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Aerial river management by smart cross-border reforestation

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ABSTRACT

In the face of increasing socio-economic and climatic pressures in growing cities, it is rational for managers to consider multiple approaches for securing water availability. One often disregarded option is the promotion of reforestation in source regions supplying important quantities of atmospheric moisture transported over long distances through aerial rivers, affecting water resources of a city via precipitation and runoff ('smart reforestation'). Here we present a case demonstrating smart reforestation's potential as a water management option. Using numerical moisture back-tracking models, we identify important upwind regions contributing to the aerial river of Santa Cruz de la Sierra (Bolivia). Simulating the effect of reforestation in the identified regions, annual precipitation and runoff reception in the city was found to increase by 1.25% and 2.30% respectively, while runoff gain during the dry season reached 26.93%. Given the city's population growth scenarios, the increase of the renewable water resource by smart reforestation could cover 22–59% of the additional demand by 2030. Building on the findings, we argue for a more systematic consideration of aerial river connections between regions in reforestation and land planning for future challenges.

1. Introduction

Reforestation has been one of the most active initiatives to mitigate global climate change impact. Being potentially a useful tool to sequestrate atmospheric carbon, it also presents co-benefits such as improving status of biodiversity loss and enhancing ecosystem integrity (United Nations Framework Convention on Climate Change (UNFCCC, 2013). These co-benefits have been included as objectives of several international agreements addressing those issues, e.g. the Aichi Targets (Convention on Biological Diversity (CBD, 2010) and the Bonn Challenge (Bonn Challenge, 2019). However, an undesirable effect of such intervention is the trade-off with downstream water availability (Connor et al., 2016; Cunningham et al., 2015; Farley et al., 2005). A dramatic decrease in river runoff is normally observed downstream of the reforestation sites compromising water supply and other ecosystem services from the river (Filoso et al., 2017; Jackson et al., 2005). This has become a major factor of low societal acceptance impeding reforestation projects and invoking conflicts (Cao, 2011; Cao and Zhang, 2015) which poses challenges for local implementation of such an intervention despite the top-down forces.

However, a usually neglected aspect of reforestation is that it can also enhance water availability through invisible aerial river connections (van Noordwijk et al., 2014; Ellison et al., 2017, 2018). Similar to surface river networks, aerial rivers (preferential pathways of moisture flows in the atmosphere; Arraut et al., 2012) connect regions, often across administrative borders and topographic watersheds. Upwind land activities govern evapotranspiration (Gordon et al., 2005; Silvério et al., 2015), the moisture input to terrestrial aerial rivers, and influence precipitation downwind via atmospheric circulation (D'Almeida et al., 2007; Ellision et al., 2012; Pitman and Lorenz, 2016; Spracklen and Garcia-Carreras, 2015). Through the hydrological cycle, this influence propagates to rivers and groundwater, thus impacting water availability (Bagley et al., 2012; Coe et al., 2011; Lima et al., 2014; Swann et al., 2015; Ramírez et al., 2017; Weng et al., 2018). Reforestation in general enhances evapotranspiration resulting in more water loss at the catchment scale compared with non-forested land cover (Brown et al., 2005; Dean et al., 2015; Farley et al., 2005). However, released from the land surface, these moisture fluxes to the atmosphere are important inputs of continental aerial rivers (Gordon et al., 2005). Through this mechanism, reforestation strengthens the delivery of water to downwind regions. A prerequisite of integrating this concept in land and water management is an assessment on how relevant it is for downwind water availability. Since aerial river connections are not directly observable, utilization of scientific tools are

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required to recognize connections between upwind and downwind regions (Ellison et al., 2018). Via numerical modelling or isotopic tracing it is possible to reveal the aerial river network connecting regions. Utilizing numerical modelling as a tool, we quantify the effect of strategic reforestation in the upwind regions on those downwind via aerial rivers, thus exploring the potential of the latter as a water resource management option.

2. Material and methods

Expanding on a previous study's methods of structuring aerial rivers (Weng et al., 2018), we use the results of the WAM-2layers moisture back-tracking algorithm (van der Ent et al., 2014) to identify the most important upwind regions influencing precipitation in our study region, Santa Cruz de la Sierra. Based on a Eulerian approach, the model traces the origin of rainfall using the water balance principle and an assumption of well-mixed atmosphere in two vertical layers according to given input data. The WAM-2layers was shown to agree well with other moisture tracking approaches in the Amazon region while having lower computation cost (van der Ent et al., 2014; Zemp et al., 2014). For our analysis, we use a simulation experiment (MOD experiment, described in Zemp et al., 2014) that utilizes observation-based climatic input data (precipitation, evaporation, humidity and wind field) spanning 2000-2010. By averaging annual means of the simulations, we get a network quantifying the contribution of evapotranspiration from each grid cell (1.5° x 1.5° longitude and latitude) to rainfall at the Bolivian economic capital, Santa Cruz de la Sierra. This network can therefore be used to determine the precipitationshed (upwind surface area providing evapotranspiration to a specific sink area's precipitation; Keys et al., 2012, 2018) of the city.

It is known that for a given location, its upwind regions can have different influences on its water resource through the aerial rivers (Keys et al., 2014; Weng et al., 2018). For planning purposes, it is actually possible to identify influential upwind regions which have greatest impact influencing a given region's water availability. We investigated a reforestation intervention in these important upwind regions of Santa Cruz de la Sierra to estimate the optimal potential of such an intervention as a water management option for the city. In order to do this for our example location, we rank the regions' importance in contributing to rainfall of Santa Cruz de la Sierra and outline the Most Influential part of Precipitationshed (MIP) of the city (see the blue region in Fig. 1) by a boundary designating the smallest area which contributes 40% of the total continentally recycled precipitation in the city. This threshold was proven applicable in reflecting the most important moisture source regions for assessing land use change impacts on aerial rivers (Weng et al., 2018); also see Appendix A. for more details outlining the MIP.

3. Study case

Santa Cruz de la Sierra in the Plurinational State of Bolivia, is one of the world's most rapidly growing cities (annual population growth rate 3.7% between 1992 and 2012; Trohanis et al., 2015) and the home of 1.4 million residents (INE, 2012). Migration flows, the main reason of the city's growth in the past decades, are expected to persist. Though the city has the highest coverage of potable water in the country, the current groundwater resources that the city relies heavily on are under stress with a continuous deepening of modern recharge front and deterioration in quality (Morris et al., 2003). Water availability for both the growing population and peri-urban agriculture is becoming uncertain (Castelli et al., 2017). In addition, more frequently occurring severe droughts in the region also intensify the water challenge faced by the city (Erfanian et al., 2017; Jiménez-Muñoz et al., 2016; Marengo et al., 2011).

Following the moisture tracking and the identification of the city's MIP, we tested the potential of managing aerial rivers by smart reforestation as an option to ease the city's water stress. Here "smart" refers to the selective decision of reforestation sites (in the MIP) considering their impacts on aerial rivers and thereby on the water reception of Santa Cruz de la Sierra. Our smart reforestation scenario in each MIP component grid cell was built according to the restoration opportunities map of the International Union for Conservation of Nature (IUCN)/World Resources Institute (WRI) for the Bonn challenge (Potapov et al., 2011; Maginnis et al., 2014; see Appendix B.) where reforestation potential was assessed by ecological conditions and local land use culture. The additional evapotranspiration input from smart reforestation in each MIP cell was determined using the measured evapotranspiration per area of a neighboring forest reference cell (with forest fraction > 95%). We then subtracted the evapotranspiration typical of pasture-land (Sakai et al., 2004), which is the major current land-use type in areas selected for smart reforestation, from the reference forest evapotranspiration per area before multiplying the area reforested. The measured evapotranspiration used for forest evapotranspiration reference was derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) evapotranspiration product MOD16ET (Mu et al., 2013). Thus the additional evapotranspiration input considered is corresponding to the forest structure and age during the observational period of the data (2000–2010). We then calculate the newly added evapotranspiration's influence on the city's water availability including annual rainfall and runoff reception. Changes in annual rainfall could be directly quantified from our networks assuming that changes in atmospheric moisture flow is proportional to changes in the contribution of this moisture flow to local precipitation (Zemp et al., 2017). This assumption is justified by a positive relationship between atmospheric moisture and rainfall in the region (Boers et al., 2014) which also implies sufficient supply of condensation nuclei in the region (van Noordwijk et al., 2015). In turn, the new runoff budget of the city's upstream basin (belonging to the larger Madeira River basin) was evaluated by balancing the changed annual basin precipitation and annual evapotranspiration. We also analyzed changes in seasonal rainfall and runoff budgets in the smart reforestation scenario based on dry (June, July, August and September) and wet (December, January, February and March) months' basin precipitation and evapotranspiration, in line with previous studies showing significant seasonal differences in the influence of aerial rivers on hydrological cycle (Trenberth, 1999; Zemp et al., 2014). For an operational scheme of the study case, we refer the reader to Appendix C.

4. Results and discussion

We found that smart reforestation of 7.1 million ha in the MIP region of Santa Cruz de la Sierra lead to an increase of 1.25% in annual rainfall reception of Santa Cruz de la Sierra (absolute rainfall gain $5.86 \times 10^8\, m^3$). This scenario further leads to a rise of 2.23% (absolute runoff gain $2.00 \times 10^9\, m^3$) in the city's annual runoff enabled by the spatial relationship between its upwind aerial river (more specifically the MIP) and upstream surface river basin. As shown in Fig. 1, the MIP region of Santa Cruz de la Sierra is located in Brazil (states of Acre and Rondônia), Peru (departments of Madre de Dios), and Bolivia (departments of Pando and El Beni). The increase in runoff in Santa Cruz de la Sierra is due to the fact that smart reforestation in the MIP of the city also enhances rainfall in the city's upstream surface river basin. Even more interestingly, the MIP region of Santa Cruz de la Sierra is largely separated from the upstream surface river basin of the city. Thus the expected local runoff decrease resulting from increasing evapotranspiration of reforestation in the MIP is not fully experienced by the city's upstream surface river basin. In fact, the precipitation increase in the basin (through the aerial rivers) results in a marked gain in runoff reception of the city. The runoff increase is more prominent in the dry season (June, July, August and September) reaching a 26.93% increase. In the wet season (December, January, February and March), gains are moderate (1.85%). Slight seasonal variation in rainfall increase

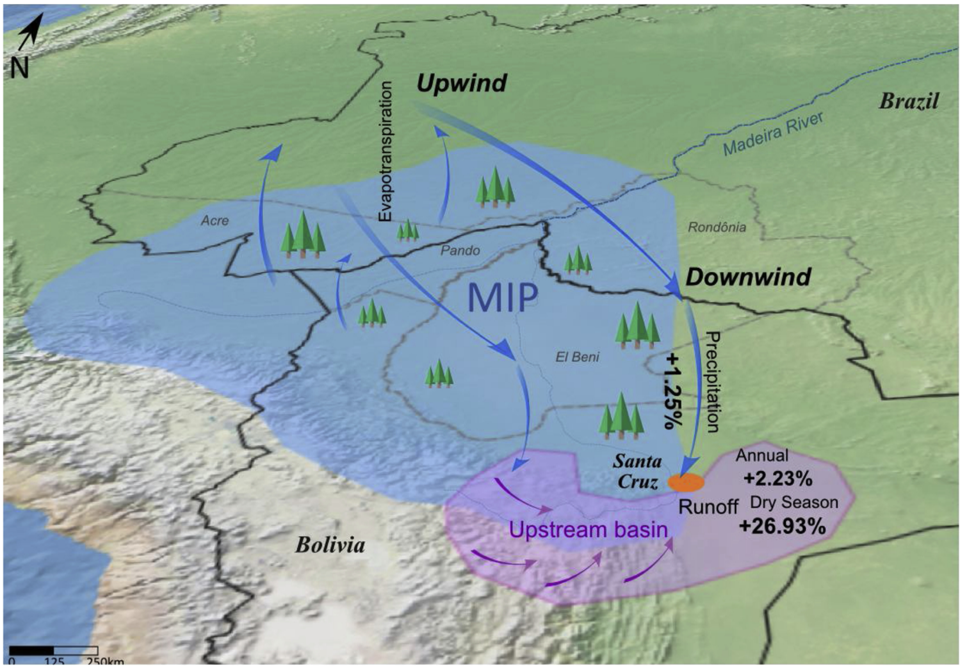

Fig. 1. Smart reforestation for water supply in Santa Cruz (conceptual representation). The Most Influential part of the Precipitationshed (MIP) is highlighted in blue and the upstream surface river basin of Santa Cruz de la Sierra is shown in purple. The blue arrows represent aerial river flows whereas the purple arrows represent surface river flows. The city Santa Cruz de la Sierra, is shown with an orange dot. See Appendix B for an actual map of the MIP and the reforestation potential sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 1
Estimated rainfall and runoff changes to the baseline due to smart reforestation.

	Dry season (June, July, August, September)	Wet season (December, January, February, March)	Annual
Baseline rainfall	$6.79 \times 10^9\,m^3$	$2.54 \times 10^{10}\,m^3$	$4.69 \times 10^{10}\,m^3$
Baseline runoff	$7.56 \times 10^8\,m^3$	$6.21 \times 10^{10}\,m^3$	$8.68 \times 10^{10}\,m^3$
Rainfall change	+1.27%	+1.24%	+1.25%
Runoff change	+26.93%	+1.85%	+2.23%

following smart reforestation is also observed (dry season 1.27% and wet season 1.24%). The rainfall and runoff gain of the study region from smart reforestation are listed in Table 1.

Uncertainties in our estimates may stem from the moisture tracking model, but moisture recycling ratios in the Amazon region estimated from the MOD experiment agree well with other studies' estimation in the same region using other datasets and other moisture tracking approaches (see the table 2. in Zemp et al., 2014). We have also validated our runoff estimation in the Madeira river basin with the historical river observation data (Molinier et al., 1996) and found a slight (8%) overestimation. This has only a small impact on our estimation of the runoff gain by smart reforestation (-8.6% of the annual runoff gain). Our calculation of the reforestation impact on aerial rivers was based on the condition of the transferability of measured forest evapotranspiration from neighboring sites and minor wind field changes after changing land cover (Bagley et al., 2014). Local convection that may be decreased by a lower local land cover heterogeneity (Baidya Roy and Avissar, 2000; D'Almeida et al., 2006) after reforestation is not considered in our study. However, this effect is minor compared to changes in aerial river flows after land-use change in the Amazon (Bagley et al., 2014). Potential increase of soil infiltration (Bruijnzeel, 2004) after reforestation are not considered in the runoff calculation, but this is unlikely to affect our results since most of the reforestation sites are located remotely (in the downstream areas or out of the upstream catchment) of the city.

Our results show that smart reforestation is an option to enhance water supply especially during dry seasons. An increase of 26.93% in dry season runoff can be beneficial for sustaining ecosystem (Anderson et al., 2013; Brienen et al., 2015) and livelihood (Castelli et al., 2017) given the past (Fu et al., 2013; Vicente-Serrano et al., 2014) and projected (Marengo and Espinoza, 2016; Seiler, 2013) lengthening and intensification of the dry season. The amount of water added to the region by smart reforestation can be used to ease the growing water stress brought about by fast urbanization (Castelli et al., 2017). Using the population growth projections implied by different Shared Socioeconomic Pathways (SSP) (Jones and O'Neill, 2016), we calculated the additional water resources needed to secure the current water consumption per capita (Instituto Nacional de Estadíticas de Bolivia (INE, 2017a,b) in the city of Santa Cruz by 2030. In the case of withdrawal being proportional to available water resources, our results imply that an early implementation (2020) of smart reforestation can gradually increase the renewable water resource of the city and ultimately cover between 22% and 59% of the additional water demand by 2030. Though the city's current water system does not extract directly from runoff, the already confirmed large dam projects (Ministerio de Hidrocarburos y Energía, 2012) will allow to benefit from our proposed management option. Such benefits might be particularly relevant given the fact that the glaciers currently sustaining runoff are retreating under climate change (Rabatel et al., 2013; Rangecroft et al., 2016; Vuille et al., 2018). In addition, induced increases in both rainfall and runoff reception will have a positive impact on groundwater recharge which the city currently relies heavily on. Smart reforestation therefore has the potential to increase water supply being beneficial in mitigating the stress on the existing water system under both population growth and climate change. Additional benefits of smart reforestation include sequestering atmospheric carbon at the reforestation sites (Don et al., 2011; Post and Kwon, 2000) and sustaining ecosystem integrity (Coe et al., 2013). Our results add new insights into trade-off between carbon sequestration and fresh water supply (Connor et al., 2016; Farley et al., 2005; Gao et al., 2014), while a win-win situation between those is presented in our case.

5. A more holistic practice of land-water management

Nationally in Bolivia, under the commitment of Ley 1333, reforestation has been also one of the priority land management targets to preserve ecosystems and their services. Under the commitment of Decreto Supremo Nº 2912, there is a Bolivian national target of reforesting 4.5 million hectares by 2030. The smart reforestation scenario includes reforestation areas of 7.1 million hectares and is therefore in line with the national target while the Bolivian part covers 45% of these areas. A full implementation of smart reforestation will require cross-border cooperation. Current implementation of reforestation is mainly planned at the upstream catchments (the Piraí river banks) aiming at the improvement of water quality downstream. Nevertheless, following this strategy, tension usually arises from a reduction of water quantity in downstream areas. In addition, the feasible sites in upstream catchments are usually limited while most of these areas are not easily accessible for development or are protected. Thus, a gap for fulfilling the national reforestation target hectares can be expected if prioritizing this traditional strategy. In this context, smart reforestation might be a good alternative to fill the gap, even more, it might be worth considered before the traditional strategy when aiming for a more water – resilient city of Santa Cruz in the future. In order to implement smart reforestation, it will be necessary to negotiate with other departments out of the Santa Cruz department, which the city belongs to. It is true that blue water and sediments losses can be expected from the reforestation sites locally and downstream. Nevertheless, the friction stemming from compromise in downstream water supply is likely small while those departments (Beni and Pando) and their downstream regions have relatively rich runoff resources. The concept of "right tree at the right place for a clear function" (Creed and van Noordwijk, 2018) can be a national strategy prioritizing those areas facing challenges. A full implementation of smart reforestation will require international cooperation because a part of the city's MIP is located in Peru and Brazil. This could be feasible when included in the context of both the Bonn Challenge (http://www.bonnchallenge.org/content/challenge) and the Initiative 20 × 20 (https://www.wri.org/our-work/project/initiative-20×20), where the Latin American countries have a common target of reforesting 20 million hectares by 2020. In addition, smart reforestation is in line with the Intended Nationally Determined Contributions (INDC) targeting atmospheric carbon reduction which increases individual country's will to participate. A recent call for the regional joint effort mitigating drought may also impose momentum for the joint management on the aerial rivers (United Nations Convention to Combat Desertification (UNCCD, 2017).

Our case implies that, similar to integrated surface river basin management requiring collaboration between upstream and downstream entities, joint management between the upwind and downwind regions is necessary for the implementation of aerial river management and smart reforestation. This requires improved understanding of spatial connections by the aerial rivers (Dirmeyer et al., 2009; Keys et al., 2017) and the effect of land use practices at upwind regions propagating to downwind regions through hydrological cycle (Ellison et al., 2017, 2018; Weng et al., 2018). Nationally, an assessment that outlines critical regions (e.g. the MIPs) to preserve aerial rivers will be a precondition of involving relevant regions for cooperation. By the time the present study was written, there is no inter-regional or international agreement explicitly governing aerial river connections. The Convention on Long-Range Transboundary Air Pollution (United Nations Economic Commission for Europe (UNECE, 1979; Sliggers and Kakebeeke, 2004) might provide a feasible framework to develop on (Ellison et al., 2017). Moreover, establishment of bridging organizations can facilitate co-production of knowledge and collaborative decision making between actors (Cash et al., 2006; Olsson et al., 2007; Crona and Parker, 2012). Interestingly, different roles in aerial river regime and surface water regime may also foster positive policy environment for cooperation between aerial river sharing entities. Take our case for instance, the upwind regions of Santa Cruz de la Sierra are located downstream of the Madeira River, receiving impacts from the city through the surface rivers, but they can exert influences on the city through the aerial rivers since they are located upwind. The reverse roles in this case imply that the shared aerial rivers might challenge current relationships between entities established from surface water regime and the according paradigms of land-water management. Nevertheless, the aerial rivers are indeed the key to bring out a more holistic one of those.

6. Conclusions

To sum up, by taking advantage of a model recognizing teleconnections through the aerial rivers, we have exposed the potential of smart cross-border reforestation as a water management option mitigating challenges of future population growth and climate change. Through transportation by aerial rivers, atmospheric water added by smart reforestation is collected and delivered to the downwind region, presenting potential in increasing both rainfall and runoff (especially in the dry season) in our study region, and certainly beyond. Different from traditional upstream catchment approaches, smart reforestation projects attest the possibility of breaking the usual trade-off in reforestation projects between carbon sequestration and fresh water supply by enhancing both for specific target regions. Prioritization of smart reforestation projects in the important upwind regions of those experiencing or expecting water stress can present significant benefits but be also in line with national and global efforts in reducing atmospheric carbon. For example, the smart reforestation project can provide preferable results watering Bolivia's fastest growing city and at the same time fulfilling the Bolivian national INDC. Beyond the study region, a more systematic consideration of the interconnection between the land and water system while planning reforestation projects should be taken. Further studies should focus on exploring smart reforestation sites that optimizes the aerial river impacts downwind for such regions. The relevance of other land use types e.g. wetlands in aerial river management should be explored as well. However, full reception of aerial river benefits from smart reforestation or other approaches will, in most cases, require cross-border cooperation, which is arguably the key to sustainably managing the interrelated systems that underlie a livable planet.

Declarations of interest

None

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Appendix A. Selection of the MIP

Apart from surface river upstream basins having clear boundary, the aerial river source regions for a given target sink, the precipitationshed, does not have fixed and deterministic boundaries (Keys et al., 2012) and can be very broad. However, due to the fact that aerial river connections between sources and sinks are spatially different (Keys et al., 2014), there exist prominent contributing source regions governing a given sink's rainfall more efficiently. The collection of the most important source regions is defined as the Most Influential part of Precipitationshed (MIP) (Weng et al., 2018).

By including the most important components of the source areas, the MIP governs a given proportion of a target sink's precipitation within the smallest land surface area. Thus for managing the aerial river, identification of the MIP can be considered a budget-efficient approach.

The selection of the MIP from the precipitationshed of a given sink requires a threshold which depends on the study purpose. Previous studies applied different standards as thresholds. e.g. 70% of the precipitation (Keys et al., 2012) or 1% of the precipitation from continental sources (Keys et al., 2017). In the present study, we are interested in the terrestrial source areas since we aim to analyze reforestation within the MIP. Fig. A1 shows the terrestrial component of the precipitationshed for Santa Cruz de la Sierra. We further use a boundary of 40% terrestrial contribution (the 0.4 contour on Fig. A1.) to determine the MIP in our study. This threshold was a trade-off between enough aerial river influences (terrestrial contribution represents 53% of the precipitation received in Santa Cruz de la Sierra) and the fast growing size of the MIP when the threshold value goes up. As Fig. A2 shows, there is a change in the characteristics of the increase of the aggregated area around aggregated 40% contribution. Up to 40%, we observe an almost linear increase while for larger contributions the area increases super-linearly (approximately exponential). Other breakpoints deliver significantly worse R^2 - values. We arrive at the 40% continental contribution as threshold applied in our study since thresholds above imply the inclusion of less efficient areas. Furthermore, the MIP identified here designates reforestation high potential areas close to the national reforestation target in Bolivia. While the chosen threshold was more policy target-oriented in our study, the selection of the MIP threshold for future studies, however, will have to follow their study purposes.

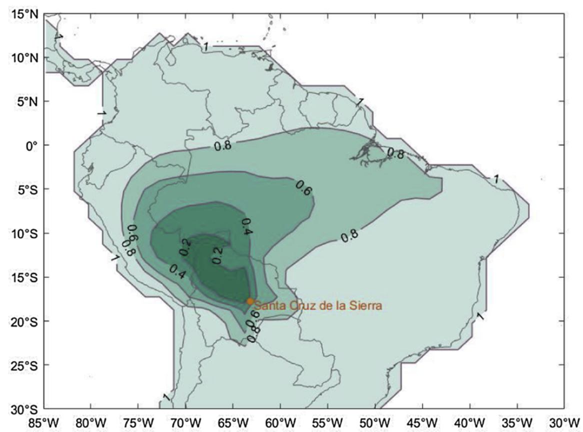

Fig. A1. The terrestrial precipitationshed of Santa Cruz de la Sierra. The contour value represents the delimited area's contribution to Santa Cruz de la Sierra's rainfall that is from the continental recycling. The 0.4 contour was the threshold used for selecting the MIP in our study (the blue region in Fig. 1). Note that the delimited areas grow quickly as the contour value grows.

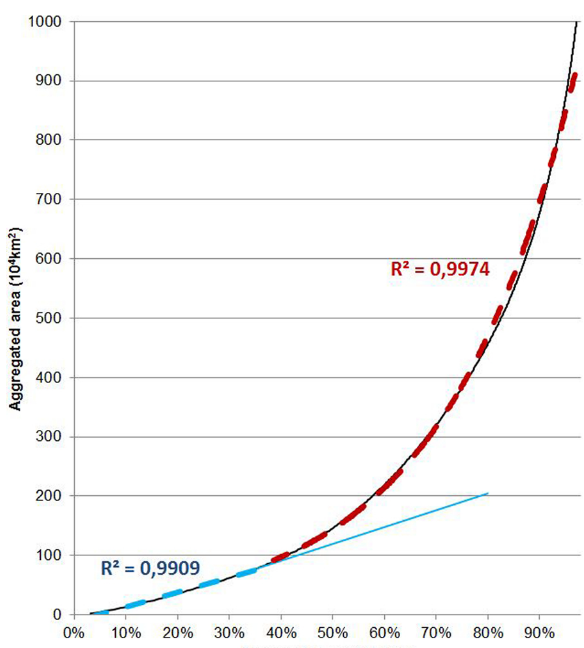

Fig. A2. MIP size-contribution relationship for Santa Cruz de la Sierra. Black solid line: size of the delimited area and its corresponding collective contribution to Santa Cruz de la Sierra's rainfall from continental source (x-axis). Blue dashed line: up to 40% contribution the aggregated area increases almost linearly (R^2 = 0.991). Red dashed line: above 40% the area increases super-linearly, very close to exponential growth (R^2 = 0.997).

Appendix B. Reforestation potential in the MIP

The reforestation potential considered in our analysis for smart reforestation was based on the restoration opportunities map of the IUCN/WRI in which the forest growing potential was assessed by climate and current land use conditions (Potapov et al., 2011; Minnemeyer et al., 2011), shown in Fig. B1. Intact forests and fragmented/managed natural forests were considered no potential for restoration. The restoration opportunities were constrained by human pressure taking into account population density and land use practices. Restoration opportunities were then categorized into four groups for degraded forestlands. These groups include wide-scale restoration (low human pressure; with potential to support closed forest), mosaic restoration (moderate human pressure), remote restoration (very low human pressure) and agricultural lands (intensive human pressure). In our MIP area, remote restoration areas are not presented. We used wide-scale restoration category as potential areas for smart reforestation because it refers to areas where closed forests can possibly grow back on a large scale (Minnemeyer et al., 2011). Note that the restoration opportunities map used in the present study was an assessment at a global scale aiming to give indication for capability of lands to support forests. Identification of local reforestation sites should be complemented by other socio-economic investigations for interventions to begin with (Maginnis et al., 2014).

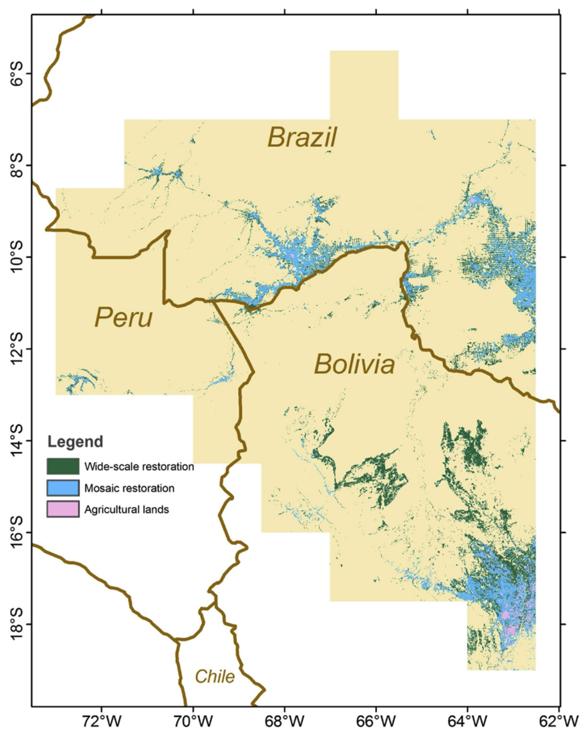

Fig. B1. Reforestation potential in the MIP. The MIP of Santa Cruz de la Sierra outlined by our network is the skin color area (conceptualized as the blue area in Fig. 1). In the present study, the wide-scale restoration category (highlighted by dark green areas) is selected to describe smart reforestation areas. Source: Global map of forest landscape restoration opportunities (Potapov et al., 2011).

Appendix C. Operational scheme for smart reforestation

See Fig. C1.

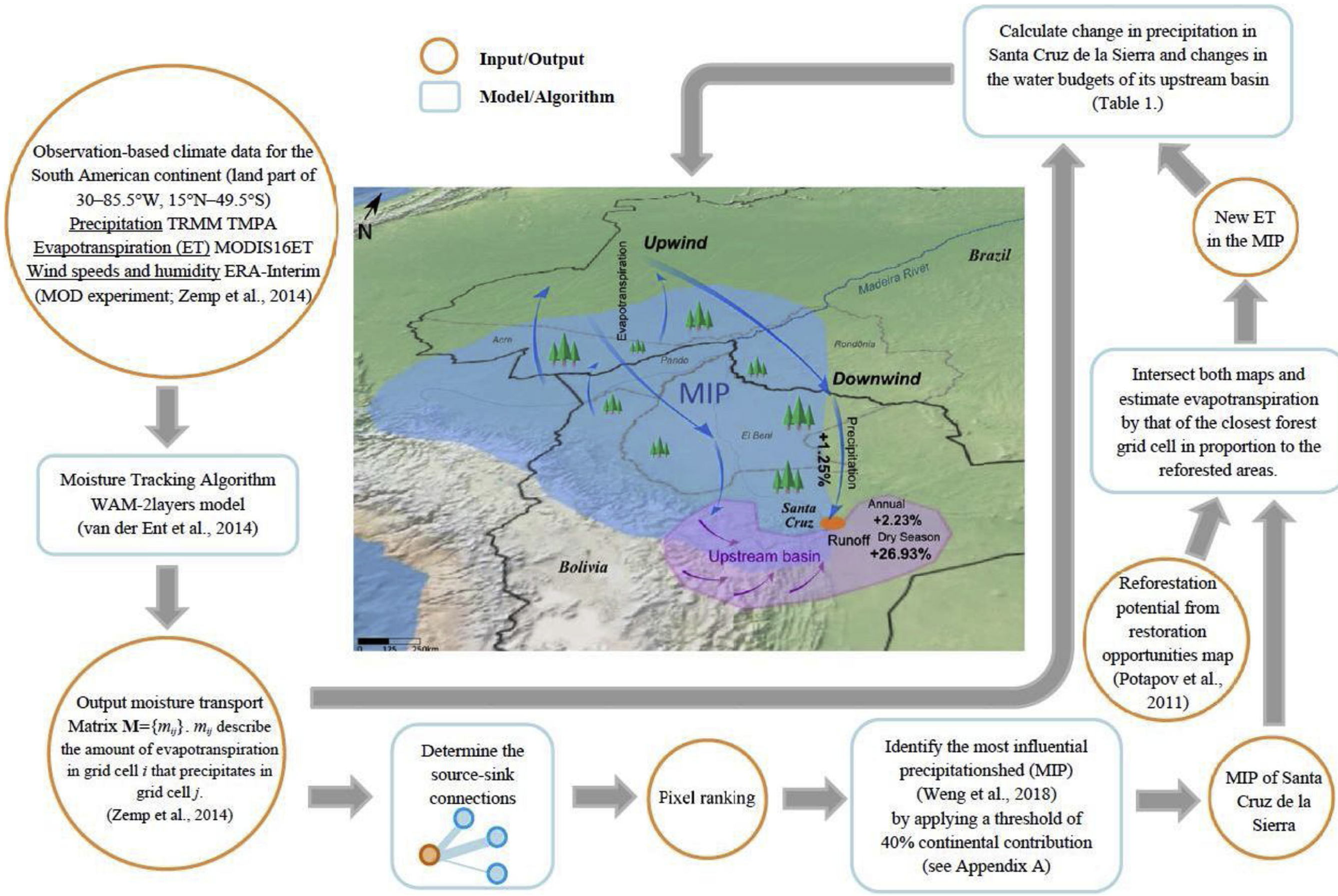

Fig. C1. Operational flow for smart reforestation. This operational scheme describes how we apply smart reforestation and estimate its potential as a water resource management option. TRMM TMPA is an abbreviation for Tropical Rainfall Measuring Mission Multisatellite Precipitation Analysis product (Huffman et al., 2007). MOD16ET is a Moderate Resolution Imaging Spectroradiometer (MODIS) evapotranspiration product using algorithm MOD16ET (Mu et al., 2013). Humidity and wind speeds input of the MOD experiment were taken from the ERA-Interim reanalysis product (Dee et al., 2011).

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