually hypothetical) restoration. We can roughly distinguish three classes of transitions out of a continuum of functional dependences. These cases are illustrated in figure 3.

1- Gradual transitions, represented by (near-) linear relationships between the forcing variable and its impact. These can be direct or lagged. For example: land-use change leads to direct biomass loss, but can also lead to delayed biomass and carbon loss through degradation and subsequent fire. Regrowth is relatively fast and symmetrical, but a cycle of decline and restoration is almost always hysteretic to some extent, depending on environmental conditions. An example is air temperatures crossing the upper limit for acclimation of photosynthetic production. This increased stress factor will ultimately lead to increased mortality. Carbon losses will follow mortality but with some delay because carbon in dead wood does not leave the ecosystem immediately. Regrowth may be possible within the time frame of such delay, however, and hence effects on ecosystem carbon budgets may be damped. Of course reversal of such decline in the first place depends on reversal of the forcing factors (climate change reversal, land abandonment), which is not very realistic in most cases. Gradual transitions are the most common and important to account for, even though they should be predictable as long as the dynamics of the underlying system is understood.

2- Non-linear but continuous transitions. In this case the sensitivity of the impacted variable to forcing rapidly increases beyond a certain value of the forcing. This often involves positive feed-back relationships, amplifying the sensitivity to and direct effect of external forcing. the case of reduced moisture inflow described above, even without the role of fire, is an example of this pathway. Below a certain threshold, regional water cycling will no longer be sufficient to support rainforests. This, together with temperature increase, is one of the governing processes in the simulations by Cox et al. (2000), where massive climate change triggered the decline. Other examples would include large scale deforestation which reduces evapotranspiration and hence the recycling itself (Boisier et al., 2014), inhibiting the regeneration of forests. Hysteresis and hence reversibility of the ecosystem is comparable to that in the linear case, although in highly degraded conditions, regrowth is likely to be slower, and hence hysteresis higher.

3- The third case consists of transitions that are highly non-linear and also discontinuous, including tipping points. In this case, a critical parameter reaches a threshold beyond which the evolution of the system becomes self-propelling. Beyond a certain threshold value, the system becomes unstable, and keeps changing until a new equilibrium is reached at a very different stable state. If the critical parameter is brought back to the “safe” side of the threshold, the system typically remains locked up in the new state, and recovery only occurs when the critical parameter has a much more favourable value than was needed to maintain the old state when it existed. Therefore, hysteresis in such a transition is much larger than in the preceding two continuous cases. In this case, it may happen that although the mean critical parameter is still in a state which can support rainforests, extreme events and perturbations push the system outside the resilience range of the equilibrium, and bring the system in the range of attraction of the other equilibrium, which is resilient to reversal. In a rapidly changing climate with frequent extreme events such as heat waves, droughts and hurricanes, one has to take into account that if a system is pushed away from its equilibrium state too far, it doesn’t necessarily change back to the old state once the disturbance is over. So a series of extremely hot and dry years could lead to the death of certain rainforest trees that cannot cope with it, allowing grass to establish, increasing fire risk, leading to higher tree mortality and a cascade of forest deterioration events. Large-scale deforestation events, even if land would be abandoned afterwards, could lead to similar situations, and the combination of such disturbance with climate extremes is even more likely to trigger such tipping points (Nobre and Borma, 2009). This kind of critical transition is responsible for the vegetation changes predicted by, for example, Lapola et al. (2009).

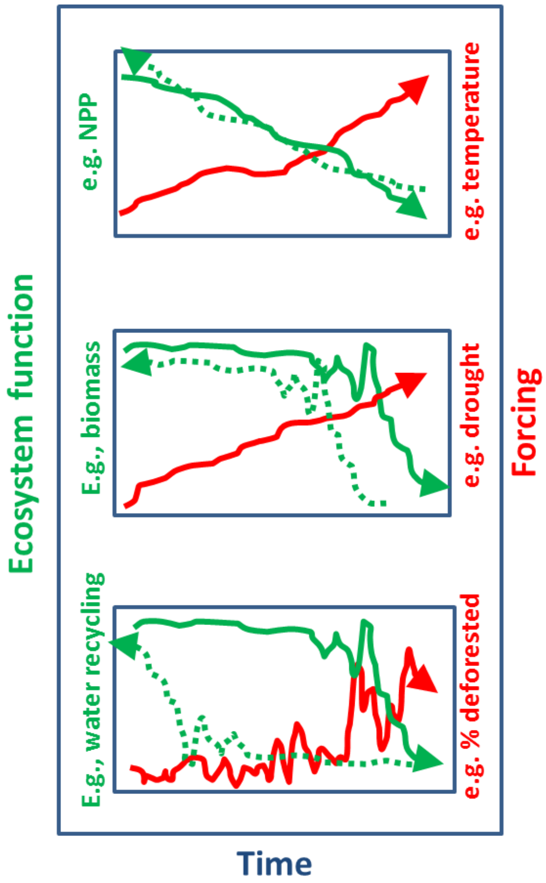


Figure 3 Three types of transition. Forcing and impact variables are for example only. Dashed lines refer to potential reversibility of the impact on ecosystem function if the forcing returns to its original state.

2.2 Conditions for Early Warning

Early warning is only possible if there is a clear, measurable signal, indicating change with sufficient delay of the actual impact to allow adaptation or mitigation, even if mitigation itself also has lagged effects. Relating to the three transition pathway types we can assume that for some examples of a gradual transition the change pathway is well predictable as long as the change in the forcing variable is known. For the unpredictable types of transitions, notably those where feedbacks create a highly non-linear response, the crucial problem is that predicting the effect of a forcing change is less straightforward if not impossible. In any case we can distinguish three types of warning (see figure 4):

A) Advance warning for failing mitigation of forcing factors. A given set of policies, in a given global environmental and socio-economical context, will lead to particular future environmental conditions. These can be projected with global models and hence the consequences of policies for the future can be projected. For the Amazon, obvious examples are global variables forcing climate change, such as emissions or atmospheric CO_2, mitigation policies controlling them or land-use change policies, which can be predicted to lead to impact on the Amazon with a range of uncertainty, using coupled Earth System models. Thus, 'very early warning' can be issued for a set of policies that will lead to Amazon degradation, and a policy 'signal' can be detected from analysing global and regional climate and deforestation mitigation policies.

B) Warning for deterioration of regional environmental conditions.
At shorter time scales the regional conditions (atmospheric temperatures, rainfall, soil moisture, deforestation percentage and pattern) are predicted to impact, with some delay, on the ecosystems. Even if the actual impact is hard to predict because of non-linearity, it should be possible to identify the regional conditions under which critical change becomes unavoidable. It should be noted that in case strong feedbacks exist between the ecosystems and the regional conditions (e.g. between rainfall, biomass and evapotranspiration), a change in regional conditions is likely to be an effect, as well as a cause of an ecosystem impact, and in that case early warning is similar to detecting an impact, as described under the next case.

C) Warning for imminent impact on the ecosystems of concern, based upon changing statistical behaviour of the system.
In the case that forcing cannot be detected or has already passed thresholds, it is possible that variables or statistics of the system affected exist that start changing first, with sufficient delay before the actual impact on the ecosystem function. Where cause-effect relationships are uncertain, as we assume here, we can only rely on other statistics of the system than the mean state. Several studies have shown that characteristics of the variance in that state, such as amplitude and autocorrelation (slowness) do often start changing before critical change occurs in the equilibrium state. As a critical change approaches, resilience starts decreasing, which enhances amplitude but also slows variability in the ecosystem state. If the stability changes more rapidly than the system's equilibrium state itself, then the variability and it slowing down can serve as early warning. But this may be system dependent. In the following paragraph we show that the use of such variability statistics is unlikely to be of much value in the case of the Amazon.

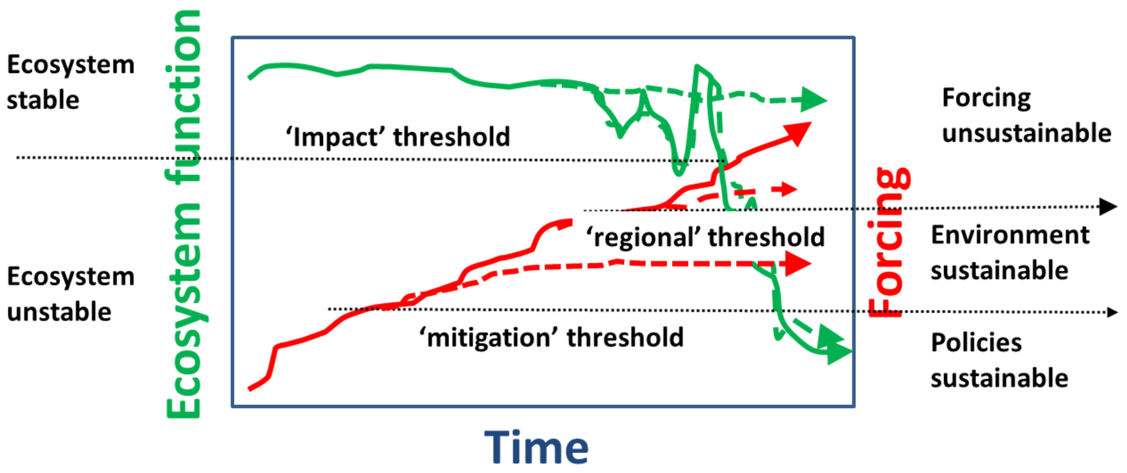


Figure 4 Possible pathways to critical transitions, showing threshold crossings at several stages along time, and range of stability of ecosystem (left) and sustainability of forcing (right).

2.3 Early warning signs in variability statistics

The metaphor often used is that of a ball rolling back and forth (changing instantaneous state) in a 'basin', forced by externally imposed stochastic variation and the potential to return to equilibrium (figure 6). Apart from external factors inducing variability in the position of the ball, the 'shallowness' of such a basin affects the variance as well as the slowness, or autocorrelation of this position. This shallowness can be regarded a metaphor for lack of resilience, Inversion of the basin leads to instability and movement of the ball into one of the adjacent basins; such an inversion is preceded by a growing shallowness of the potential well, and hence by larger variability and slower return to equilibrium. It is a crucial, and so far unresolved question, under which conditions this type of early warning does occur, and under which conditions it does not. If the potential basin shape is determined by the same forcing as the equilibrium system state, then it seems unlikely that the change of the equilibrium (represented by a changing position of the potential minimum) will come later than the increase of sensitivity to random perturbations (gradual disappearance of the potential well), and so EW signals will be of limited value. It is even possible (and a common observation in simple models for the Amazon: Boulton et al. (2013); Meesters et al. (2015a, in prep)) that a critical transition occurs at the end instead of at the beginning of the decline, though it remains very uncertain whether this happens in reality.

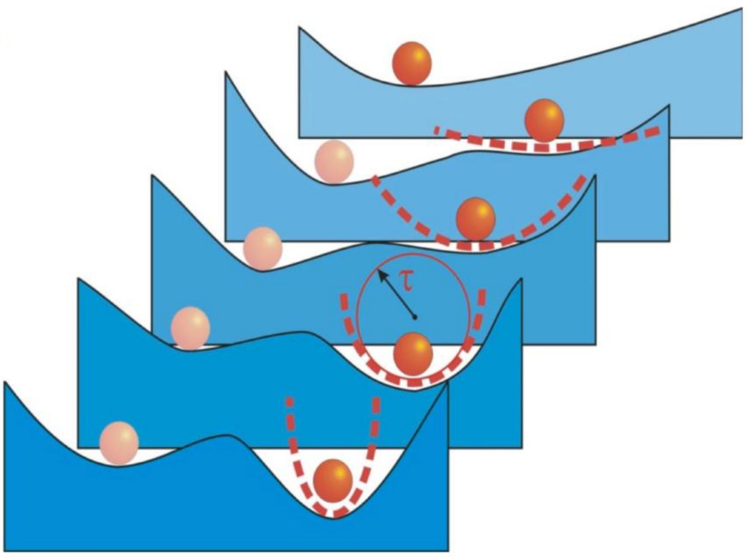
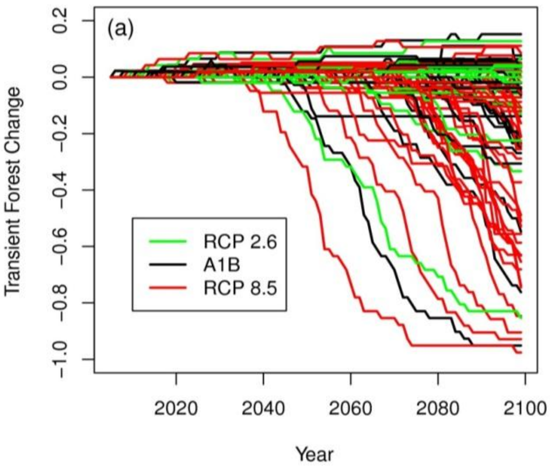


Figure 5 Schematic illustration of the systems theory proximity to a tipping point: the potential wells represent stable attractors, and the ball, the state of the system. Under gradual anthropogenic forcing (progressing from dark to light blue potential), the right potential well becomes shallower and finally vanishes (threshold), causing the ball to abruptly roll to the left. The curvature of the well is inversely proportional to the system's response time τ to small perturbations (reproduced from Lenton et al., 2008).

The image of the ball rolling in a stable basin, though it is dominating in overviews such as Lenton et al. (2011), may not be appropriate if the location and shape of the potential basin is itself dependent on the fluctuating external parameter: then, instead of the ball being pushed to and fro within the basin, the shape of the basin is changing back and forth, which may lead to large amplitudes even when the basin remains fairly stable (Meesters et al., 2015a, in prep). For vegetation dynamics in a climate with drought stress, precipitation and soil moisture content become external parameters of this kind. The strength of the fluctuations then mainly reflects the sensitivity of the vegetation equilibrium to external parameters, not the nearness of a critical transition; actually, the fluctuations may even diminish as a critical point is approached (Dakos et al., 2012; Meesters et al., 2015a in prep).

Moreover, increased amplitudes can announce a critical point but they can also be a direct consequence of increased fluctuations in the external forcing (Boulton et al., 2013.) This constitutes a second reason why a rise of fluctuation amplitudes is not an unambiguous predictor of the approaching of critical transitions.

Monitoring of autocorrelation times (in e.g. leaf mass or biomass) has been proposed as a tool for predicting critical transitions, as their growth is a more robust predictor than increased fluctuations amplitudes (Dakos et al., 2012), though little work has been done so far on checking this hypothesis in a rainforest stability context. But here a serious problem shows up. The considered time series is typically a series of *annual* numbers of precipitation, drought stress etc., because sub-annual data mainly show seasonal fluctuation. Thus, relevant oscillations have relatively long periods (many years), and to monitor an increase one will have to resolve even much longer periods. It is unlikely that the required time window fits into the limited time scale of the decline. Boulton et al. (2013) investigated coupled GCM-vegetation model results predicting a decline of the Amazon system with a time scale of a century, and could not detect a growth in autocorrelation time, which the authors also attributed to the too short time scale of the decline. Meesters et al. (2015a, in prep), show the same for fast decline, whereas the growth is well visible if the decline takes a couple of centuries (fig 5).



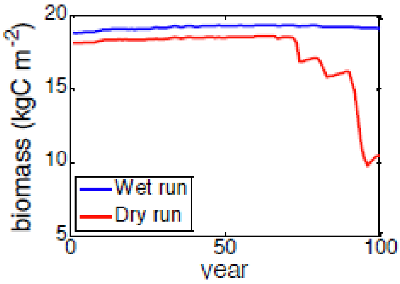


Figure 6 Simulations exploring pathways of climate-induced degradation with (left) the complex HADCM-3 model (Boulton et al., 2013) and (right) very simple model by Meesters et al. (2015a, in prep).

3. Identifying thresholds and indicators

3.1 Thresholds

In the previous sections we have explored the forcing's and possible pathways of change in the Amazon, including a discussion on the behaviour of the system in its approach to transitions. We have discussed whether change would be detectable, but so far it is not clear at what amount of change an early warning system should issue an alert. Ideally, this should be at a stage that either i) ecosystem services are reduced to a level such that preventing their demise is more beneficial than the gains from the activity that causes their demise (e.g., forest biomass becomes more valuable than the timber and potential agricultural yield of the land) or ii) loss of the ecosystem service is not reversible within a time horizon relevant to a region's interest (e.g., biodiversity loss will not reverse within several generations).

In the first case, any pathway of change can cross such threshold, which is defined by societal interests independent of the processes that lead to change. In the second case, the reversibility is crucial, which does depend on the process involved. As we have seen before, change can be induced by a) monotonously changing forcing such as climate change or deforestation, or b) by extremes forcing a tipping point. In case a), reversal can start when the forcing reverses, but in the case of climate-induced forest die-back, climate change cannot reverse quickly and neither does forests regrow quickly. In case b) the forcing has to reverse more than back to normal in order to 'tip' the system back, and even then regrowth is usually slow. For a non-linear process with positive feed-backs, a threshold defined along these lines will be at more conservative levels than one defined directly from society, i.e. at a point before society 'feels' the consequences. However, even while in an ideal world, the point-of-no-return can possibly be defined from science alone, the criterion of the maximum reversal time horizon is subjective and should be defined independently by society.

The world is not ideal, of course, and usually large uncertainty exists on almost every aspect of the change process: the development and control of the forcing is uncertain, the rate and even nature of the change process is, and so are the data collected to detect change. Therefore, the precautionary principle applies and it is essential that the magnitude of uncertainties is quantified as well and that reasonable allowance s made for these in the definition of thresholds or critical values.

Thus, practical thresholds can be set by society. Examples are low rainfall and temperature limits, navigability ranges of rivers, maximum allowed flooding, minimum required carbon sequestration and moisture transport out of the region, etc. It should be the role of science and an early warning system/service, however, to quantify the additional safety bands on such thresholds because of reversibility, feedbacks and uncertainty.

A special case of thresholds consists of thresholds in mitigation policies. Here, non-reversibility and uncertainty play an important role. Climate models (or, in the case of deforestation: land-use policies) should be used to assess the range of consequences of a given mitigation in a given global situation, but also the reversibility in climate or land use and account for that in assessing the relation of policy level to risk.

Especially if the impact has a delayed response to the forcing, early warning is straightforwardly defined. If such delay is associated with hysteresis in the system, this means that reverse change is difficult, in which case extra caution should be taken. If there is no delay in the response, allowance should be made for time to respond. If the environmental response is continuous in nature but stochastically poorly defined, monitoring more than one variable may help to constrain the response and forecast degradation. If not enough is known about the response, more research is likely to improve predictability. The uncertainty of the impact prediction as a function of the EW signal should be quantified as much as possible, and accounted for in the formulation of alerts.

3.2 Indicators for early warning

In the previous sections we have analysed how for a particular phenomenon an EW signal may be detected and how thresholds or critical conditions may be defined. Despite the different interpretation, the actual indicator variables are often the same. Indicators can be divided in forcing and impact variables, however, and can be further subdivided in long-term trends and dynamical statistics. Trend analysis should not only consider linear change but also non-linear decline, according to the time development expected, or analysing other predicted relationships.

A special class of indicators is represented by mitigation policies. Indicators can be defined of GHG emission mitigation policies that, given the state of the global climate, inevitably lead to conditions in which Amazon degradation is likely to occur. A similar argument holds for 'regional forcing's', where climatic or land-use conditions are such that degradation will occur with some delay.

In the Appendix to this report, Table 1, we present an overview and classification of possible critical transitions, their causes, effects, indicators and possible monitoring to observe such indicators.

4. Strategies for monitoring

Based on the systematics of transitions, thresholds and indicators we propose to classify monitoring into eight categories: two focussing on lagged forcing, two on short-term (regional) forcing and four separate impact categories. Lagged forcing, as discussed, can be related to both climate mitigation policies and land-use change policy. The related short-term forcing's relate to regional climate interacting with the Amazon forests and the state of land-use or forest remains affecting the regional environment for forests. As for impact monitoring, focus should be on the state of the carbon cycle, the water cycle, biodiversity and soil nutrients. However, we will not discuss the latter here.

4.1 Lagged climate or land-use policy forcing

Indicators for crossing 'mitigation' thresholds should be based upon model forecasts and scenarios, given sets of policy actions, as the actual impact would be only forecasted for a date in the future. Indicators for such thresholds include predicted regional weather patterns with temperature or precipitation anomalies exceeding a regional threshold that was set before by sensitivity studies, or a road network, population or economic activity exceeding a threshold beyond which deforestation levels are predicted that are higher than sustainable for the forests. Also the threshold itself may change, for example the road network may not change but nevertheless become a threat because climate change enhances the sensitivity to deforestation. These thresholds deal with delayed effects and the time scales involved will be very different between indicators, scenarios and policies involved in them.

Understanding the approach to mitigation thresholds and identifying indicators for them comes close to analysing the impact of policies, decisions and development, both at regional and international levels. While the latter includes UNFCCC treaties and global economic development, the former includes the installation of protected areas, legislation such as the Brazilian Forestry code, but also new planning for infrastructure such as roads and hydropower dams (AMAZALERT project, D2.4; Von Randow et al., 2014). An approach to a mitigation threshold consists of the combination of policies, measures and development, 'moving' towards preconditions where, according to analysis and model studies, impact thresholds become unavoidable. Even in policy and development, real thresholds could occur. This would be the case, for example, if mitigation is clearly becoming ineffective and would be abandoned, or if combating global food scarcity or other global crises would start overriding the interests of combating climate change and trigger enhanced deforestation. Therefore, as with all long-term scenarios, there is high uncertainty in this approach, which nevertheless should be tackled and provides 'sense of direction' to contemporary policy.

4.2 Regional climate forcing

Regional forcing of climate-induced degradation is mainly a function of changes in temperature, rainfall and seasonal variation in these (e.g., dry season length). Instead of rainfall, soil moisture change is a more direct forcing of forest degradation. The sensitivity of the region's forests is not the same everywhere, but depends on variables such as geographical position (e.g. distance to the coast or Andes mountains affects the sensitivity of rainfall to recycling rates) soils, vegetation type as well as atmospheric CO_2 concentrations (possibly affecting resilience). Considering these variables as independent indicators of forcing is problematical, however, because regional climate is affected by the state of the land surface itself through feedbacks. Therefore more independent indicators could be derived from the atmospheric conditions outside of the Amazon system, such as the moisture and heat inflow into the region. These would have to be monitored through sets of meteorological observations along the north-eastern coast of South-America combined with weather models. Regional temperature observation, despite its dependence on surface conditions, should definitely be part of a monitoring system, and considered a forcing variable, as it also impacts on human wellbeing in the region independently.

An example of a possible climate monitoring, applied to reduced forest productivity is given by Kay et al. (2014) (AMAZALERT deliverable D3.4). Here extreme events in historic data sets, such as the 2005 drought that caused widespread forest mortality, are used to calibrate a drought indicator, such as the 'monthly cumulative water deficit' (MCWD). This yields a quantified indicator where a MCWD threshold value can be defined that causes mortality similar to the 2005 drought. Projecting future or monitoring current MCWD across the Amazon basin could be used as an indicator of (projected) severe forest degradation.

4.3 Regional land-use forcing

Density and spatial patterns of forests and other land-use types affect evapotranspiration rates, radiation and atmospheric heat budgets. These in turn drive the hydrological cycle. Several monitoring systems for the state of the regional land use are in place in the region (see below). Next to total areas of deforested land, it is important to record the type of land-use that has replaced the forests, as well as their spatial patterns. Increasingly sophisticated methods are becoming available to monitor surface forest cover. For example, combinations of radar, optical and LIDAR remote sensing are enabling the observation of even very small-scale disturbance, road building, mining activities, etc. As these techniques in principle also can serve to assess biomass, they are discussed in a little more detail in the next section.

4.4 Impacts on the carbon budget

The mean state and variability in net ecosystem productivity and carbon budgets is observable in various ways. Firstly, biomass and NPP should be monitored directly, preferably through remote sensing methods (visual and radar), but also including surface flux towers and biomass inventories. Potentially, such variation in carbon uptake by the land surface can also be monitored through regional atmospheric CO2 concentrations, using the developing network of monitoring sites and atmospheric flow and inversion models (e.g. Gatti et al., 2014). New and upcoming multispectral remote sensing techniques need to be considered, that would enable the monitoring of photosynthetic activity (Fluorescence, Xantophyll band emissions, Frankenberg et al., 2011), or stress. Even if observations would be made from regular aircraft platforms rather than from satellites, such observations could add valuable and high time-resolution information on the vitality of vegetation.
Exciting new capabilities for monitoring basin-wide biomass and forest structure are under development using (so far, airborne) LIDAR techniques (Asner et al., 2010). These authors showed for a survey on Peru that carbon density can be mapped at 1.1 m horizontal resolution with an uncertainty of only about 11%, and forest height with an RMSE of less than 3.5 m. Slightly more established is mapping forest carbon proxies from radar remote sensing (SAR), also yielding very detailed information (Reiche et al., 2013, 2015). Figure 7 shows examples of these techniques and figure 8 provides an overview of available and planned space borne observation platforms for optical/RADAR remote sensing of forest cover.

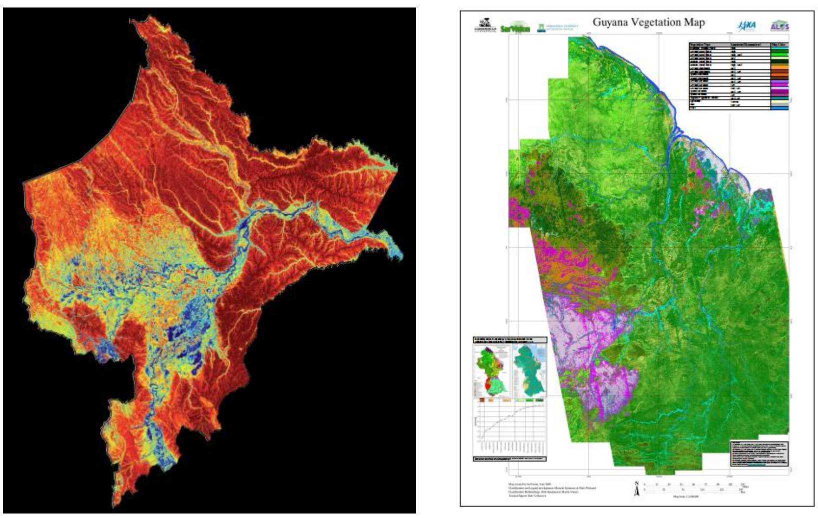


Figure 7 Examples of detailed forest cover and forest density maps generated by LIDAR (left: Peruvian Amazon, Asner et al., 2010) and SAR (right, Guyana, Sar-vision, Wageningen, unpublished)

The surface carbon budget is not only dependent on short-time productivity and soil processes, but also on longer-time scale processes, or short-term events with a long lag time such as mortality and decomposition of dead vegetation (Johnson et al., in prep; Verbeeck et al., 2014, AMAZALERT Deliverable D2.5). The key difference between changes in mortality and productivity is in the timescales of response, and the importance of extreme events. Mortality events are short-timescale effects, so are more dependent on and sensitive to extreme events, such as drought or extreme rainfall and storms. Increased mortality from sufficiently large fires could also cause large scale tree loss within a few years. This was shown by studying mortality and its legacy in dry years such as 2005 (Phillips et al., 2010), as was applied as a possible risk indicator by Kay et al (2014, see section 4.2). Mortality does not lead to immediate carbon emissions, as these depend on decomposition rates. Therefore, monitoring the ecosystem carbon budget alone does not provide the desired time resolution if the state of the vegetation is to be used as an early warning signal. In principle, severe mortality events should be detectable from remote sensing information. It will be important to quantify the severity (in climate, forest response and other impacts) accurately in extreme years. The importance of extreme events is emphasised by the asymmetry between mortality and regrowth timescales: timescales of any subsequent forest regrowth are much longer. This asymmetry, as pointed out by Meesters et al. (2015, in prep) poses limitations to the detectability of fluctuations in forest state for use as early warning signals.

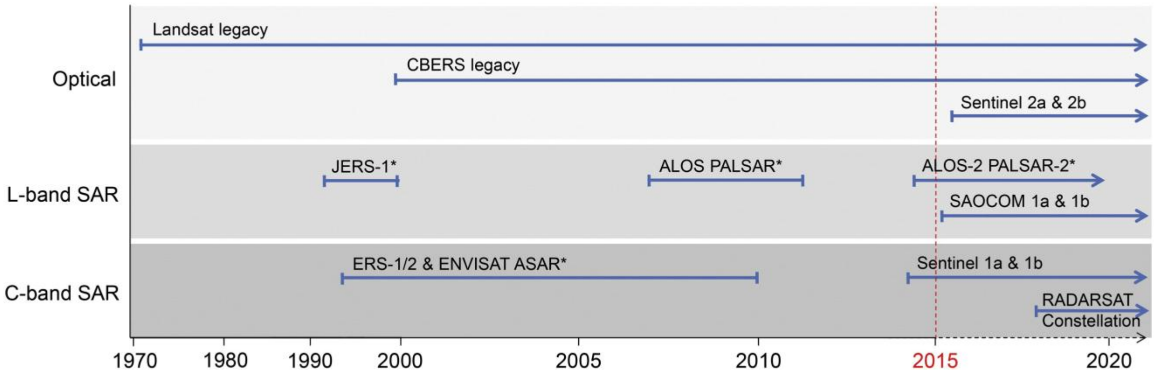


Figure 8 Current and anticipated medium resolution optical and SAR satellite missions selected by CEOS Space Data Coordination Group as core missions to provide time series data in support of worldwide forest mapping. Important missions with non-core status due to restricted data access policy in 2014 are denoted with an asterisk (copied from Reiche et al., 2015, as adapted from CEOS, 2014).

An important ecological variable is the condition of forest trees. Healthy evergreen trees can withstand defoliation from drought or herbivory, but each time its condition will decline, up to a point where they will not be able to recover anymore. Vitality can be monitored trough remote sensing (NDVI).

As an opposite to mortality, vitality of forests can be monitored, and recruitment and regrowth are crucial to the degree of reversibility of forest decline. It should be investigated whether specific monitoring of secondary regrowth forests is informative. This could be done using methodologies similar to those proposed for general forest productivity.

4.5 Impacts on and forcing by fire

The role of fire in critical transitions of the Amazon region is potentially large and fire indicators (magnitude, intensity and variability) should definitely be considered as indicators of change. Latest simulations with the HADGEM2-ES model project major increases in fire weather risk, and new coupled simulations in the Brazilian Earth System Model (BESM) also point out the important role of fire in the development of biomass over the 21st century (Betts et al., 2004; Cardoso et al., 2014; AMAZALERT Deliverable D3.3.; IPCC, 2014). Fire could have its own threshold, and it has been suggested that a threshold of fire size has already been crossed (Brando et al., 2014). The strength and exact mechanism of this effect is under debate, however (Good et al., 2015, in prep.). It is evident from this that the representation of fire dynamics needs to be greatly improved in vegetation models and coupled ES models.

Besides better representation in models, indicators of fire and fire risk should be monitored as part of early warning. Several techniques for region-wide fire monitoring on the basis of remote sensing are already in place. Monitoring fire risk would mean the monitoring of moisture levels in vegetation as well as fuel load (dead biomass and grasses) and its exposure (openness of vegetation). It is important to further develop techniques to distinguish agricultural and pastoral maintenance fires and actual forest fires.

4.6 Impacts on the hydrological cycle and energy balance

At the same time, variability in the hydrological exchange can be monitored: rainfall, evapotranspiration and soil moisture can be observed using combinations of surface measurements (flux towers, weather stations, rain gauge networks) and remote sensing. New techniques to monitor rainfall distribution patterns are under development, for example making use of short-wave radio signals transmitted in mobile phone networks (Leijnse et al., 2007). Since mobile phone networks have now proliferated deeply into Amazonia, this can provide extremely valuable high-resolution information. Meesters and Dolman (2015, in prep.) show in their simple model study that soil moisture appears central and among the most sensitive variables to forest degradation. Rainfall exclusion experiments, such as Nepstad et al. (2004, 2007); Da Costa et al. (2010) and Rowland et al. (in prep) can provide valuable information on the impact and time lags involved in drought effects. Studying past drought-mortality events such as the 2005 drought can also be used to quantify indicators (Kay et al., 2014). Large-scale and high-resolution (time, space) soil moisture mapping may be the most promising monitoring option for early warning. A promising new technique is under development that would enable large-scale monitoring of soil moisture status using cosmic neutron radiation (Zreda et al., 2012). Other relatively new techniques are those related to passive microwaves, i.e., radar remote sensing. Both techniques produce information on total moisture in soil plus vegetation rather than soils only. However, for the purpose of assessing fire risk and drought stress this might be more an advantage than a disadvantage. Regional discharge and river runoff can and is being observed in various hydrological monitoring networks. This variable, together with rainfall, is a more direct measure also of direct risks. Regional atmospheric moisture and energy budgets, for example inferred from frequent tower and aircraft measurements and satellite data can also contribute to assessing changes in the hydrological cycle. The regional energy balance, coupled to the hydrological cycle, entails variability in surface temperatures (which, for example, feedback to productivity) and heat transport (which is essential in the generation of rainfall (Marengo, 2004)).

4.7 Impacts on biodiversity

Drought exclusion studies (Da Costa et al., 2010; Nepstad et al., 2007) and studies in such LTER plots (Baker et al, in press) show that drought stress is likely to lead to shifts in species composition (favouring the more drought-resilient species). The same may hold for other types of stress, such as high-temperature stress and (and in combination with) effects of elevated CO_2. New experiments that are currently being established, such as Elevated CO_2 experiments (AMAZAON-FACE, Lapola et al., 2009; Tollefson, 2013) will shed more light on the processes as well as offer a monitoring site to detect climate-induced change. Thus shifts in composition can serve as sensitive indicators of change, if we understand the relationship between stress and species resilience. Ter Steege et al. (2006) show that a relatively small fraction of all species in Amazonia tend to dominate almost everywhere. Monitoring the dynamics of such species in observation plots is likely to provide consistent information on change across the basin. Several networks of Long-term ecological (LTER) monitoring exist in the Amazon (see below), which, combined with the rich information from biomass inventory plots very efficiently serve as a source of information on the dynamics of vegetation composition and vitality.

4.8 Impacts on and forcing by socio-economics

The socio-economic situation in Amazonia both drives and is impacted by changes and degradation in ecosystem services. These relationships have been extensively studied in AMAZALERT, through a series of stakeholder workshops, resulting in a set of scenarios driving land-use change. Thus, monitoring of some of the main drivers of land-use change should be part of an EWS. Conversely, forest degradation and breakdown of the hydrological cycle will also impact on the socio-economic situation. Therefore, indicators can be derived reflecting this impact.

Overall, there is a wealth of social, demographic, economic, institutional, health, etc. indicators that is being collected. In general, however, indicators are measured either infrequently, or at very long intervals. Also, they are usually based on interviews, samples, or otherwise not directly useful for monitoring purposes. Lastly, the spatial detail differs but is generally rather coarse.

An important prerequisite for any of the following variables to be included in a monitoring system would be to closely analyse the quality of the data and possibilities to increase frequency of measurement and/or sample and/or spatial detail. This holds particularly for social and institutional variables, and only to a lesser extent for economic variables.

Economic:
In general, a wealth of information is available to monitor the (changes in) economic values of sectors that are exploiting the natural resources in the Amazon, importantly agriculture, forestry, and mining. In addition, concrete indicators could be:

- GVA Agriculture (% of total GDP) – to monitor the contribution of agriculture in total GDP.
- GVA Forestry (% of total GDP) – to monitor the contribution of forestry in total GDP
- National and Foreign direct investments in large infrastructure plans, roads, water, gas/oil (USD) – to monitor foreign investment and interest in further exploitation of the Amazon
- Inflation rate (%) – to monitor the strength of Brazilian Real and thus of potential for export increase
- Export of Amazon products (USD value of soy, milk, beef, etc.) – to monitor pressure on Amazon forests
- Payment of Ecosystem Services (% of total income) – to monitor the potential economic effect of PES.

Social, institutional:

- Rural/urban population growth (persons) - to monitor rural exodus.
- Household size (persons) – to monitor family size and therefore family needs
- Labour force (persons) – to monitor manual labour as opposed to mechanisation and intensification
- Legal structure and property rights (% of municipalities that have cadastre complete) – to monitor degree to which land ownership is officially documented.
- Control of corruption index (-) – to monitor degree to which corruption and thus illegal activities change
- Crime rates (number) – to monitor illegal activities
- Rate of literacy (% of population above 18) – to monitor education
- School enrolment (% of population below 18) – to monitor education
- Gini coefficient – to measure inequality
- Percentage of people below poverty line (% of total population) – to monitor income distribution as well as people without options to conserve forests
- Child mortality (% of total births) and other health indicators – to monitor health aspects of quality of life
- Involvement of civic society (membership of NGOs; sports clubs etc.) – to monitor overall social capital; often used as one of the proxies for ‘happiness’.

Overall, this list includes many crucial, slow variables that are often considered steering transitions and determining tipping elements. If social and human capital degrade, there will be less basic support for sustainable policy making, a new economic model, and/or investments of ecosystem services. Particularly when e.g. national policies and foreign investments can mask the lack of local/national support, the decrease of social capital indicators can lead to a potential tipping point towards strongly accelerated deforestation. Many variables are either indirect or composite indices of parameters that need to be monitored. As such, it will need (much) more discussion.

5. Robustness of an EWS

In operating an early warning system (EWS) it is important to specify and communicate uncertainties as precise as possible. Here we briefly list the various sources of error in projected critical transitions and the causes of such uncertainty.

5.1 Effective model validation

A key question in applying an EWS is, how do observations really relate to model output? What is of importance here is whether models successfully represent observed variability, especially in conditions where tipping points are approached. First of all, as already mentioned before, output of coupled models can be used to test and tune an EWS, if the output contains known tipping points. Second, an operational EWS should contain a component where the network of observations is regularly compared with the models used, so that models and parameters can be adjusted or even assimilated against data.

5.2 Natural internal variability.

This is probably the easiest issue to handle. It would lead to uncertainty in estimates of threshold proximity. Internal variability can also cause a threshold to be crossed (noise-induced tipping). Clearly there is substantial random variability in the type of extreme event that could cause this. Nevertheless, also a threshold crossed as a consequence of natural variability is important to detect. The natural variability itself cannot be controlled, but mitigation actions can in principle aim at reducing the risk that thresholds will be crossed.

5.3 Uncertainty in future evolution of natural forcings

Natural forcing may change, gradually, or episodically, such as through eruptions of large volcanoes. The latter could for example shift the ITCZ and affect Amazon rainfall for prolonged periods, possibly triggering other tipping points. Of course, a volcanic eruption is something not going unnoticed and its consequences could probably be forecasted reasonably well. On the other hand, an eruption itself is almost impossible to forecast.

5.4 Limited physical understanding

Any EWS plan should attempt to build robustness to our lack of understanding. This includes both the design of the EWS and how it is tested. This uncertainty includes both fundamental lack of understanding and known limitations in model simulations. Several issues of both categories are addressed in AMAZALERT, but not all and uncertainty will always remain, persisting in any design of an EWS. Applying statistical methods (Chris Boulton, pers. Comm.), where a range of forcing variables is always used in modelling, represent one approach, but there are questions about how effective they might be. They still require understanding: one has to decide what to monitor and attempt to interpret any apparent slowing down signal. One effect can have a variety of causes. For example, reduced biomass can be a consequence of enhanced mortality or of reduced productivity, mortality can be caused by fire, drought or even heat stress.

6. Relevant Existing Monitoring Systems

Brazil already has different monitoring systems that were established in the Amazon region, which provide monthly or annual assessments of rates of deforestation, forest degradation are fire activities, and state of hydrological and meteorological conditions throughout the region.

One example of such system is the 'Hydrological Monitoring of Occidental Amazonia', operated by the Brazilian Geological Service (CPRM), supported by hydrometeorological, telemetric, water quality and sediment stations operated by the National Agency of Waters (ANA, 'Agencia Nacional de Águas'). Since 2007, CPRM issues monthly detailed reports of the state of the river levels and analyses of proximity to exceptional flood or drought conditions. The process is based on the monitoring of water level variations of many strategic river stations (figure 9). The products of this activity allows government bodies of civil defence to take precautionary actions to avoid or minimize impacts related to extreme hydrological events.

Monitoring of meteorological data is still very sparse in Amazonia. The agency SIPAM summarises rainfall radar data and rainfall station data (sosamazonia.sipam.gov.br), together with the Brazilian meteorological service INMET and UEA, the state university of Amazonas. Further meteorology data, however, are even sparser and information on (soil) moisture is absent, except for a handful of research stations operated within the LBA programme (lba.inpa.gov.br). At the LBA towers (most complete data are from Manaus-K34 tower and Tapajos-K67 tower but more are available), usually a full set of meteorological data is collected as well as high-time resolution data on water, energy and CO_2 exchange between the forests and the atmosphere. Currently, a large initiative is under development, to establish continuous, high-quality observations on atmospheric concentrations of many gases and aerosols, as well as forest-atmosphere exchange, north of Manaus (ATTO initiative, the Amazon Tall Tower Observatory).

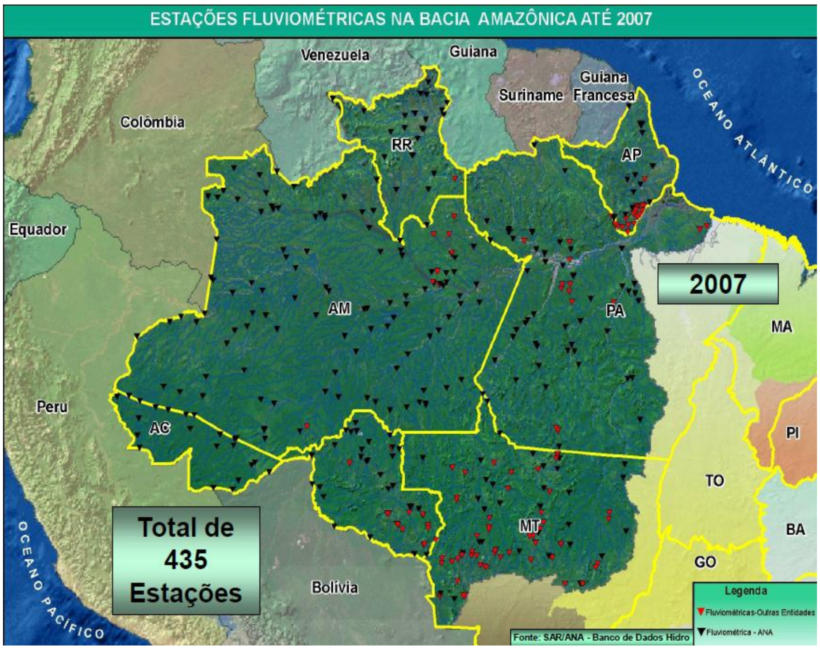


Figure 9 The river gauging network of ANA (black triangles) and associates (red triangles)

One particular program aiming as a conservation policy effort launched in mid 2000s, using satellite imaging to monitor deforestation on state and municipal levels, was a pivotal program to increase law enforcement in Brazil and produce a 70% decline in deforestation in the Brazilian Amazon in the past 10 years: the Action Plan for Prevention and Control of Deforestation in the Legal Amazon (PPCDAm). Launched in 2004, this tactical-operational plan integrated actions across different government institutions and proposed novel procedures for monitoring, environmental control, and territorial management.

The use of the Real-Time System for Detection of Deforestation (DETER) was a key change introduced by the PPCDAm program, which linked the detection of deforestation events by government agencies using data from the MODIS satellite sensor with policing activities of the federal and state environmental enforcement agencies. Developed by the National Institute for Space Research (INPE), DETER is a satellite-based system that captures and processes georeferenced imagery on forest cover in 15-day intervals. These images are used to identify deforestation hot spots and issue alerts signalling areas in need of immediate attention.

The Brazilian Institute for the Environment and Renewable Natural Resources (Ibama), which operates as the national environmental police and law enforcement authority, targets law enforcement activities in the Amazon based on these alerts. Prior to the activation of DETER, Amazon monitoring depended on voluntary reports of threatened areas, making it difficult for Ibama to locate and access deforestation hot spots in a timely manner. With the adoption of the new remote sensing system, however, Ibama was able to better identify, more closely monitor, and more quickly act upon areas with illegal deforestation activity.
In addition to the adoption of DETER, PPCDAm promoted institutional changes that enhanced monitoring and law enforcement capacity in the Amazon. These changes increased the number and qualification of law enforcement personnel, and brought greater regulatory stability to the investigation of environmental crimes and application of sanctions. Overall, the command and control framework established by the PPCDAm, which relied heavily on satellite data, represented both an improvement in the targeting and an increase in the intensity of monitoring and law enforcement activities in the Amazon.

INPE has a program of Remote Sensing of Amazonia that includes four operational complimentary systems: PRODES, DETER, DEGRAD and QUEIMADAS (fires). PRODES is operated since 1988 and estimates annual rates of clear-cut deforestation, when there is full removal of forest cover in areas higher than 6.25 ha. A drawback of PRODES is that it does not detect partial degradation of forest resulting for example from fires or selective logging.

Since PRODES data were not sufficient to fully assist governmental actions of prevention and surveillance, due to the time scale that it is produced and to only include clear cutting detection, the DETER system was developed, with the objective of including both clear cut deforestation actions and forest degradation. This system provides the location and approximate dimensions of new occurrences of vegetation cover change compared to a previous image. To get higher temporal frequency in its assessment, DETER uses satellites that cover the Amazon region with higher frequency, but which images have a lower spatial resolution. As a consequence, DETER assessments of deforestation amounts are less accurate than PRODES.

Still, part of the DETER initiative was also developed to detect different stages and patterns of forest degradation, originating in a new product, the DEGRAD system. This is a new system, started in 2008, mapping areas that are not fully deforested, but using techniques of image processing in two consecutive images, show signs of forest degradation and trends towards clear cut deforestation, as illustrated in figures 10 and 11.

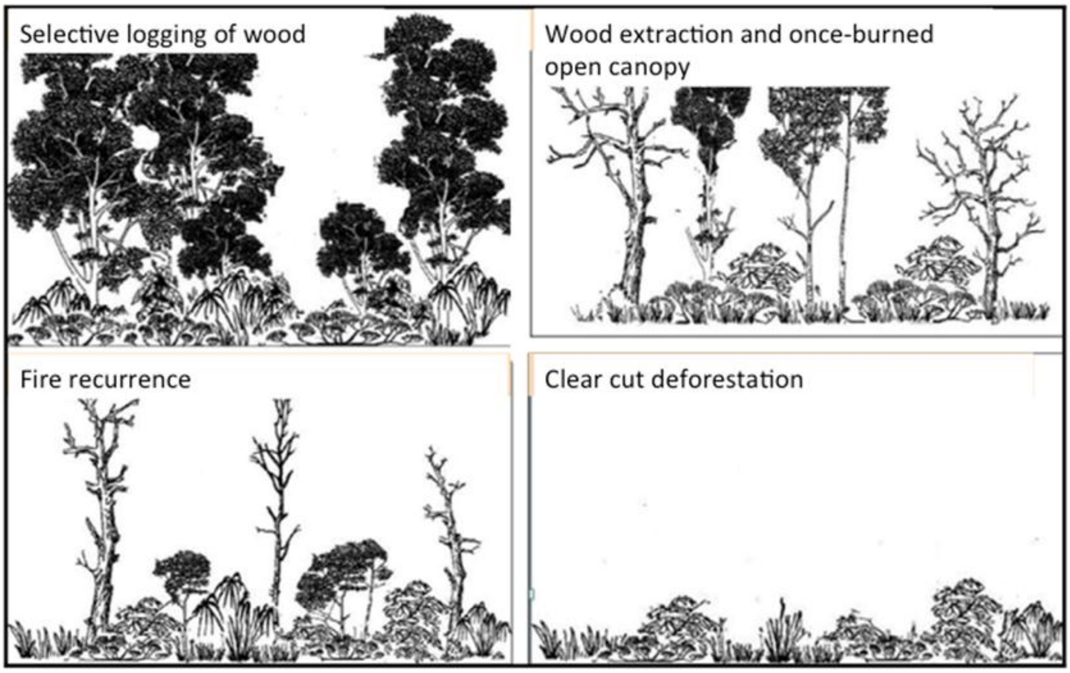


Figure 10 Illustration of sequential degradation of repeatedly burned forest in Amazonia. Adapted from Barlow and Peres (2008).

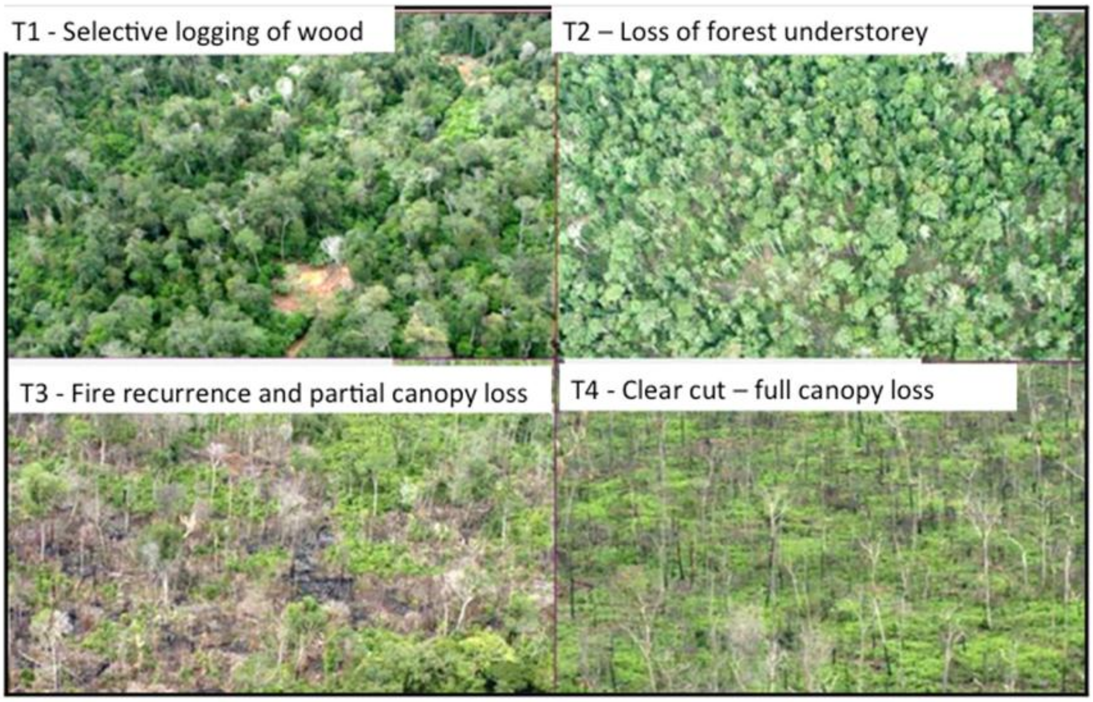


Figure 11 Photography of the different stages of forest degradation monitored by INPE's PRODES / DETER / DEGRAD systems.

Additionally, Brazil also maintains, since 1985, a monitoring system of fires in the whole continent, based on INPE's fire detection algorithms that identify heat sources in satellite images of low resolution, like the ones from NOAA, GOES, TERRA, AQUA and METEOSAT satellites. All results and reports from the fire monitoring system QUEIMADAS is publicly available in the portal http://queimadas.inpe.br, which includes the operational fire activity monitoring at 3-hourly intervals and prediction of fire risk in the vegetation.

Motivated by the conservation efforts of the PPCDAm program, the new Brazilian Forest Code, was approved and signed into law in 2012, with important features that could help integrate governmental and voluntary interventions in Amazon degradation dynamics. One key feature established in the new law is the requirement that every rural property should be registered in a national Rural Environmental Registry system (CAR, 'Cadastro Ambiental Rural'), describing in detail its land boundaries and land use. The CAR sidesteps the ongoing challenges to full land titling that plague large areas of the Amazon region, as it requires landholders to self-report their property boundaries and focuses instead upon land occupation and georeferenced property boundary databases that facilitate satellite-based monitoring (Nepstad et al., 2014). Integrating the information provided by landholders in the CAR system, the Ministry of Environment is now developing a set of online tools (www.car.gov.br) that automatically alerts whether or not there is need to recover areas of permanent protection (APP) or legal reserves.

In contrast to monitoring environmental variables, there are several important initiatives for basin-wide monitoring and analysis of the dynamics in biomass, biodiversity and associated functionality of the forests. A prime example is the RAINFOR network of biomass plots, representing all of Amazonia (www.rainfor.org, figure 12) The network consists of many plots, some of them with single inventories of above-ground biomass, but with an increasing number of them re-inventoried to determine mean NPP. The network is currently expanding its data collection into other type of functionality data.

In parallel, the Brazilian PPbio network (ppbio.inpa.gov.br), starting in the reserva Ducke near Manaus, AM, is rapidly developing. This network aims to monitor sets of key species (plants as well as animals) along transects, to characterize changes in biodiversity. The network is currently expanding the number of monitoring sites in Amazonia and intensifying collaboration with the RAINFOR network. Landmark biodiversity inventories have been made by Ter Steege et al., (2013, the Amazon Tree Diversity Network (ATDN, http://web.science.uu.nl/Amazon/ATDN/), figure 12).

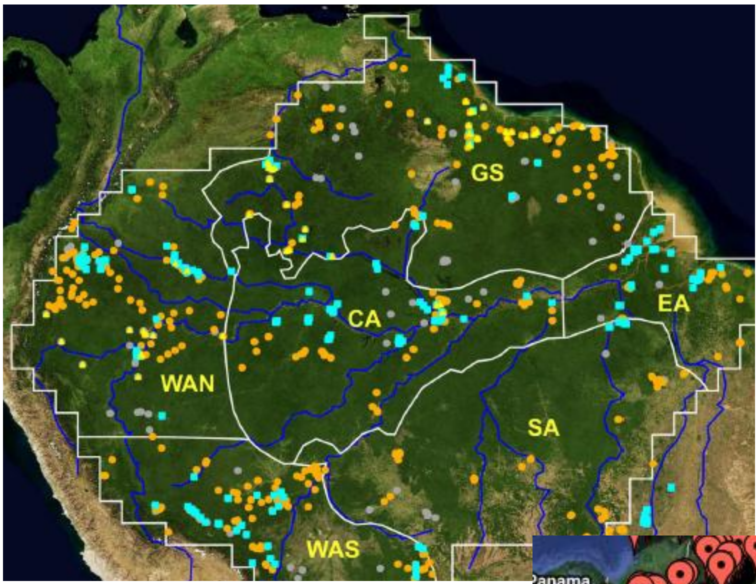


Figure 12 Maps showing the biodiversity sampling network used in Ter Steege et al., 2013 (top, colours refer to landscape type sampled) and the RAINFOR biomass plots network (right, colours refer to sampling frequency, yellow sampled only once).

7. Stakeholder consultations

Selected stakeholders (Appendix, Table 2) have been consulted during two different workshops: first in November, 2013, in Brasilia, and second in October, 2014, in Belem. During those workshops, followed by a questionnaire by e-mail, stakeholders were asked for their opinions on 1) priorities for ecosystem services that need to be monitored; 2) Institutional embedding (who should operate an EWS, who are the users and which institutions can formulate response policies?) and 3) ways to communicate warnings if/when they arise. The results of this enquiry can be summarised as follows.

7.1 Opinions about target ecosystem services (see also AMAZALERT D1.4)

Carbon storage was mentioned frequently, but the hydrological cycle, linked to atmospheric water transport on the continent and hydropower was more prominent. Biodiversity is generally mentioned, as such and in relation to forest resilience and extraction of fish, wood and forest products. Stakeholders value the role of Amazonia in maintaining a favourable climate. The maintenance of nutrient cycles by the forests is also mentioned, as well as the prevention of erosion.

7.2 Opinions about monitoring

An overview of stakeholders' opinions on Ecosystem services and monitoring is given in the Appendix, Table 3. An overriding opinion on monitoring systems was, that many monitoring systems already exist in Brazil. These are outlined in detail in section 5. The main task for an EWS should be to bring them together and build long-term data base, while mainly providing the analysis methodology and, where necessary, promoting a few complementary monitoring systems. Most monitoring targets that have been described in section 4 were also mentioned by stakeholders.

Although the most prominent advice was to create an EWS that integrates all available monitoring systems, several stakeholders advised to focus on a few target ecosystem services and the monitoring that is needed for it. Also there was clear advice to provide regional-scale detail.

The last stakeholders meeting was combined with presentation of the FP7-ROBIN project. This project is developing an 'Ecosystem integrity' index which combines multiple data sources characterising the state of biomass carbon and biodiversity.

7.3 Involvement of institutions

Many of the relevant institutions were mentioned as potentially suitable to host an EWS, from all sectors: governmental, services, scientific and NGO (Appendix, table 4). Also most of these institutions were mentioned as potential users of an EWS and implementers of response policies.

In the second meeting, however the consensus opinion was that there should not be one single agency hosting and executing an EWS for Amazonia. Rather, such a system should be a community effort, where most of the relevant monitoring systems, active institutions and user communities should collaborate to bring together the relevant data and warnings, according to stakeholders. There was no further opinion on which institution should co-ordinate such an effort.

7.4 Communication

The stakeholders suggested many ways to communicate warnings, but most of them refer to public accessibility of the information, and with some, informing government (Appendix, Table 4). This opinion was clearly reiterated at the second workshop.

Several means of communication were suggested. A publically accessible data base with a transparent portal should be the basis, and alerts could be communicated through email lists accompanied by reports and press releases. Workshops and seminars, as well as internet communication groups should serve to share results and status of Amazonia at a regular basis. Specific working groups could be set up to focus on specific regions within Amazonia.

As far as government is concerned, all government agencies should be informed, including the parliament.

8. Outline of an Early Warning System for critical transitions in Amazonia

Previous sections of this report set out the concepts and methodologies to provide early warning in a systematic way, discussing analysis methods, ways to define thresholds and indicators and approaches to monitoring. We also discussed the state of the art in Amazonian monitoring systems and views of a Brazilian stakeholder community (institutional, industry and NGO representatives) on priorities for monitoring. Based on this, it is now possible to propose an outline for an Early Warning System for critical transitions in Amazonia.

8.1 Structure of an EWS

A systematic, stepwise approach is proposed, first identifying the problem, the associated causes and thresholds, then the nature of likely transitions related to the problem, and finally planning and implementing monitoring systems.

Step 1: *identify the ecosystem service of concern and identify their forcing and thresholds.*
In the case of Amazonia, the impacted ecosystem *services* are multiple but mostly boiling down to the presence of forest biomass, the water cycle and biodiversity. An EWS for critical transitions in Amazonia typically warns for long-term risk of transitions. Therefore, both modelling and projection of transitions should be based upon on long-term data and long-term models. Thus, delayed forcing by climate change or land-use change should also be considered, and in this case the effective forcing's are embodied in policies.

The likely *forcing* of transitions will come from changes in mean temperature and mean as well as extremes in regional moisture transport. The sensitivity to these forcing's is a function of atmospheric CO_2 concentration, the remaining forest fraction and fire risk.

Thresholds should be defined in two ways. First, society (ultimately, government) needs to define the maximum level of acceptance of change in derived ecosystem services, such as carbon storage needed, rainfall/soil moisture levels, river regime lows and highs, and biodiversity. Subsequently, science should translate and further tune these thresholds by identifying the critical levels in forcing variables, taking into account the type of transition expected.

AMAZALERT did not result in detailed guidance on the critical levels for such thresholds. The modelling studies did show forest decline in response to extreme climate change, especially in the south-east of Amazonia. However, these scenario studies are not suitable to derive threshold (or 'critical') values, because the differences in forcing are discontinuous. Moreover, critical values that would be derived from such model studies would merely reflect the assumptions and parameter settings in the models, rather than show novel insight. AMAZALERT did generate new information relating to temperature thresholds, showing that forest productivity may be less sensitive to high temperatures than assumed in many models. The implication of this would be that high temperature thresholds are more likely between 35 and 40°C than in the lower thirties.

In general it can be stated that forests become vulnerable to drought and fire-induced decline if soil moisture drops below about 0.75% of field capacity (Nepstad et al., 2004), and can be assumed resilient to fire as long as precipitation is more than 1.2 times potential evapotranspiration (Hirota et al., 2010).

There is a clear need to systematically investigate threshold values observed in both models and data sets, and to assess the information from experimental studies such as rainfall exclusion experiments (Nepstad et al., 2004; Da Costa et al., 2010).

Step 2: *identify the transition process and associated need for analysis tools and procedures*
The type of transition is important when defining the monitoring and analysis procedures needed. If a gradual transition is expected that is (near-)linearly responding to forcing, then the transition is well-

predictable. However, the transition can still be difficult to mitigate. Monitoring the impact on the ecosystem service of concern needs to be done, but is not enough. The forcing needs to be monitored as well, preferably long in advance. As stated above, it are the policies that lead to long-term change that need to be monitored, and global as well as regional climate change and land-use change models should be used to project the impact of certain sets of policies. In the case of Amazonia, global climate policies and mitigation measures should be regularly analysed and their consequences, specifically for Amazonian climate, specified. Similarly, land-use policies should be evaluated for their long-term effects on land-use patterns. This is a process similar to the IPPC regional impact studies (IPCC, 2014, WGII AR5, Chapter 27 for Latin America). An alert should be issued if the projected regional forcing variables exceed critical levels.

AMAZALERT analysed in detail the current set of IPPC scenarios and their consequences for Amazonia (Kay et al., 2014, AMAZALERT D3.4) but could not detect 'critical transitions' in scenarios and associated policies, as even in the most severe scenario, change in forests was rather moderate.

If the transition of concern responding to forcing in a (strongly) non-linear way, it is even more important to project long-term change in forcing as a result of policies, just like in the preceding case. But here, direct monitoring of impacts, even though still necessary, is less effective since generally mitigation will be very hard when change is first detected. In the case of such non-linear transitions, modelling the effect of the regional environment and land-use patterns on impact is indispensable, as it is the only way to forecast highly non-linear change. It has to be realised that the ecosystem will never be in equilibrium and usually lagging behind, leading to high variability and imposing the need for conservative alert thresholds. In the case of Amazonia, the sensitivity of the hydrological cycle to global climate and regional land-use patterns need to be modelled and better understood, as well as the sensitivity of forest biomass, productivity, recruitment and mortality to soil moisture, in the context of prevailing temperatures and CO_2 concentrations and accounting for fire feed-back. Modelling these sensitivities has been implicit in AMAZALERT modelling of climate effects, extreme climate and land-use scenarios affected Amazonia, especially in the south-east, but model results are not sufficient to further define such thresholds.

If the transition is extremely non-linear, to an extent that discontinuities (tipping points) are likely, then even modelling the impact is of limited value, as the transition becomes unpredictable. In this case, both long-term and short-term response projections should focus on the change in and effects of extremes, as these can tip the system across discontinuities. Projections should also concern the mean state of the forcing and ecosystems, and in that case detect when the system becomes unstable. As discussed in section 2.3, such unstable ecosystems are predicted to show high variability and slower fluctuations, but these usually show up too late to enable mitigation. Advanced statistical analysis is necessary to identify early warning signals in this variability, where research should focus on finding ways to detect changes in autocorrelation as soon as possible. To warn for this type of critical transitions, monitoring should also focus on extremes, variability and periodicity (autocorrelation), in the impacted variable but primarily in forcing and expected long-term climate.

For Amazonia, the same processes, at similar long and short time scale should be modelled and monitored as in the previous case. However, important additional indicators are interannual variability in rainfall, moisture transport and their seasonal variability, temperature and their direct impacts such as fire intensity and extent, forest productivity, regeneration and mortality. AMAZALERT did not detect this type of critical transitions in its modelling studies.

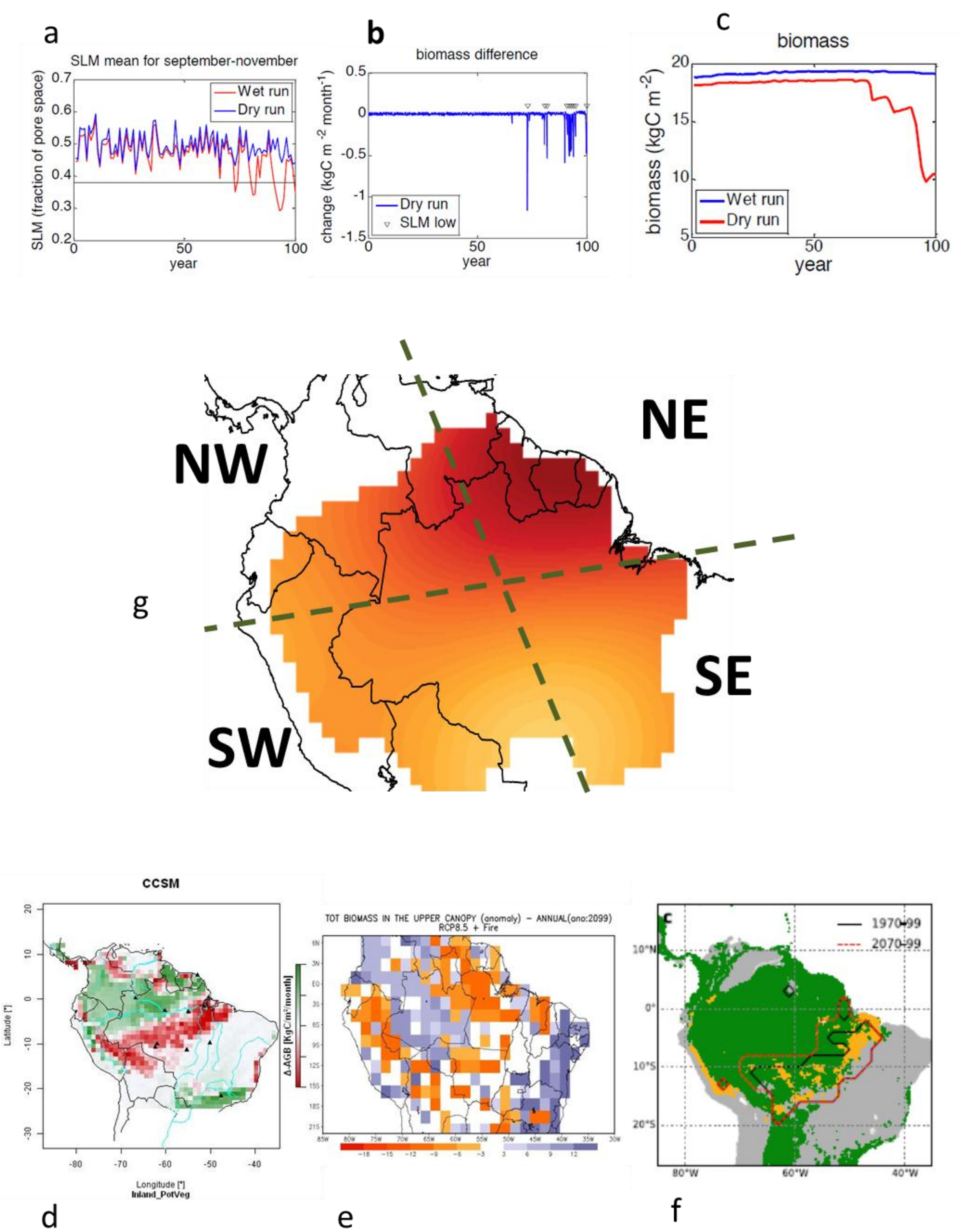


Figure 13 summary of AMAZALERT results leading to advice on monitoring in the basin. a),b), c): results from zero-dimensional modelling (Meesters et al, in prep) showing that soil moisture (a) is likely to be the most sensitive parameter associated with biomass degradation (changes in b, totals in c); c),d), e): simulations with DGVM (a) showing climate change effect alone on biomass, uncertain combined effects of land-use, climate and fire (e) and simulated likely change of dry-season length. Finally, g) shows a rough indication of four zones in Amazonia where one can assume different priorities for monitoring. Underlying colour code is interpolated biomass.

Step 3: *bring together existing and new implement monitoring systems*
From the analysis of the most likely critical transitions in Amazonia, it is clear that the most urgent variables for monitoring are those relating to moisture transport and soil moisture in the basin, and those relating to the dynamics of biomass, fire, and biodiversity.

Figure 13 shows an attempt to summarise insights from the AMAZALERT project that may help identify regional priorities for monitoring. First of all, modelling suggests that soil moisture in one of the most sensitive and most direct parameters related to degradation of biomass. Secondly, the various model simulations performed in AMAZALERT indicate: 1) high risk of degradation in the SE of Amazonia, because of the combination of land-use change risk and climate; 2) high uncertainty about both climate change and fire susceptibility in the NE (i.e., Northern state of Para, and Guianas); 3) a robust climate and forests in the NW; and 4) a yet relatively undisturbed but very sensitive SW, which is at the same time essential for moisture recycling to the south of the continent. This suggests that more intensive monitoring is especially needed in the NE (particularly N Para state) and the SW (particularly S. Amazonas state, Acre, S. Peru and N Bolivia). Rainfall monitoring should be intensified also in the NW, whereas in the SE, a strong focus should be on shorter-term forecasting and adaptation to change.

The inventory of existing and planned monitoring shows that there are already extensive systems monitoring land-use change, biomass and biodiversity, and that the river discharge monitoring network is also well developed. There are several initiatives to monitor and warn for fire and fire risk. This does not mean that these variables do not need any more attention, but to the contrary, there are excellent grounds to expand and improve these networks, where technology is tested.

Perhaps surprisingly, there are still caveats in monitoring of physical forcing variables: the existing monitoring networks for reliable meteorology and precipitation are still sparse and mainly used to support short-term weather prediction. Routine data on atmospheric moisture transport (inflow from the Atlantic ocean, transport within the Amazon) are almost absent and soil moisture data, the variable that affects productivity most directly, are all but absent.

For an EWS, long-term trends need to be analysed, thus long-term data are required. Of all relevant existing data sets, the responsible agency that hosts the EWS should promote that data sets are brought together in a harmonised and accessible manner, or are publicly available in an accessible format. The likelihood of success of such a data base is high, because most stakeholders expressed their preference for this. New, complementary monitoring sets need to be installed, preferably managed by agencies that already operate other monitoring systems.

Therefore, we propose the following list of existing and new monitoring, based upon the more elaborate and systematic treatment in section 4 of this report.

Monitoring of long-term policy impact, through analysing regular updates of climate change mitigation policies and –plans as well as land-use change policies. The long-term consequences for Amazonia of these policies should be projected, using procedures similar to the IPCC CMIP processes (e.g., Brovkin et al., 2013) but simplified to using only a subset of models that represent the spread of all global climate models and regional land-use models.

Monitoring regional climate, the hydrological cycle and energy balance, analysing trends and variability based upon a sufficiently dense network of weather observations, rainfall gauges and river discharge data. As discussed, especially the meteorological observation network in Amazonia needs expanding and improving. Reliable data on temperature and atmospheric moisture are needed, as well as wind data, not only to better quantify warming trends but also to enable the quantification of heat and moisture transport across the basin. The moisture input from the Atlantic ocean should be quantified. Combinations of surface stations and airborne or remote observations should serve this aim. Rainfall monitoring should aim to combine standard gauge networks with airport radar and other novel techniques. Soil moisture appears to be the central variable of interest. Although ground stations should be used for calibration, this is best monitored basin-wide using a variety of novel remote sensing techniques. The runoff gauge network by ANA is already in place, and efforts should concentrate on integration and standardisation. Also here novel remote sensing techniques have potential.

Monitoring fire risk and fire incidence is already well developed in several sub regions of Amazonia, to warn for short-term risk. Monitoring fire incidence is already possible mainly through remote sensing techniques. It is important to distinguish natural and anthropogenic fires. To monitor fire risk, the moisture content of vegetation and soil as well as the fuel load are important. While the former can be obtained from the moisture monitoring discussed in the previous paragraph, monitoring fuel load should be part of biomass monitoring (next paragraph), where fractions of mortality, dead material and grasses should be made explicit.

Dynamics of the carbon budget is already being monitored by several consortia, in several ways. Methods range from networks of biomass plots, via novel remote sensing techniques, to atmospheric inversion analysis. It is important to not only monitor biomass, but also its composition in dead and alive material and in ecological groups, especially woody and herbaceous. Furthermore, dynamical parameters are essential, such as recruitment, regeneration, productivity, mortality and decomposition. The main challenge for an Amazonian early warning system would be to ensure that these additional variables are monitored as well as, standardisation and continued accessibility of data.

Regional land-use is, like the carbon budget, already well-monitored and again, new and improved techniques are being developed regularly. It is important to not only monitor deforestation, but also to qualify the type of land use. Again, for an early warning system, it is important to standardise data and ensure accessibility. Linked to land-use data, sets of other socio-economic data can be collected as well as information on other industrial activity such as mining and hydropower.

Regeneration capacity, as a more integrated indicator, could be monitored basin-wide by combining biomass and land-use monitoring, focusing on natural regeneration areas. The rate of regeneration is a measure of resilience in the Amazonian biome.

Biodiversity monitoring networks are, again, already fairly well-established or under development, often linked to the consortia monitoring biomass and vegetation. The same applies here for the early warning system as in the previous two paragraphs. An additional indicator that could be pursued for monitoring would be a measure for connectivity, fragmentation patterns, and large-scale diversity. At the analysis side, the challenge here is to establish clear links between trends in biodiversity indices and forest vitality, or stability.

Integrated ecosystem functioning should be monitored in a small set of 'sentinel' (or: 'canary in the coal pit') sites. At such sites, preferably already part of existing networks (biomass, biodiversity, ecophysiology, long-term ecological observation sites (LTER)), the flows of carbon and water, vegetation dynamics, species composition, and stress factors should be monitored in an integrated way. If possible, other parameters and processes should be taken into account, such as those related to nutrient cycling and atmospheric chemistry, aerosols, etc. This enables the quantification of interactions between the variables observed for the EWS and the use of those interactions as additional indicators of change. At the same time, such sites would serve to develop and test new theory and model implementations. The location of these sits should be chosen with care, to represent the whole of Amazonia, with emphasis on the more vulnerable south-east, but also including central Amazonia, the more fertile south-west, the Guianas and the wet north-west. Several of such initiatives already exist within networks such as the large-scale biosphere-atmosphere experiment in Amazonia (LBA), and the proposed network of sentinel sites should be built upon these as much as possible.

Socio-economic forcing's and impacts
There are many economic indicators that can be measured and could be monitored. Indicators will mostly provide information on short-term or medium-term changes in pressure on the Amazon forests through economic exploitation of its resources. Likewise, there are many social, demographic and institutional indicators that could be measured at least indirectly and that could then be monitored. Social indicators will mostly provide information on slow, long-term changes. Within tipping point concepts, understanding slow variables is essential in understanding when tipping points might occur. Thus, arguably it is essential that particularly social indicators are included in the Early Warning System to monitor long-term trends in e.g. poverty, crime, education, and health. A list of important indicators is given here:

- Rural/urban population growth (persons) - to monitor rural exodus.
- Household size (persons) – to monitor family size and therefore family needs

- Labour force (persons) – to monitor manual labour as opposed to mechanisation and intensification
- Legal structure and property rights (% of municipalities that have cadastre complete) – to monitor degree to which land ownership is officially documented.
- Control of corruption index (-) – to monitor degree to which corruption and thus illegal activities change
- Crime rates (number) – to monitor illegal activities
- Rate of literacy (% of population above 18) – to monitor education
- School enrolment (% of population below 18) – to monitor education
- Gini coefficient – to measure inequality
- Percentage of people below poverty line (% of total population) – to monitor income distribution as well as people without options to conserve forests
- Child mortality (% of total births) and other health indicators – to monitor health aspects of quality of life
- Involvement of civic society (membership of NGOs; sports clubs etc.) – to monitor overall social capital; often used as one of the proxies for 'happiness'.

Step 4*: report and communicate warnings, advice on measures*
In planning an early warning system, also the means and users of communicated alerts should be provided for, as well as at least the beginning of policy response strategies. Even though it should be up to independent policy makers and government to decide on policy response, it is useful to focus on issuing warnings that can be responded to.

On reporting and communication, the feedback by stakeholders was quite clear. Reporting should be done for a broad audience, through web portals, regular bulletins and newsletters, and technical reports to all levels of government and institutions. Scientific results should be published in the international literature. Also, regular seminars and workshops, including all stakeholders in monitoring and policy, should be organised. In case of increasing alert levels, special task forces should be considered.

Early warning signals and tipping points are associated with large uncertainty, non-linear behaviour and potentially high impact. The combination of these makes communication very difficult: uncertainty causes indifference, non-linear behaviour goes against normal human perception and high impact with high uncertainty carries the risk of being accused of doomsday prophecy, discrediting the science community especially if an EWS it is perceived to 'get it wrong'. One thing to make clear is that an EWS can only warn in terms of increased risks and changing probabilities. A suggestion made through the community (P. Good, Pers. Comm, based upon a UK government meeting in London, March 2011) was to actively think of the kind of metaphors that could be used in communicating such risks.

The type of policy response depends on the ecosystem service that is most threatened. In almost all cases, contributing to limiting global climate change and regional deforestation is necessary. Generally measures split into mitigation (including both global emissions and regional activity, such as fire) and adaptation. The plausible policy actions would be different for different types of early warning.
- First, the possible action depends on the type of threshold, or whether there are thresholds at all instead of gradual transitions. If there is still resilience in the ecosystem service at threat, then aggressive mitigation, moving the system back from the threshold, could be effective whereas if the tipping point is already inevitable, adaptation measures are needed. In case of gradual transitions, setting limits to further change could be sufficient.
- Second, it is important to consider what can and what cannot be controlled. Emissions of greenhouse gases, deforestation, fires, water use, etcetera, can in principle be controlled whereas global climate and regional moisture recycling cannot.
- Third, the time scale of the predicted threshold change is important for deciding on the scale and sustainability of policy actions.

Where *carbon storage* is concerned, policy would have to be targeting enhancement of conservation in high-biomass ecosystems, fire protection, agricultural planning that stimulates low emissions and high storage, such as no tillage crops, bioenergy crops, agroforestry and timber.

The conservation of carbon stocks can be part of specific climate change mitigation mechanisms such as UNFCCC-REDD+ . In this case, the feasibility and permanence, i.e., value of investments in REDD projects can be affected by projected climate-induced losses in carbon stocks, or in case of REDD+, associated loss in biodiversity and other ecosystem services. Thus, the design and valuation of REDD measures and projects should include early warning systems at long time scales: such as analysis of policies and their implications.

If the *water cycle* is threatened, focus should be on optimising the water recycling through remaining forest and replacement land-use, as well as on adaptation to droughts as well as floods. This includes strategic spatial planning of forest reserves or forestry and crops with high water demand and low albedo (reflectivity, i.e. dark crops) to minimise disturbance of the water cycle, flood protection measures or relocation of people to adapt to flooding, and optimising agricultural water use in case of droughts. The hydropower industry needs to redesign its future, long-term planning for higher variability in discharge and less dependence dams. Thus, there are strong linkages between long-term strategic planning in water resources and agriculture and early warning for climate-induced degradation, In this case, also long-term projection on the basis of policy analysis should be included.

Where climate-induced *biodiversity* loss is of concern, conservation measures are also important, as well as spatial planning to optimise forest fragment patterns and connectivity. Diversity and specie composition can also be triggered by shifts in water cycling. For example, species may shift according to their resistance to drought. Of course, biodiversity loss can be triggered by several other factors, but these are beyond the scope of this EWS.

8.2 Possible institutional arrangement for an Early Warning System

The scientific knowledge on Amazon functioning and its response to climate are constantly improving and changing, as well as insights in and prediction of global climate change. As explained in the section on monitoring system options, so do observational techniques. This will most likely continue to be like this for many decades to come, which is also the typical time horizon for potential Amazon degradation. Therefore, it is recommended to build a relatively small core-group of internationally active scientists who, from a dedicated charge, regularly bring together the various available data streams with latest models and insights, and who evaluate the risks for degradation using contemporary tools (figure 14). Ideally such early warning work should be integrated in their day-to-day research activities, and be discussed with and reviewed by the international research community as well as by regional institutional entities in Amazonia or South-America.

An alternative would be to build overviews of synthetic indices. For example this could consist of combining several monitored quantities, and their statistical trends or variability, into an integrated 'ecosystem stability index'. This would assist accessibility of the information for policy and the general public, but also 'freeze' scientific insights on the interpretation of observations and models in a way that may inhibit up-to-date warning. It appears more fruitful if scientists and policy advisers each time make use of the latest insights to report on the state of the Amazon and its risk for degradation.

It is necessary to regularly interact with a) the institutional communities that maintain monitoring systems; b) the wider scientific community and c) regional, national and international policy makers. To this end, both annual dedicated conferences need to be organised as well as an annual 'state of the Amazon' report published.

We recommend the establishment of a small unit, based in a scientific institute such as the Brazilian INPE, INPA or equivalent, with long-term funding for about five to ten scientists, including data analysts, climate and vegetation modellers, GIS specialists, social scientists and communication experts. Ensuring collaboration with partners from Bolivia, Peru, Ecuador and Colombia as well as Venezuela and the Guianas is important. Regular rotation of people and maybe also the institutional base (on a tendering basis) is to be recommended as well.

The cost of such a unit would therefore include:

- five salaries at senior scientist level
- five at junior level,
- funding for PhD, MSc studentships, internships and visiting scientists
- funding to acquire data sets
- funding to support and strengthen monitoring networks where necessary
- high-level computing environment,

- access to powerful modelling mainframes
- coverage of international travel twice a year
- funding to organise an 'Amazon monitoring stakeholders meeting' up to 50 participants, each year
- funding to organise a 'state of the Amazon' meeting, up to 50 participants, each year, including an open science conference part and a (smaller-scale) policy briefing and interaction.
- Funding to contribute with side events to relevant United Nations meetings or equivalent.
- funding for annual reporting
- hosting of the unit at a research institute including library facilities

In the event of apparent increased risk for imminent degradation, appropriate additional effort will be necessary, with dedicated focus groups to further analyse the problem and investigate potential options for action. It is difficult to speculate on the format to such effort long before it is needed.

The 'early warning unit' that is described here should be subjected to regular review. We propose that every five years, the unit invites a small international review committee to report separately on the quality, efficiency and impact of the unit.

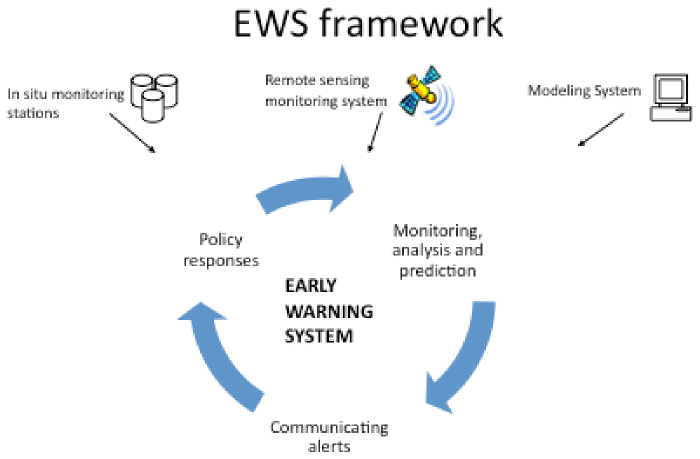


Figure 14 simplified structure for an early warning system

9. The way forward from this proposal

This document is a combination of setting out the theory, basis and methodology of a possible early warning system for critical degradation in the Amazon, followed by an inventory of institutional needs and existing monitoring systems. This is then followed by an outline proposal for such a system, both specifying the skeleton for analytical approaches and procedures and advice on where monitoring should be developed further and how data could be brought together. Finally, we propose an institutional arrangement for such a system.

This document requires follow-up. What is needed is that it is presented to several key stakeholders and governmental institutions to evaluate the need and realism of such a system and for proposals to amend these ideas.

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Appendix : Tables

Table 1 - summary of potential critical transitions in the Amazon, consequences, indicators and monitoring options.

class	Process	Causes (forcing type)[1]	Primary consequence (impact type)[2]	Ecosystem service affected	Indicator	monitor
Carbon cycle	Decrease GPP	Drought (3) High temperature (1) Nutrient loss (1)	NPP loss (2)	CO_2 sink Reduced productivity forest products Reduced appeal for tourism Cultural capital Air quality: Health (fire -> respiratory disease); Transport (smoke closing airports)	Degrading greenness, foliage, biomass	Flux data Regional [CO_2] Biomass plots Remote biomass Remote sensing multispectral
	Increase respiration	Drought (3) High temperature (1)	NPP loss (2) Soil carbon loss (1)		Degrading biomass Degrading soil carbon	
	Reduced recruitment	Gpp loss (1,3) Fire (3) Biodiversity change (1)	Biomass loss (2,3)		Opening canopies	Remote sensing secondary vegetation Permanent plots
	Increased mortality	Drought (3) Floods (3) Storms (3) Biodiversity change (1) Deforestation (2)	Biomass loss (2,3)		Increase of dead matter	Remote sensing of gaps and defoliation Permanent plots
	Increased fire incidence	Drought (3) Previous fire (1, 3) Mortality increase (1,3) Land-use change (2)	Biomass loss (3)		Degradation Opening canopies Fire frequency	Fire monitoring remote sensing Fire susceptibility: moisture, openness, fuel load
Water cycle	Reduced evapotranspiration	Reduced rainfall Reduced GPP Reduced biomass	Reduced moisture transport and recycling Reduced/increased?/Changed? water stress	Regional water recycling Water provision for agriculture & other sectors, e.g. hydro power Flood protection Navigability ->	Degrading vegetation Increased river discharge	Flux data Catchment studies Surface temperatures
	Reduced precipitation	Global/regional climate effects Reduced	Reduced soil moisture Reduced river discharge		Precipitation? (and related indicators, e.g. cumulative	Rainfall network TRMM Soil moisture

[1] Numbering as in section 2.1 – first set
[2] Numbering as in section 2.1 – second set

		evapotranspiration		access to markets and services Disease control	rainfall, drought indicators, refer to WMO Task Team on Climate Risk and Sector-Specific Climate Indices) Lower river levels	
	Reduced runoff	Reduced evapotranspiration Reduced rainfall	Reduced river discharge		Lower river levels	River discharge
biodiversity	Changing competition	Drought High temperature Increased CO_2	Shift in species composition	Reduction in gene pools Reduced pollination service, affecting forest regeneration Effects on carbon sequestration? Tourism Cultural capital	Changes in key species abundance	Permanent plots Monitoring individuals
	Species loss	Habitat loss Over-exploitation Hunting	Degrading biodiversity		Changes in key species abundance	Inventories, plots, DNA fingerprinting
	Habitat loss	Deforestation Degradation Changing river levels	Degrading biodiversity		Changes in key species abundance	Remote sensing habitat inventory
Nutrients	fire	Deforestation Pasture burning	Slow recovery Changed vegetation type	Regrowth capacity of forests Agricultural fertility Air quality: Health (fire -> respiratory disease); Transport (smoke closing airports)	Degraded vegetation type	Soil inventories Remote sensing biomass density
	Topsoil erosion	Deforestation	Bare soils River siltation Slow recovery			
	Repeated logging	Economic demand	Soil degradation Slow recovery			
Economic	Financial capital	Total assets	Lack of financial resources for sustainability measures	All forest services	GDP growth	Production, investments
	Agricultural importance in Amazon economics	Areal extent (+)	Clear cut deforestation		GVA agriculture (%)	International trade
	Forest cover	Opening of forests (+)	Forest degradation		GVA Forestry	International trade
	Economic importance of Amazon	Exploitation of natural resources (+)	Natural resource depletion		Investment rates	International corporations
	Export	Production in Amazon (+)	Clear cut deforestation		Inflation rate (+/-) Production of ag. products (+)	International (meat) demand
	Forest cover	Value of standing	Lack of forest protection		PES (0)	Ecosystem

		forests (-)				services valued
Social	Urban system	Urban population density (-)	Increase in inequality and poverty	Biodiversity, forest fragments	Rural outmigation (-)	Urban pull
	Rural system	Emptying of countryside (+)	Lack of social fabric in countryside		Labour force (-)	
	Legal system of protection	Illegal land ownership and deforestation (+)	Lack of control		Property rights (0)	Government control
		Illegal activities (+)	High rates of illegal activities		Control of corruption (0)	Government control
					Crime rates (0)	
	Education	Education of adults (0)	Behavioural change towards sustainable thinking		Illiteracy rate (0)	Government programs
		Education of youth (0)			School enrollment (0)	Access to school system
	Inequality	Income differences (+)	Rural poverty		Gini coefficient (0)	Multiple
	Income level	Low income (0)	Poverty		Poverty	Economy
	Health system	Health status (+)	Affects quality of life		Child mortality	Multiple
	Social capital	Quality of life (0)			Civil society involvement	

Table 2 - List of stakeholder institutions responding to detailed questionnaire regarding Early Warning System

INSTITUTION
MMA - Diretoria de Zoneamento Territorial
MMA – Serviço Florestal Brasileiro
ANA - Agencia Nacional de Águas
EPE - Empresa de Pesquisas Energéticas
TNC - The Nature Conservancy
Banco BASA
INPA – Coordenaçao de dinâmicas ambientais
MMA - general
Embrapa – Rio de janeiro

Table 3 – Ecosystem services and monitoring assessed as important by stakeholders

Class	**Ecosystem service affected mentioned by stakeholders**	**Monitoring mentioned by stakeholders**
Carbon cycle	Carbon storage 4x	Fire feedbacks and forest degradations NPP Emission of greenhouse gases Disturbed forest cover by selective logging Fires
Water cycle	Water provision and transport by Amazonia 'flying rivers' Hydroelectric potential Hydro-sedimentological cycle	Extreme years and dry season length
biodiversity	Conservation of biodiversity 2x Corridors 2x Resilience of the forests Fish resources Wood extraction Extraction of non-wood products (nuts, fruit, oil, rubber)	Deforestation and fragmentation (size, shape, linkage of fragments) Monitoring of threatened species and loss of habitats of endemic species Vegetation cover as indicator of biodiversity
Nutrients	Import of nutrients from Sahara Nutrient cycling Soil quality control Agro-pastoral productivity	Soil use changes
Climate	Climate control 2x Seasonality control Air quality control	None specific
General	Need detailed EWS for Whole Amazonia, with sub-regional warning	Need monitoring of laws and public policies
Erosion	Erosion control 2x	Mass movements

Table 4 – stakeholders' opinions on implementation of an EWS

Category	**Host institution**	**User institution**
Government ministries	Science, technology and innovation Environment Education Agriculture Integration Marine (Army) Army State Environmental Agencies Amazonia state and municipal agencies collaborating to develop an observational network	Science, technology and innovation Education Agriculture, agricultural development, mining and energy Environment- Secretariat for forestry and biodiversity Amazonia state and municipal agencies
Government services	National water agency (ANA) Meteorological institute (INMET) Centre for management and protection of the Amazon (CENISPAM) Forest Service (SFB) Nature protection agency (IBAMA) Natural disasters monitoring and warning centre (CEMADEN)	National water agency (ANA) Nature protection agency (IBAMA) Chico Mendes institute (ICMBio) Indigenous peoples organisation (FUNAI)
Research institutes	Space research (INPE) Amazonian research (INPA) Emilio Goeldi Museum (MPEG) Agriculture (EMBRAPA) Public Universities	INPE
NGO	IMAZON Chico Mendes institute (ICMBio)	IMAZON