# AMAZALERT Delivery Report

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Potential use of an Early Warning System for irreversible loss of ecosystem services in Amazonia

A reconnaissance report

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1. **Summary**

This document consists of an inventory of all issues relating to the development of a proposal for an Early Warning System for rapid degradation of Amazonian ecosystem services. We cover both technical aspects of monitoring, modeling and analysis of data, as well as the criteria and difficulties that are involved in practical implementation of such a system. Currently there is debate, and substantial uncertainty, whether or not the Amazon could experience climate and land-use induced critical transitions in the coming century. Ensemble model forecasts suggested before that critical conditions arise around 2 degrees global warming and 40% deforestation. Whether or not such changes might occur, it is important to design early warning systems for critical transitions.

The most important ecosystem services of the region, maintenance of the water cycle and the carbon cycle, are affected by a range of factors and the integrity of these factors needs to be protected, not only against critical transitions but also against gradual change. The kind of policy action to be taken in response to early warning (prevention or adaptation, regionally induced or triggered by global factors) depends very much on the type of change (e.g. rapid or slow, global or regional) that is to be expected. Communication and political motivation of policies against critical transitions is difficult and needs good preparation.

Typically, an EWS would consist of a) a monitoring system; b) a set of analysis tools, based upon time-series statistical analysis, 3) a modeling system that simulates future development of the region and interprets the monitoring results and 4) a communications division. Monitoring and analysis should be performed with a large redundancy in instrumental set-ups and in data sources, to enable successful evaluation. The system should be robust, which is to say that ‘false positives’ and uncertainty in early warnings should be minimized. This means first and foremost that models used need to be accurate and precise, representing the most up to date knowledge on global forcing as well as on ecosystem processes.

Finally, this report provides an initial listing of potentially to be used factors to be monitored. All these need to be evaluated for realism in the upcoming periods of AMAZALERT.

2. **Introduction**

The concept of global ecosystem services has become a powerful paradigm for understanding the link between the functioning of ecosystems and human welfare, which is expressed by the economic and ecological quantification of the services in regards to sustainable development. The role of tropical forests in the global climate system and the uncertainty of the exact magnitude of this complex interaction has become a major concern to the scientific community, and understanding this link is critical for a wide range of decision-making contexts.

The Amazon Basin is now home to more than 25 million people in Brazil, and the forest cover for this region has declined to about 80% of its original area (INPE 2011). Whilst the forest area continues to be reduced, several regional development programs and market drivers provide opportunities for the expansion of the
agriculture, logging and urbanization in replacing the natural vegetation. A great challenge faced by the region is to maintain the ecosystem services provided by the Amazon forests and their complex ecological processes, as well as the needs of the growing human population in the region, as in communities elsewhere, in face of global environmental changes.

Recent studies showed that the Amazonian forest is resilient to considerable natural climatic variation, but global and regional climate change forcings interacting with land-use change, logging and fire in complex ways might lead to forest ecosystems that are increasingly vulnerable to degradation (Davidson et al. 2012).

The study of possible critical or ‘tipping’ points of the Earth system has been gaining importance in recent years, with the objective of quantitatively establishing the likelihood of crossing a threshold that could cause an element of the Earth system to rapidly change into another stable equilibrium. The climate–vegetation equilibrium in the Amazon has been identified as one such tipping element of the Earth system (Lenton et al. 2008) possibly presenting bi-stability: one equilibrium state is obviously the present climate–vegetation state with tropical forests covering most of the basin and a second stable state would have tropical savannas (or other type of drought-adapted and fire-adapted vegetation) replacing forests in a large portions of the basin. Once a tipping point is transgressed, the time scale for fully reaching the new equilibrium state can be ‘abrupt’ in comparison to natural time scales of change, or still may take several decades to a century for the establishment of the new vegetation–climate state (Jones et al. 2009).

It has become increasingly clear that threats like global climate change or land use pressures could negatively affect Amazon land cover over the next 30-50 years (Sampaio et al. 2007; Nepstad et al. 2008). Analysis of an ensemble of coupled climate-land surface simulations suggested that deforestation of more than 40% could significantly reduce rainfall, and global climate change, even at 2°C warming has the potential to lead to irreversible degradation of the Amazon basin’s current ecosystems to a more savanna-type ecosystem (Cox et al, 2000; Nobre and Borma 2009). More recent ensemble studies have in turn cast substantial doubt on this (Cox et al, 2013; Good et al, 2013; Huntingford et al, 2013).

Whether a real Amazon forest ‘die-back’ is realistic or not, it is plausible that the Amazon basin is under threat from climate change and society, especially where these interact, and it is of great importance to enable South-American society, the EU and the international community to inform itself of any trends and the risk of major loss of Amazonian ecosystem services. While systems are in place to monitor land-use change and rivers (e.g. ANA, PRODES-INPE 2010), there is little else operational to systematically monitor the state of the climate, the biodiversity or even the regional economy. When, as stated above, we know more about the risks and mechanisms of loss of ecosystem services, it should be possible to design an operational, basin-wide system that enables us to raise the alert with a clear evidence base, before it is too late to intervene.
3. Which ecosystem services and other properties of the Amazon would be important to monitor and prevent from tipping into a degraded state

An EWS should be relevant to broader impacts on ecosystem function: not just forest dieback, but it should look at the whole system given the many interconnections. Wide relevance of such a system is useful in justifying a wider range of observations.

Main ecosystem services of the Amazon region have been listed in Tejada-Pinell et al, 2012 (AMAZALERT Deliverable D1.4). Overall, the main ecosystems services in the Amazon were stated to be water supply, river access and fishing (also related to biodiversity), climate regulation, carbon sequestration, soils for agriculture and providing living space to wild plants and animals and the protection of biodiversity. Besides, the region is home to several cities and smaller communities.

More specifically, the following quantifiable phenomena affect these services:

- **Precipitation.** Rainfall is crucial to maintain both natural vegetation and agriculture, replenish rivers and maintain evapotranspiration, which in turn helps to regulate climate at both regional and global scales.

- **Recycling of moisture and evapotranspiration** are responsible for about 30% of rainfall, especially in the Central-Eastern part of the basin, and to some extent also for rainfall in regions south of the basin. This process, controlled by both surface vegetation and atmospheric flow (advection, convection and convergence), is one of the basic engines behind the Amazon’s existence. Quantification of this process is more complex than for precipitation, as it has to be inferred from combinations of precipitation data, evapotranspiration assessments, isotopic composition of water and regional climate models.

- **River discharge.** River discharge affects navigability, i.e. communications and habitability of river margin people communities in the region, as well as fisheries and the vitality of floodplain ecosystems (*varzeas*). Not only average discharge is important, but also peak and low flow values.

- **Biomass and productivity** of vegetation (forests) determine the amount of carbon stored and sequestered by the region. Carbon stored in soils is even more persistent, and is fed by biomass production. Furthermore, biomass in forests represents large economic value in terms of timber.

- **Agricultural productivity**, in the Amazon mainly consists of grass for cattle, to a limited amount soy beans, a range of newly developed, sustainably produced cash crops (Açai, Guarana, etc), palm oil and various regional products. All these depend on climate and well-maintained soils.

- **People migration and economy.** Migrations can be both an indicator of change and a cause of change. Economic developments in the region affect migration and colonisation patterns. Migration can enhance deforestation but also be a consequence of a degrading environment.

- Land-use change itself affects most of the variables mentioned above, through changing the proportions forest and non-forest and their services, as well as being associated with fire and air quality (smoke and nitrogen emissions).
Different kinds of changes that may occur in the region

Shifts between alternative stable states are the most worrying transitions for the Amazon region, since they tend to be hard to forecast and difficult to reverse. However, their magnitude and spatial extent may vary, and sometimes not be of large impact. An early warning system should be designed to forecast such changes, but should not ignore the likelihood of other types of changes, for example more gradual degradation or in general changes that are easier to reverse but still of high impact such as gradual increase of openness and fragmentation of forests, gradual changes in rainfall and river discharge, or population increase. More common and more associated with trend analyses, such changes are in principle easier to detect in advance, but on the other hand, may be associated with unexpected processes, and may be perceived as less urgent by public and policy.

4. What policy actions might be triggered by an early warning system?

An EWS is only of use if it is able to inform some useful (policy) action. Therefore, it makes some sense to start by considering what actions are possible/plausible. Generally these 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 could and what could not be controlled. Emissions of greenhouse gases, deforestation, fires, water use, etc, 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.

5. Outline of potential functioning of an Early Warning System for the Amazon

Figure 1 outlines a possible set-up for an early warning system for the Amazon. The basis of such a system is long-term monitoring of critical indicators, of which we give some possibilities further in this report. These indicators should be quantities that are relatively accessible, and easy to monitor at high temporal and/or spatial resolution. In particular, they should be shown to represent the variability of the Amazon ecosystem services and other important tipping phenomena (as set out in a previous section) in such a way that their behaviour near critical transitions reliably points to imminent change in the state of that particular ecosystem service.
Monitoring could be achieved in many ways. It includes:

- Direct monitoring of biophysical/environmental quantities, relating to water, vegetation, biodiversity and atmosphere, making use of existing or new institutions that ensure continuity and data access.
- Direct monitoring of socio-economic indicators naturally makes use of different, more centralised, methodologies.
- Indirect monitoring includes collection of remote sensing information, such as is already done for deforestation by INPE/PRODES, and would usually concern properties of the land surface but could also concern large-scale atmospheric composition and properties (remotely sensed or not) and international trade figures.

An early warning system should also include a modelling framework, functioning in two ways:

- First, integrated modelling studies, such as carried out in AMAZALERT, should lead to evaluation and choice of the most effective indicators and methodologies to detect early warning signals. This is achieved by evaluating a range of modelled forecasts into the future, exploring the full spectrum of potential environmental changes. Also, the modelling system can be used to simulate the monitoring system, to evaluate whether the latter picks up those signals that are especially sensitive. The modelling system should also enable

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**Figure 1.** Framework of a possible Early Warning System for irreversible loss of ecosystem services in Amazonia.
continued research, development and adjustment of the EWS to enhanced and changing insight in the future.

- Second, an integrated modelling system should be part of the early warning system, to interpolate observations and interpret and forecast their impact.

The EWS should be managed by one or two central institutions, preferably in South America (e.g. Brazil and a hispanic-speaking country) where a (small) crew of scientists is responsible for maintaining and updating the system, operationally summarising the state of the Amazon, detecting trends and threats, and issuing reports on this on a regular basis. If threats become urgent, this institution should also issue alerts, initiate dedicated task forces and advise to policy as appropriate. Finally, the effectiveness of policy responses should be evaluated, perhaps by a third party institute from a different geographical region.

Communication of warnings

The issue of communication of warnings is an important issue, since effective policy actions would only happen if the issues are communicated correctly. This should not be underestimated: it is a major challenge to communicate these complex issues to non-science audience, policy and individuals.

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.

6. Computational tools to analyse Early warning signals

Detection on basis of changes in variability

Following the realisation that many components of the Earth system are essentially chaotic and non-linear and potentially contain ‘tipping points’, or technically: bifurcation points, where positive feedbacks occur (e.g. Lenton et al. 2008; Scheffer et al. 2009; Hirota et al. 2011), it was realised that such tipping points could sometimes be more predictable than it seemed. The fact that time series of phenomena nearing tipping points display patterns of variability that are different from patterns away from tipping points has attracted considerable attention in recent years (Lenton et al. 2008; Dakos et al. 2012). Such ‘Early Warning signals’ can express themselves in different ways, depending on the probabilistic distribution of the state of the system under consideration and the (variability of the) external forcing. A popular visualisation of tipping points and early warning signals is the ball (indicator of system state) that rolls about (forced by external energy) in a surface
with two valleys (two stable states), separated by a hill or ridge, representing the probability distribution of the system states (figure 2). Probability of moving from one valley to the other is reduced by the hill, inducing resilience, but once the ball is in the other valley in what is also a resilient state, moving back is difficult, requiring even more energy than the first move, because such a ‘move’ from one state to the other involves changes in the variance of the system indicator. This could be increased variance, but also slowing of temporal variability, ‘flickering’, or combinations of all these (table 1, from Lenton et al, 2008, and Dakos et al, 2012).

Figure 2 - Visualisation of tipping points
In recent years, several studies have summarised technical tools to detect early warning signals from time series and spatial distribution data (Dakos et al. 2012). On-line toolboxes, such as the published in http://www.early-warning-signals.org/ are being made available, including advice on what kind of tools and detection statistics would be most useful in which situation. These tools stay so far, however, fairly theoretical and their practical applicability still has to be proven.

**Detection on basis of exceedance of critical thresholds and attribution to anthropogenic causes.**

Next to, but also in combination with methods based on detecting changes in variability, other methods could be employed. Analysis of trends and changes in trends in the relevant quantities at various time scales is an obvious approach. Assessing the probability of observed values given observed and modelled climatic distributions allows identifying outliers. This also allows assessment of the degree of anthropogenic influence in the system’s state, if distributions are modelled either using only natural drivers or including human drivers.

Given previously established ranges of environmental variables that can sustain the existing forest type, exceedance of critical thresholds in observed distributions of the...
same variables can indicate risk of a transition to different vegetation states. Examples of such methodology are shown in Christidis et al. (2012) and Good et al (2013).

*Using forecasts*

Finally, an approach that could be considered is to employ longer-term (eg seasonal) forecasting methods, as is to some extent already being used operationally. Extreme droughts or wet periods, years of low productivity, etc., could in the near future, with increasing predictive power of earth system models, definitely play a role in early warning systems.

*Combining methods*

In designing an early warning system for the Amazon, at this stage clearly room should be reserved for improvement both on signals to be detected and for the detection methods themselves. From the evidence so far it is clear that an EWS should combine multiple methods, to enhance chances for detection of approaching tipping points but also to reduce risks for ‘false positives’.

**7. Robustness of an EWS**

*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 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.

*An EWS should be robust to natural internal variability.*

This is probably the easiest issue to handle. It would e.g. 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 if 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.
**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.

**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.

**8. Which indicators might be strongest and most suitable predictors of imminent changes to an alternate state?**

A plan for and EWS should contain a specified list of possible variables to be monitored. So far, a rough, non-exclusive inventory has been done. In short, the more observational data sets are involved, the better and the higher the chances of detecting valid tipping point events.

All observations, however, have limitations, such as areal coverage, random or systematic error, sensitivity to the actual quantity of interest. Different observations have different limitations, so it makes sense to have a set of complimentary observations. This makes an EWS more robust to limits in both understanding and observations (many observations of an inter-connected system gives less scope for misinterpretation through lack of understanding or through observational inadequacy).

Observations, the more the better, also enhance understanding of the system under observation, aids in model validation and improvement and improves the potential impact of the system on society and policy arenas.
Include observations of driver processes as well as the relevant impact

Where possible, both drivers and impacted variables should be observed. For example, climatic variables (temperature, precipitation) need to be observed as well as productivity and evapotranspiration, and fire as well as fire impact.

Include different types of ‘observations’

It is important to include different ways of observing the same quantity, to increase redundancy in data. For example, surface temperatures and precipitation (weather stations) and biomass (plot data or even high-time resolution automatic increment measurements, also showing stress) as well as remote sensing-derived data. It is important, however, to critically account for cross-validation (e.g. ground-truthing) of different methodologies. Also, as most observations need to be implemented for the long term, issues on compatibility between successively improving methods need to be taken into account.

List of possible variables to be monitored

Examples of possible phenomena and quantities to be monitored could include the following. It should be realised that such a list should be open and expandable. If an EWS goes operational, it will cover many decades and within that time frame many innovative monitoring methods will be developed.

- Sea Surface Temperature (SST) is a an indicator of global-scale change
- Precipitation (patterns, quantity) Rainfall is a primary drives as well as an ecosystem service that can be affected. Rainfall statistics are a crucial component of any EWS. Improving the network of rainfall observations, radars and/or TRIMM satellite observations is crucial. Analysis could be done on direct data, but also on gridded interpolations and longer-term running means as these indicate changes in climate rather than weather.
- Climate modes (ENSO, Atlantic Oscillations, etc) are often correlated integrating indicators of high-impact changes or episodes in regions such as the Amazon.
- River flow and discharge across the basin’s river network are, like rainfall, essential elements of any EWS. They will be affected by almost any change in the region. Especially if also water quality, sediment load, carbon content are included, also vegetation changes are affecting river outflow.
- Evapotranspiration is the prime driver of recycling, but hard to monitor at large scale. Satellite data-based products (through, e.g. GEWEX) could be a solution.
- Atmospheric CO₂ concentrations over the tropical belt, provided they are measured over a representative network and interpolated well (e.g. through
CarbonTracker (Peters et al. 2007), reflect bulk changes in carbon uptake and emissions. These in turn reflect changes in vegetation, if anthropogenic emissions are known, i.e. could potentially be used to monitor overall Amazon productivity changes.

- **Surface temperatures**, measured both through a well-designed meteorological network and through satellite observations, are also key in both affecting vegetation as well as humans, and integrate several processes that may be subject to ‘tipping’.
- **Biomass observed at high temporal resolution** represent the key ecosystem service of interest. Observations could be done using remote sensing (eg S-band Radar) and well-referenced/calibrated automatically registering growth bands in forest plots across the basin.
- **Several remote sensing indices** represent **surface greenness and productivity** such as the NDVI and EVI
- **Occurrence of fires** can be monitored from remote sensing as well. Care should be taken to distinguish natural from human-induce fires, where the latter are usually associated with agriculture/ranching rather than with any aspects of the natural system state. In assessing fire frequency, the main metric should not be the simple occurrence or area, but the extent and severity of damage done by the fire.
- **Economic indicators**, such as the GDP of the region, transport, trade and migration patterns
- **Agricultural productivity** could depend on climate change in different ways. Severe drought leads to reduced productivity, but high rainfall also inhibits productivity and accessibility of land. Therefore the dependence on climate is likely non-linear.

**Fast-response options in the EWS?**

One might consider a plan for more comprehensive measurements, to be deployed e.g. if a major drought is starting/predicted, such as was done during the dry year 2005. This would be to enhance resolution and potential for adaptation when we fear a tipping point is approaching, the recovery rate can be considered an index for approaching tipping points, and such observations also enable analysis of extreme conditions as a possible proxy for future climate. In case such provisions for detailed monitoring are taken, it should be ensured that control data sets are available from other areas or previous, normal years.

**9. Conclusions**

We investigated the most important issues relating to the design of an Early Warning System for critical transitions in the Amazon region. Preparing an EWS requires a multi-disciplinary approach. First, The goals of an EWS need to be defined, in terms of what it would warn for and what kind of action would be expected to follow warnings. Then, through model analysis and analysing data sets, the most efficient monitoring and analysis tools and networks need to be designed. Finally, the system should be made robust, i.e. giving accurate warnings that can be relied upon.
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