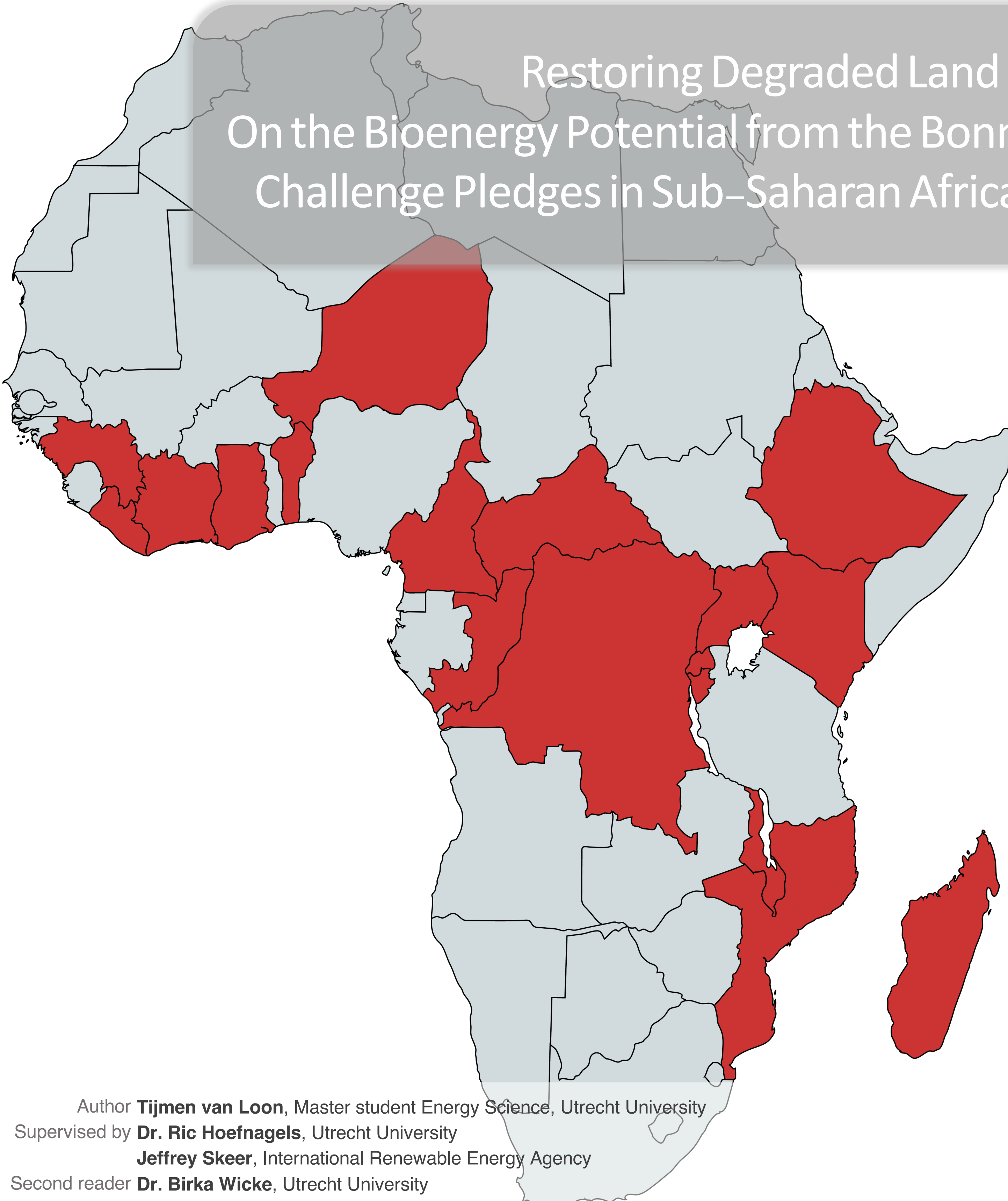
Utrecht University

Restoring Degraded Land :
On the Bioenergy Potential from the Bonn Challenge Pledges in Sub-Saharan Africa



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Abbreviations

AFR100	African Forest Landscape Restoration Initiative
BMUB	Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsichterheit
FAO	Food and Agriculture Organization of the United Nations
FLR	Forest Landscape Restoration
GHG	Greenhouse gas
GIS	Geographic Information System
GLADA	Land Degradation Assessment in Drylands
GLADIS	Global Land Degradation Information System
GLASOD	Global Assessment of Human-induced Soil Degradation
GPFLR	Global Partnership on Forest Landscape Restoration
ha, Mha	Hectare, million hectares
IEA	International Energy Agency
IMAGE	Integrated Model to Assess the Global Environment
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IUCN	International Union for Conservation of Nature
J, GJ, PJ, EJ	Joule, gigajoule (10^9 J), petajoule (10^{15} J) exajoule (10^{18} J)
LPJmL	Lund-Potsdam-Jena managed Land
NEPAD	New Economic Partnership for Africa's Development
PBL	Planbureau voor de Leefomgeving
PIK	Potsdam-Institut für Klimafolgenforschung
ROAM	Restoration Opportunity Assessment Methodology
SRWC	Short Rotation Woody Crop
SSA	Sub-Saharan Africa
UNEP	United Nations Environmental Programme
WEC	World Energy Council
WRI	World Resources Institute

Abstract

Bioenergy, currently the largest source of renewable energy, is expected to play an important role in the future energy mix. However, its large scale use can also have adverse impacts when looking at a broader sustainability perspective, including expansion of cropland resulting in (indirect) land use change. This can be avoided by using underutilised degraded land to grow dedicated bioenergy crops, because this type of land is usually unsuitable and economically unattractive for food crops. Moreover, perennial crops such as short rotation woody crops (SRWCs) could provide different ecosystem services.

A possibility to unlock the potential of degraded land might come in the form of the Bonn Challenge. The Bonn Challenge is a global effort to restore 150 million hectares (Mha) of deforested and degraded land by 2020 and another 200 Mha by 2030. Although bioenergy is not the main objective of the Bonn Challenge, growing bioenergy crops could provide extra economic incentives and possibly additional greenhouse gas emission mitigation by replacing fossil fuels. In a first rough global estimate, the SRWC potential from the Bonn Challenge was estimated to be between 33 and 67 EJ yr^{-1}, assuming that the total restoration area of 350 Mha would be used for bioenergy crop production (IRENA 2016a).

However, some key factors were not considered in determining this potential: local conditions were not taken into account and an average yield was assumed for all regions. Furthermore, it does not show for which countries growing bioenergy crops could be interesting in their restoration strategy. Therefore, keeping in mind both the opportunities and risks posed by bioenergy from degraded land, it is important to give a more accurate estimate of the bioenergy potential in context of the Bonn Challenge. The present study seeks to address this need by estimating the sustainable potential from restoration pledges made to the Bonn Challenge. The focus is on Sub-Saharan Africa, which is considered a leading continent due to the large number of pledges from Sub-Saharan Africa countries.

Two analyses were done. First, the biomass potential for all 18 pledges in Sub-Saharan Africa was estimated using the area pledged by each country as input. This analysis used a geographic explicit method as summarised in Figure A. Scenarios were used to provide insight in the impact of key uncertain factors on the total potential. The scenarios (step 3, Figure A) were used to see the effect of different management strategies a country could use to restore their pledged area. They varied in the share of the pledge used for SRWC plantation and in the location that is used: either the use of land with a high yield (*Resource* focused), a high degree of degradation (*Restoration* focused) or a high degree of degradation while excluding agriculture (*Restricted*) was prioritised.

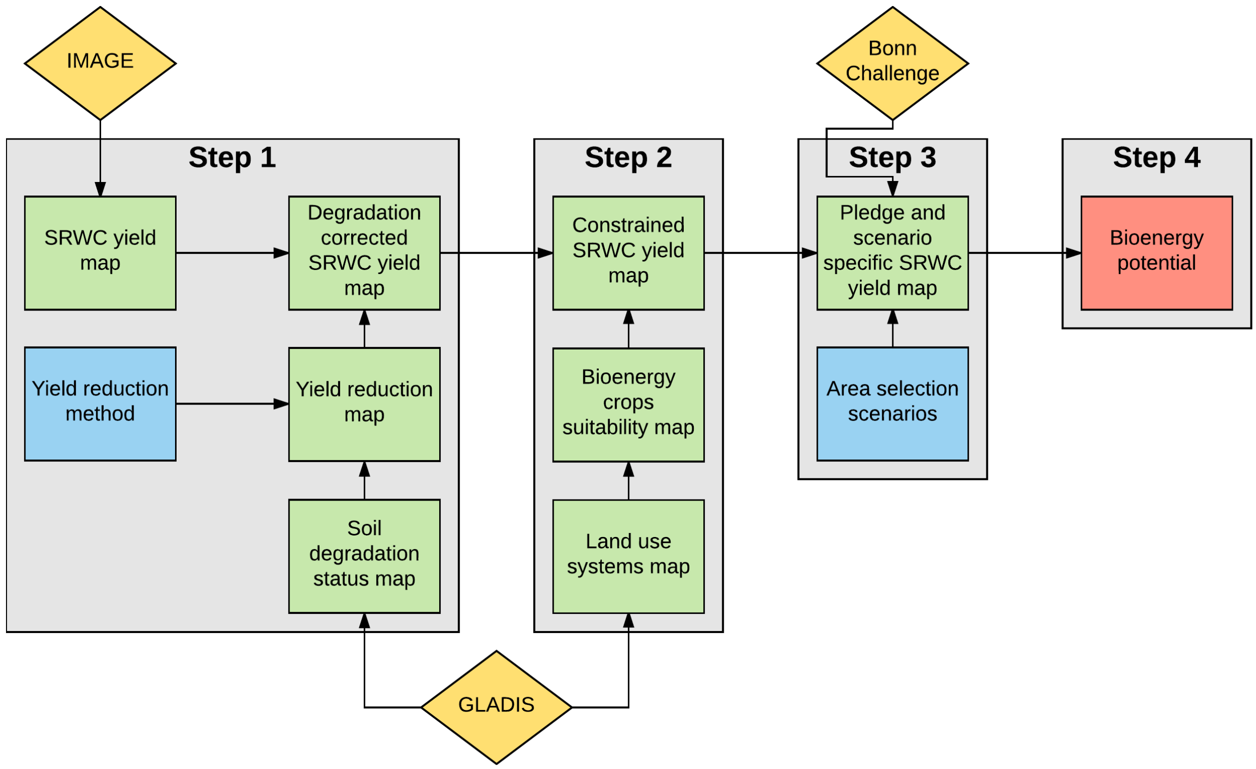

Figure A Overview of the analysis for Sub-Saharan Africa restoration pledges. Sources of input data are shown in yellow, maps in green, other methods in blue and results in red.

The findings of this analysis are shown in Figure B. If all pledges are completely used for bioenergy production (*Resource* scenario), the potential of SRWCs is estimated to be 6.01 EJ yr^{-1}. However, a restoration strategy as considered in the *Resource* scenario is considered infeasible. The scenarios a) using a lower share of the pledges and b) focussing on the use of land with a high degree of degradation are thought to give more realistic estimate of the potential. They still result in substantial potential of 0.20-1.85 EJ yr^{-1}. Congo and Congo DRC are estimated to have the highest potential, while Benin and Niger have a very low potential.

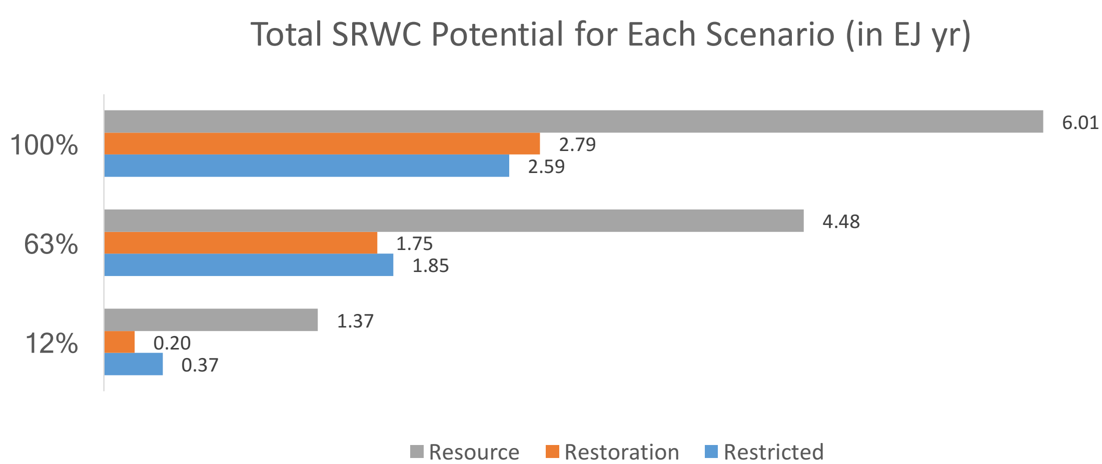

Figure B Total SRWC potential of Sub-Saharan Africa restoration pledges for each scenario

Next to the Sub-Saharan Africa analysis, a more detailed country level analysis was conducted for Rwanda and Kenya. This analysis used studies on the potential areas suitable for restoration and the potential restoration options on these areas. The results show that Rwanda has a potential of 45 PJ yr^{-1} on 1.4 Mha when the restoration strategy as proposed by the ROAM[1] assessment is executed. Kenya has a potential of 28 PJ yr^{-1} on 2.2 Mha. This method could be applied to other countries once their ROAM assessments have been completed.

From the present study, it is clear that bioenergy could contribute substantially to the Bonn Challenge by providing additional economic benefits and sustainable biomass supply. The underlying principle behind the initiative, forest landscape restoration, includes restoration activities in which cultivation of perennial bioenergy crops could be envisioned. Sustainable bioenergy production could give a boost to the Bonn Challenge, by providing extra economic incentives and possibly additional greenhouse gas emission mitigation by replacing fossil fuels. Depending on the strategy used for restoring the pledged area, the bioenergy potential could be substantial. The restoration strategy will be completely depended on the goals and opportunities in each country. Conducting studies on a country level is therefore necessary in order to provide a more detailed potential. Incorporating this in future ROAM studies is an interesting option, as these studies involve engagement with local stakeholders.

When the original estimate (33-67 EJ yr^{-1} on 350 Mha) is converted to the 75.4 Mha assessed in the present study, this yields a potential of 7.1-14.4 EJ yr^{-1}. The results of the present study show that this estimate is likely too high. Using more detailed data in a future study could reduce the range of potential further.

[1] ROAM (Restoration Opportunities Assessment Methodology) is a methodology developed to assist countries in assessing their potential for forest landscape restoration.

1 Introduction

The worldwide use of bioenergy has increased greatly over the last years (IEA Bioenergy 2016; IRENA 2016b), mainly driven by an increase in demand for low-carbon energy (Schueler et al. 2016). At present, global bioenergy use is estimated to be a little above 50 exajoule (EJ) yr^{-1} (Creutzig et al. 2015) and in future projections, especially in ambitious climate change mitigation scenarios, the increasing trend is likely to continue, with bioenergy expected to play an important role in the future energy mix (IPCC 2014). The use of bioenergy on a large scale has the potential to reduce greenhouse gas (GHG) emissions, reduce reliance on fossil fuels and improve opportunities to develop the agricultural sector (IPCC 2011, Nijsen et al. 2012).

However, bioenergy can also have negative impacts when looking at a broader sustainability perspective. Using land for energy crops could, directly or indirectly, lead to the conversion of natural vegetation to agricultural land, thereby lowering biodiversity and enhancing GHG emissions (Searchinger et al. 2008). It can also lead to different GHG emissions, such as nitrous oxide (N_2O) because of fertilizers (Smeets et al. 2009). Finally, if bioenergy crops are grown on productive land, it may compete with food, feed and material production for land, water, capital and labour (Eickhout et al. 2008; Rosegrant 2008).

Many of these disadvantages are related to direct land use change and the implied indirect land use change[2]. Land use change issues might be avoided by using degraded land to produce bioenergy, because this type of land is usually unsuitable and economically unattractive for food crops. Growing bioenergy crops on degraded land, especially perennial crops, could significantly increase the productivity of the land and would have little negative impacts on biodiversity and GHG balance (Nijsen et al. 2012; Immerzeel et al. 2014). Using land with no or little previous productivity can contribute to social and economic development in rural regions.

There are also several possible disadvantages. Because of the difficult growing conditions on degraded land, growing perennial energy crops will require more effort over a possibly long period of time. Even then, the expected yields in these areas will be lower than on high quality land. Furthermore, these degraded lands are often a crucial resource for poor rural communities (Öko-Institut & UNEP 2009; Schubert et al. 2009; Dornburg et al. 2010; van Dam et al. 2010). It is important not to overstate the availability and productivity of these areas, as it may divert attention from other necessary actions to lower pressure on the agricultural land, like increasing yields on existing cropland and lowering the demand for land-intensive products (Gibbs & Salmon 2015).

However, while keeping in mind the disadvantages, it is clear that degraded lands offer a potential source for growing bioenergy crops. A possibility to unlock this potential might come in the form of the Bonn Challenge. The Bonn Challenge is a global effort to restore 150 million hectares (Mha) of deforested and degraded land by 2020 and 350 Mha by 2030. The first target was issued by civic, business and government leaders in a meeting hosted by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) and IUCN in 2011. In 2014, this target was extended by the New York Declaration on Forests, which calls to restore another 200 Mha by 2030. The Bonn Challenge is overseen by the Global Partnership on Forest Landscape Restoration (GPFLR). As of March 2017, a total of 40 pledges in 35 countries spread over four continents were made: Africa, Asia, North and South America. These amount to a total of 148.38 Mha land to be restored (IUCN 2016b).

Africa is the continent that accounts for the largest share of global degraded land (Nachtergaele et al. 2011), making it especially suitable for restoration under the Bonn Challenge. Therefore it is not

[2] Direct land use change refers to the clearing of forests or grasslands to use the area for bioenergy crops directly. Indirect land use change could occur when existing cropland is used for bioenergy production. This causes higher crop prices, which leads to farmers clearing more natural vegetation for food/feed crops (Searchinger et al. 2008).

surprising that Africa is seen as the leading continent for the Bonn Challenge (IUCN 2016a). Under the African Forest Landscape Restoration Initiative, AFR100, 18 Sub-Saharan African countries are expected to pledge 100 Mha and had already pledged a total of 75.36 Mha as of March 2017, accounting for over half of the total land pledged for restoration globally. Several countries have underlined their commitments by carrying out assessments to estimate their restoration potential. Among the countries that finished an assessment are Rwanda and Kenya, both of which have also published their findings (MNR Rwanda 2014; MENR Kenya 2016).

The Bonn Challenge uses a forest landscape restoration (FLR) approach, aiming to restore the ecological integrity of the land, while also providing benefits for people by creating multifunctional landscapes (IUCN & WRI 2014). Sustainable bioenergy production, not conflicting with food, feed and material production, could be part of this. As such the momentum created by the Bonn Challenge offers an opportunity. Vice versa, sustainable biomass production for energy might also provide a boost to the Bonn Challenge. It could improve the economic sustainability of the projects undertaken, as well as provide additional GHG emission mitigation by replacing fossil fuels. Furthermore, the extra incentive given by bioenergy crop production could increase the chance of success of the Bonn Challenge. In Africa, another benefit could be that additional bioenergy production could lower the high energy insecurity of the region, as well as generate employment and income, thereby reducing poverty.

Energy crops can be subdivided into oil containing, sugar and starch crops, like jatropha, oilpalm, sugar cane, corn or weed, and lignocellulosic crops. These include grassy crops, like miscanthus and switchgrass and short rotation woody crops (SRWCs), like poplar, willow and eucalyptus (Vis & van den Berg 2010). Analyses have shown that current practices to convert plant oil or carbohydrates into biofuels might have limited capabilities to lower emissions (Crutzen et al. 2008; Fargione et al. 2008). Furthermore, those crops do not grow well on degraded land and would compete with food production (Searchinger et al. 2008). Therefore high expectations rest on the lignocellulosic crops. As FLR aims to increase the health and/or the number of trees in an area, SRWCs are the ideal crops to plant for restoration. SRWCs are especially well suited for landscape restoration because they can grow on non-prime agricultural land and could provide different ecosystem services: increase soil carbon sequestration (Matos et al. 2012; Qin et al. 2016), reduce soil degradation processes like water and wind erosion (Blanco-Canqui 2016) and improve wildlife habitat (Haughton et al. 2016).

A first rough global estimate of the SRWC potential from the Bonn Challenge was made: between 33 and 67 EJ yr^{-1} from restoring the total of 350 Mha (IRENA 2016a). This is in the range of studies calculating the global potential for dedicated bioenergy crops on degraded land, which give estimates between 5 EJ yr^{-1} and 147 EJ yr^{-1} (Hoogwijk et al. 2005; van Vuuren et al. 2009). This wide range is due to several factors. Firstly, different studies have different goals, different scope and system boundaries and evaluate different time frames (Thrän et al. 2010). Secondly, studies focus on different biomass resource types and different types of biomass potentials. Thirdly, different methodologies and approaches are used to calculate the bioenergy potential estimates. Finally, a variety of datasets and scenario assumptions are used for aspects like yields, conversion factors and sustainability criteria (Batidzirai et al. 2012).

1.1 Research Aim

Keeping in mind both the chances and risks discussed above, it is important to give a more precise estimate of the bioenergy potential from land pledged to the Bonn Challenge. The present study therefore seeks to assess this opportunity, focussing on the African continent, by answering the following research question:

What is the sustainable potential of biomass for energy from restoring degraded land pledged to the Bonn Challenge by African countries?

Because of the large discrepancies in estimates, different attempts were made to harmonize the bioenergy research potential assessments (Vis & van den Berg 2010; Batidzirai et al. 2012). In the Best Practices and Methods Handbook (Vis & van den Berg 2010) a set of best practice guidelines is given, which are followed in the present study.

Next to an analysis on continental scale, Rwanda and Kenya will be analysed in detail, as they are two of the leading countries and have a relatively high data availability to determine the potential of biomass. The method used for these country analyses should be scalable so it can be used also for countries in future studies. The following sub questions are to be researched:

1. *What areas within the countries that made a pledge are identified to be restored?*
2. *What restoration activities are planned in each country?*
3. *What is the status of land degradation in these countries?*
4. *What is the expected bioenergy yield from restoration areas?*

The biomass potential largely depends on two factors: the available land area and the yields of cultivated biomass (Wicke 2011). The first two sub question deal with the available land area. Both Rwanda and Kenya have already assessed which area has the potential to be restored, the available land is very well defined. This is not the case for countries that did not complete a ROAM assessment, however. Both sub questions are further discussed in section 2.1.

The other two sub questions deal with the biomass yields. The type and severity of degradation will influence the expected yields, which is why it is important to get an insight in the status of land degradation. This is done in the present study using the GLADIS (Global Land Degradation Information System) database (Nachtergaele et al. 2011). The bioenergy crop yield is estimated using data from the IMAGE (Integrated Model to Assess the Global Environment) model (Stehfest et al. 2014). Both are treated in section 2.2 on input data.

2 Background and Input Data

2.1 Background

In section 2.1, background on the Bonn Challenge is summarised in the following sections:

- 2.1.1 On forest landscape restoration (FLR), the concept underlying the Bonn Challenge.
- 2.1.2 On the study assessing the global opportunities for FLR.
- 2.1.3 On the methodology developed to assess local FLR potential, the Restoration Opportunities Assessment Methodology (ROAM).
- 2.1.4 On the application of ROAM in Rwanda.
- 2.1.5 On the application of ROAM in Kenya.
- 2.1.6 On the basis of the Bonn Challenge, degraded land.
- 2.1.7 On the mapping of degraded land on a global scale.
- 2.1.8 On the key messages on the Bonn Challenge.

2.1.1 Forest Landscape Restoration, the Concept Underlying the Bonn Challenge

The Bonn Challenge is based on forest landscape restoration (FLR), which is defined as "the long-term process of regaining ecological functionality and enhancing human well-being across deforested or degraded forest landscapes" (IUCN & WRI 2014). The Forest Landscape Restoration Handbook describes the four key features of FLR in this definition (Rietbergen-McCracken et al. 2007):

1. FLR is a participatory process based on adaptive management of the landscape and it requires a consistent learning and evaluation framework.
2. FLR seeks to regain full ecological functionality, meaning that it is not about replacing just one or two forest functions (i.e. the goods, services and processes that forests deliver) across the landscape, as that tends to be discriminatory and unsustainable.
3. FLR looks to enhance human well-being as well as ecological functionality; according to the so-called the double filter criterion the two objectives should be as balanced as possible.
4. FLR is implemented at landscape level, which means that decisions on site-level restoration should be taken within a landscape context.

FLR is not necessarily about returning to the original state of forest. It should be seen as a forward-looking approach to help strengthen the forests while keeping future options open (Rietbergen-McCracken et al. 2007). This, in combination with the focus on the landscape level, means that after restoration there typically will be a balance between different land uses across the landscape (IUCN & WRI 2014). Activities that can be included in FLR are (Rietbergen-McCracken et al. 2007):

1. Rehabilitation and active management of degraded primary forest
2. Active management of secondary forest growth
3. Restoration of primary forest-related functions in degrade forest lands
4. Promotion of natural regeneration on degraded/marginal lands
5. Ecological restoration
6. Plantations and planted forests
7. Agroforestry and other on-farm trees

Finally, it is necessary to mention that FLR aims to increase the number and/or health of trees in the area of implementation (IUCN & WRI 2014).

2.1.2 Estimating Forest Landscape Restoration Potential on a Global Scale

A first assessment of global opportunity for forest landscape restoration was commissioned by the Global Partnership on Forest Landscape Restoration (GPFLR) before initiation of the Bonn Challenge. In this assessment, it was estimated that more than 2 billion ha offer opportunity for FLR, as shown in Figure 2.1

(Laestadius et al. 2011), about 15% of the total global land surface area. This is in a similar range with land degradation studies, which estimate degraded land between 0.5 to 6 billion ha (Gibbs & Salmon 2015).

Laestadius et al. (2011) first estimated where forests could potentially grow if there were no human interventions, i.e. the potential forest coverage. Data on climate, soil type and elevation were used, as well as the current and historical forest extent. The map of *potential* forest coverage was then compared with a map of *current* forest coverage to identify areas that have been *deforested*. Next, *degraded* areas were identified as land where tree cover is lower than its potential. Finally, areas with a high human pressure were excluded: densely populated areas (>100 persons/km^2), cultivated areas and intensively used areas.

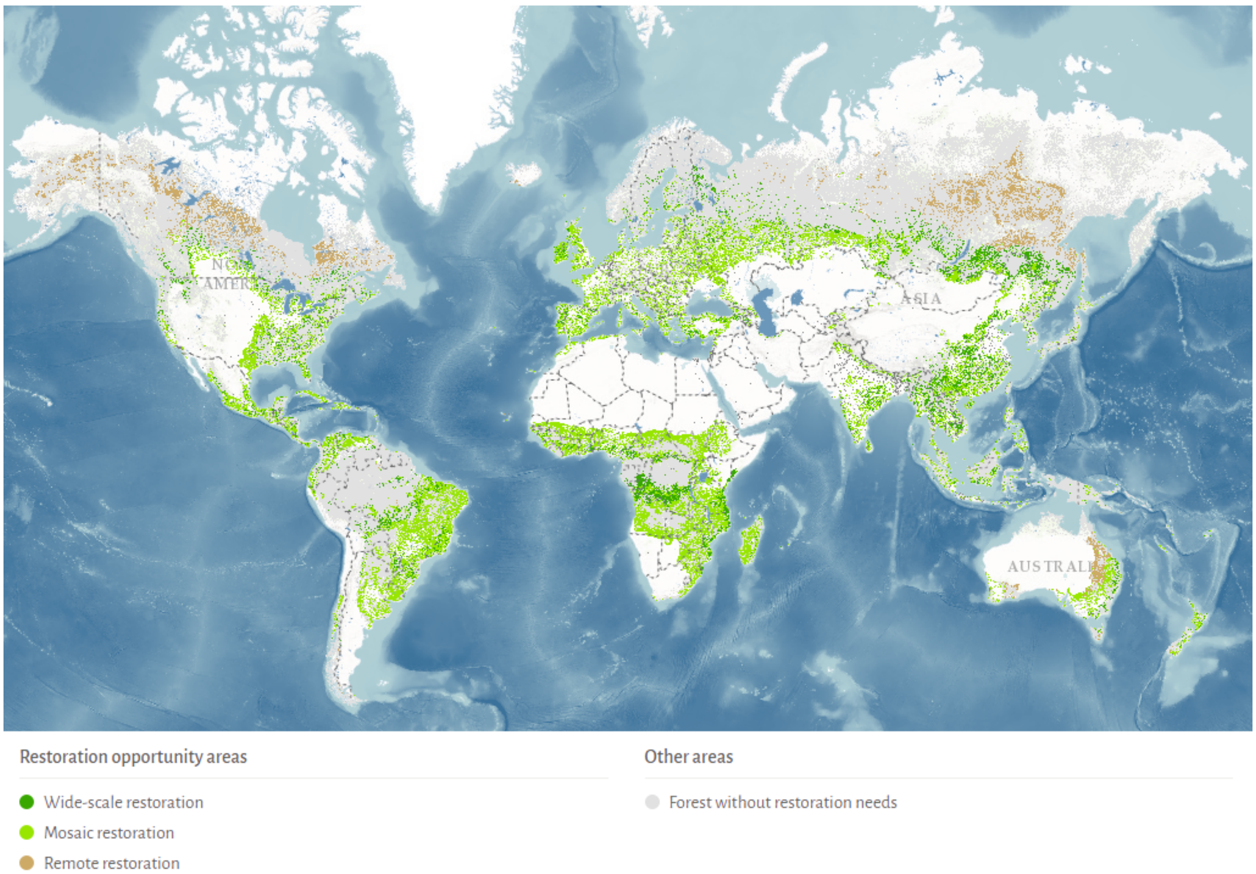

Figure 2.1 World forest landscape restoration opportunity according to Laestadius et al. (2011)

In the Laestadius assessment, restoration opportunity is divided in three different categories:

1. 0.5 billion ha of land is suitable for wide-scale restoration. This is land with a population density of less than 10 persons/km^2 and the potential to support a closed forest (canopy of >45%).
2. 1.5 billion ha is found to be suitable for mosaic restoration, making it the biggest opportunity in terms of area. Mosaic restoration is assumed to be the most likely option in an area with a moderate human pressure (10-100 persons/km^2). In such areas, forests are combined with other land uses that incorporate trees. Examples are agroforestry, small-holder agriculture and buffer plantings around water courses or settlements.
3. 0.2 billion ha offers an opportunity for remote restoration. These areas are unpopulated lands far away from human settlements, mainly northern boreal forests that have been degraded by fire. These would be difficult (i.e. costly) to restore actively, but could naturally regain health and function.

Although Laestadius estimates are in the same range as global land degradation studies, the goal was not to map degraded land but rather to map the opportunity for FLR. As there are various reasons why forest cover may be lower than its potential, this land is not necessarily degraded. Also, land might be degraded in regions where no FLR potential exists. Land degradation is treated in detail in section 0.

2.1.3 Estimating the Forest Landscape Restoration Opportunity on a Country Level

While the study by Laestadius et al. (2011) presents the big picture for FLR potential, its low resolution (i.e. level of detail) and lack of country specific input data makes it of little use for country level decisions (IUCN & WRI 2014). The Restoration Opportunities Assessment Methodology (ROAM) was developed to assist such decisions, by providing analytical input to national or sub-national FLR policy planning. ROAM is not designed to identify specific restoration projects, but it can serve as a starting point by identifying areas that are most suitable for restoration (IUCN & WRI 2014).

During a ROAM assessment, different sides of the restoration opportunity are explored. The total magnitude of restoration opportunity in an area is determined, considering social, economic and ecological factors. The different types of restoration in a country, and in which specific places, are determined. The costs and benefits of different restoration strategies are assessed. Finally, the policy, financial and social incentives that exist or are needed to support restoration efforts in a country are identified, as well as the important stakeholders (IUCN & WRI 2014).

The ROAM method was initially tested in four countries: Ghana, Rwanda, Mexico and Guatemala (IUCN & WRI 2014). As of February 2017, ROAM assessment reports have been completed for four African countries: Rwanda, Ivory Coast, Kenya and Uganda (MNR Rwanda 2014, MINEDD Ivory Coast 2016, MENR Kenya 2016, MWE Uganda 2016). Furthermore, assessments are being made in Brazil, Colombia, Costa Rica, DR Congo, El Salvador, Ethiopia, Ghana, Guatemala, Indonesia, Kenya, Madagascar, Malawi and Nicaragua (Diana Mawoko personal communication 21/02/2017, IUCN 2016b).

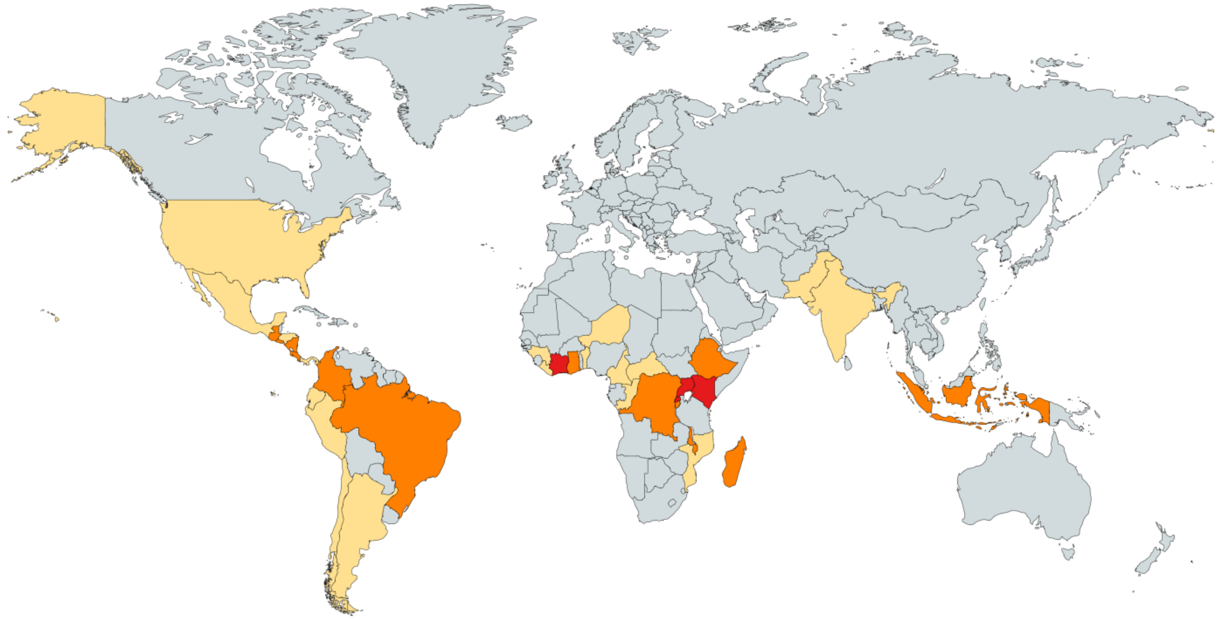

Figure 2.2 Overview of countries that had made Bonn Challenge pledges as of March 2017 (yellow), countries that in addition were undergoing a ROAM potential assessment (orange) and countries which had completed a ROAM assessment report (red).

2.1.4 The Forest Landscape Restoration Opportunity in Rwanda

Rwanda was the first African country to pledge to the Bonn Challenge, as well as the first to complete a ROAM assessment (MNR Rwanda 2014). The objective of Rwanda is to achieve border-to-border forest and landscape restoration, reversing countrywide national resource depletion. Since Rwanda is densely populated, pressure on its existing natural resources is high. This causes degradation, deforestation, soil erosion and loss of biodiversity. FLR would support different sustainable development objectives: improved ecosystem quality and resilience, creation of opportunities for rural livelihoods, increased water and energy security, and support for low carbon economic development. The goal of border-to-border restoration is reflected in the pledge of 2 Mha by 2020, which is around 75% of the total area of the country.

The ROAM assessment for Rwanda was carried out by a team of government professionals and experts from WRI and IUCN. The assessment areas with the most urgent restoration needs, the most immediate benefits and the greatest chance of success were mapped. Relevant stakeholders contributed to the process through consultative workshops. Landscape restoration opportunities were assessed by conducting a geospatial analysis and a cost-benefit analysis. Success factors for FLR were determined using a Rapid Restoration Diagnostic developed by IUCN and WRI. The methods and results of the geospatial analysis are detailed below, as they are used later on in this study.

Four types of land use were found that could benefit most from restoration by introducing trees and management practices: traditional agriculture, poorly managed woodlots, poorly managed timber plantations and deforested land. Based on these uses, six restoration interventions were identified:

1. Using agroforestry on steep sloping land (3-30°) currently used for traditional agriculture, applying soil conservation measures such as terracing. The selection criteria for this option are treated in detail below.
2. Using agroforestry on flat or gently sloping land currently used traditional, including both cropland and pasture/rangeland. The selection criteria for this option are treated in detail below.
3. Rehabilitating existing eucalyptus woodlots that are currently managed in a sub-optimal way. The selection criteria for this option are treated in detail below.
4. Rehabilitating existing pine timber plantations currently managed in a sub-optimal way.
5. Protecting and restoring existing natural forest, mainly in protected areas.
6. Establishing or improving protective forests on sensitive sites, like ridge tops with steep sloping land, riparian zones and wetland buffer zones.

The first three restoration options are identified as interesting for feedstock production for bioenergy. As this data is used as an input in the analysis, it is important to note their selection criteria. The applicable area for all restoration interventions was selected based on the following geospatial datasets: land cover, forest cover, elevation, slope and finally the locations of national parks, forest reserves, wetlands, lakes, rivers and administrative boundaries. GIS software was used to collect and analyse this data.

Potential areas for agroforestry on steep sloping land were determined by isolating areas that were shown to be cropland from the land cover dataset, non-forested from the forest cover dataset and having a slope between 3 and 30°. Areas for agroforestry on flat or gently sloping land were identified with the same datasets, this time also including grassland/shrub land from the land cover dataset and using a slope lower than 3°. It is important to note here that no criterion on land degradation was included in the selection for agroforestry areas. Areas that could benefit from the third option were selected by isolating the eucalyptus plots in the forest cover dataset. No data on the management status of these plots was available, so it was assumed that all plots could benefit from this restoration intervention.

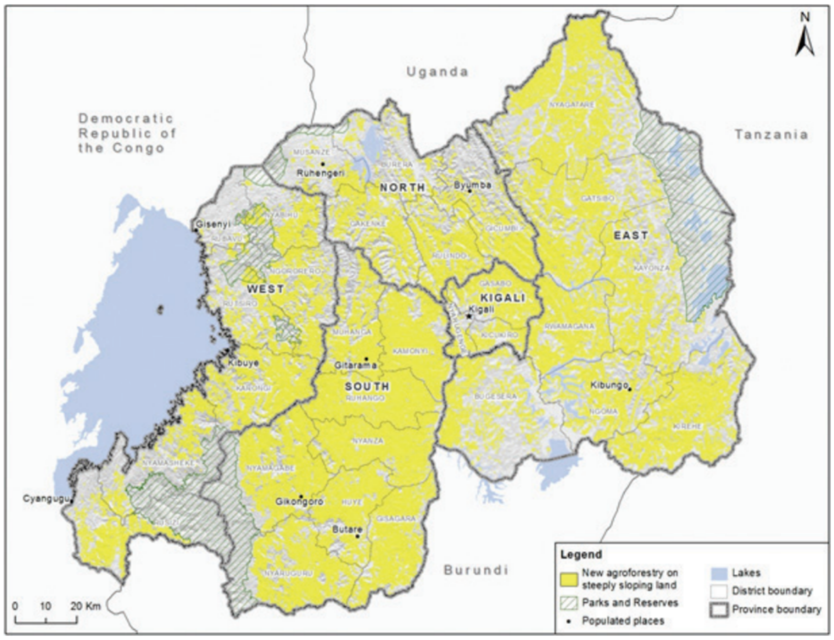

Figure 2.3 Opportunity areas for new agroforestry areas on steeply sloping lands in Rwanda (MNR Rwanda 2014).

The analysis shows a total restoration opportunity of 1.52 Mha, of which 1.37 Mha is of interest for bioenergy, as shown in Table 2.1.

Table 2.1 Potential area for each restoration option in Rwanda (MNR Rwanda 2014)

Restoration option	**Restoration potential (in ha)**
New agroforestry on steeply sloping land	705,162
New agroforestry on flat and gently sloping land	405,314
Improve management of existing woodlots	255,930
Improve management of existing timber plantations	17,849
100m buffer of closed natural forest	3,456
Restore degraded forest in parks/reserves	10,477
Protective forests on ridgetops with very steep slopes (>30°/55%)	10,745
Protective forests on ridgetops with steep slopes (12-30°/20-55%)	31,695
20-m riparian buffer – replace eucalyptus with native species	3,152
20-m riparian buffer – reforest non-forested areas	19,586
50-m buffer of wetland perimeters	57,362
Total	**1,520,728**

2.1.5 The Forest Landscape Restoration Opportunity in Kenya

In Kenya, the process of ROAM assessment is still ongoing. However, a tree-based landscape restoration potential map was published, along with a technical report describing the methodology used (MENR Kenya 2016). Forest restoration has a high priority in Kenya, which is shown by several policies. One of these is the pledge for restoring 5.1 Mha land by 2030 made to the Bonn Challenge and AFR100. Another example is the plan to reforest and maintain a tree cover of at least 10% of the country under the 2010

Constitution (Government of Kenya 2010). To support these goals, a working group was formed to assess the landscape use challenges in the country, as well as the corresponding landscape restoration options. Furthermore, it was tasked with mapping where the different options could be implemented. The resulting maps are meant to identify priority landscapes; additional mapping has to be carried out at landscape level to meet the specific needs of an area (MENR Kenya 2016).

The land use challenges identified were habitat fragmentation/loss of biodiversity, forest degradation, loss of soil fertility, overgrazing/free grazing, deforestation, soil erosion, siltation and sedimentation of waterbodies, water stress on water bodies and soils, flooding, landslides and climate change. To combat these land use challenges, the following seven restoration options were selected (MENR Kenya 2016):

1. Reforestation of natural forests on protected areas that had recent forest cover, or afforestation of protected areas that are without forest cover for a longer period.
2. Rehabilitation of degraded natural forests, i.e. areas that still have forest cover, but that are showing signs of degradation.
3. Use of agroforestry on cropland, subdivided in areas with currently less than 10% tree canopy cover and areas with a tree canopy cover between 10 and 30%. Having a tree canopy cover of 10% on agricultural land is required by law in Kenya (Government of Kenya 2009), which could make the first option a priority. Some areas might benefit from a higher tree canopy cover however, especially areas with degraded soils. 30% was identified as the upper threshold to regenerate degraded land while not affecting agricultural production in a negative way. The selection criteria for this option are treated in detail below.
4. Planting of commercial tree and bamboo plantations on potentially marginal cropland and un-stocked plantation forests. On cropland with a low productivity it might be more beneficial to switch to a plantation, while designated plantations with a very low tree canopy cover can be restored. The selection criteria for this option are treated in detail below.
5. Establishment of tree-based buffer zones along water bodies and wetlands.
6. Establishment of tree-based buffer zones along roads.
7. Restoration of degraded rangelands. This was not one of the original restoration options, but selected after stakeholder consultation because of the large area size and the importance of rangelands to livelihoods and biodiversity. Improving management practices and restoring silvo-pastoral systems and grasslands could improve grazing quality and wildlife habitat.

Of these restoration options, option 3 and 4 are identified as feasible for producing feedstock for bioenergy. Selection criteria were selected for each of the options, after which corresponding national level spatial datasets were determined. For agroforestry on cropland, agricultural land was included from a current land cover dataset. However, large-scale irrigation agriculture was excluded, it was assumed that this type of agriculture would not benefit from a higher tree cover. Next, in the tree canopy cover data set, selections were made for areas with less than 10% tree cover and a tree cover between 10 and 30% for the two different options. Slopes higher than 35% were excluded, as well as protected areas. As in Rwanda, the areas identified for restoration with agroforestry are not necessarily degraded.

For option 4, establishing plantations on marginal cropland and un-stocked plantations, the concepts of marginal cropland and un-stocked plantations had to be defined. For marginal cropland, the cropland was included within a 10 km buffer between agro-climatic zones 4 and 5, as well as zones 2 and 3 for the area surrounding Lake Victoria. These agro-climatic zones were defined by Sombroek et al. (1982) based on moisture availability, with 1 being humid (1100-2700 mm annual rainfall) and 7 being very arid (150-350 mm). Note that this zoning method is different than the agro-ecological zoning method used by the FAO. Agriculture areas in these buffers potentially have marginal yields due to ecological stress and low levels of precipitation. From these defined marginal croplands, only areas with a precipitation of more than 400 mm per year were included, as trees need this to have acceptable survival rates (Hijmans et al. 2005). Also, only areas within 10 km of roads were included, as areas further away were assumed to be too isolated to be easily accessible, which is assumed to be important for these commercial plantations. Like with option 3, areas with a slope above 35%, as well as protected areas were excluded. Un-stocked plantations were simply defined as plantations that have a tree canopy cover below 15%.

The results of the analysis are shown in Table 2.2. Next to the potential, also three different scenarios of restoration by 2030 are proposed: a conservative, intermediate and ambitious one. The conservative scenario is chosen as input in the analysis, as it corresponds with Kenya's pledge to the Bonn Challenge. Following this scenario, a total of 2.2 Mha of land will be restored by 2030 that could produce feedstock for bioenergy applications.

Table 2.2 Potential area and 2030 target for each restoration option in Kenya (MENR Kenya 2016)

Restoration option	**Restoration potential (in Mha)**	**Restoration target 2030 in conservative scenario (in Mha)**
Re- and afforestation of natural forests	1.3	0.1
Rehabilitation of degraded natural forest	3.5	0.7
Agroforestry on cropland with under 10% tree canopy cover	2.7	1.4
Agroforestry on cropland with 10-30% tree canopy cover	2.2	0.4
Commercial plantations on marginal cropland	2.7	0.3
Commercial plantations on un-stocked plantations	0.3	0.1
Buffer zones along water bodies and wetlands	0.1	0.1
Buffer zones along roads	0.3	0.2
Restoration of degraded rangelands	25.7	1.9
Total	**38.8**	**5.1**

2.1.6 Degraded Land, the Basis of the Bonn Challenge?

Degraded land has seen much attention lately because of rising demands of food, feed and fuel, combined with a shrinking agricultural land base in many world regions. The increase of population and growing meat consumption cause a projected doubling of global demand in agricultural products by 2050 (FAO 2006). An additional pressure on land comes from the energy policies adopted by many countries to encourage more bioenergy production (WEC 2011). An important component to increase (food) production will be to increase the yield of existing cropland. However, this will not be sufficient by itself (Ray et al. 2013). The expansion of agricultural area often comes at the expense of natural ecosystems, leading to loss of ecosystem services (Gibbs et al. 2010). By using degraded land for crop expansion, these environmental impacts could be largely avoided (Fargione et al. 2008). This is especially true for perennial bioenergy crops, as they are thought to be more resistant to lower conditions than most food crops (Tilman et al. 2006; Gelfand et al. 2013).

There are many different definitions for degraded land. Wiegmann et al. (2008) presents a set of comprehensive definitions for degraded land and related terms. Degraded land is defined as land that suffered from a long-term loss of ecosystem function and services, caused by disturbances from which the system cannot recover unaided (UNEP 2007). Marginal land is land on which a cost-effective food and feed production is not possible under given site conditions and cultivation techniques (Schroers 2006). Waste land is land that is characterized by natural physical and biological conditions that are per se unfavourable for land-associated human activities (Oldeman et al. 1991). It must be noted that the above definitions are not used in all available literature. This is mainly the case with the terms degraded and marginal land, which are often used with interchangeable definitions (Lewis & Kelly 2014). For this reason, several studies are used here in which marginal land has a similar meaning to the given definition of degraded land.

The Bonn Challenge could be a means to capitalise on the potential of degraded land. However, the Bonn Challenge is not just about restoring degraded land. The official goal is to restore deforested and degraded land (IUCN 2016b). Deforested areas are not necessarily seen as degraded. Without deforestation, most productive agricultural areas would not exist (FAO et al. 1994). The ROAM assessments show that even areas that are not necessarily degraded or deforested, are considered as options for FLR (MNR Rwanda 2014; MENR Kenya 2016). Still, the topic of land degradation is important for the present study, as a (large) share of the restoration will take place on degraded lands and the biomass yields might be greatly impacted by it (Blanco-Canqui 2016).

Because the present study aims to provide a methodology to estimate the yields of all Bonn Challenge pledges, land degradation and the associated yield loss are preferably incorporated using globally consistent data. As a method for the assessment of land degradation on a country level is missing (Bruinsma 2003), the focus lays on a global land degradation mapping method.

2.1.7 Mapping Degraded Land on a Global Scale

The utilization of degraded lands holds potential, but due to the use of highly uncertain degradation datasets, the potential of degraded land, e.g. for energy, is often overestimated (Gibbs & Salmon 2015). This poses severe risks, as it may misinform policymakers. Because the location, area and condition of degraded land is not well understood, a reality-based strategy is hindered. There is no clear consensus on the degraded land area, on a global level, but also on country level. Furthermore, no comprehensive country level assessment method exists to keep track of degradation conditions (Bruinsma 2003).

The high variance in estimates has multiple causes. Firstly, the definition of degraded lands is not always the same. Often it is used to describe a whole set of processes, e.g. desertification, salinization, erosion, compaction. However, sometimes only a part of these processes is included in the term (Gibbs & Salmon 2015). Furthermore, some studies include degradation due to natural causes, others only include human induced degradation (Wiegmann et al. 2008) and it is often difficult to distinguish between these.

On top of this, the temporal and spatial scope of studies differs. Some estimates focus on the current status of land, i.e. looking at past degradation, while others consider the ongoing degradation processes and even others treat the risk of future degradation. Furthermore, lands with a natural low productivity are sometimes included as degraded lands. Finally, some efforts have focussed on soil degradation, while more recent ones look at land degradation in a broader sense, also including vegetation (Gibbs & Salmon 2015).

There are four different main methods to quantify degraded lands: expert opinion, satellite-derived net primary productivity, biophysical models and the mapping of abandoned cropland. Each of these shows a part of the conditions, but they all have their weaknesses as well (Gibbs & Salmon 2015).

The oldest method to assess degraded lands is that of expert opinion. Although subjective and qualitative, this method is still widely used. This is expected to remain so, because degradation will remain a subjective concept with location specific benchmarks (Sonneveld & Dent 2009). The most widely known map based on expert opinion is the Global Assessment of Soil Degradation (GLASOD), commissioned by UNEP (Oldeman et al. 1991; Oldeman 1988). It was the first attempt to map worldwide human induced degradation and although it is relatively old, it is still used (Nijsen et al. 2012). Despite several limitations, including the qualitative judgments used as input and the coarse spatial resolution, it remains the only globally consistent information source on land degradation (Gibbs & Salmon 2015).

The second approach is the satellite-based approach, which has the potential to improve the spatial representation of degraded land in a consistent way. It is both quantitative and repeatable. However, the disadvantages are that it tends to neglect soil degradation, it can only measure degradation after 1980 and it is difficult to distinguish between naturally low productive and (human induced) degraded areas. An example of this approach is the Global Assessment of Lands Degradation and Improvement (GLADA) project of FAO (Bai et al. 2008). Part of this project is to quantify ongoing degradation between 1981 and 2003 using the normalized difference vegetation index (NDVI), used to assess vegetation condition and productivity. Deviations from the normal NDVI could indicate land degradation, if other factors like rainfall, climate and land use are taken into account. The methods for GLADA received criticism (Wessels et al. 2012), and the satellite-based assessments will never be able to capture the full picture of degradation. However, the approach can still provide valuable clues and could identify ongoing degradation hotspots.

Biophysical modelling is the third method. It is broadly used to map potential productivity and crop suitability, commonly using global data sets on climate patterns and soil type. Combining these with observations of productivity, they can be used to map degradation. A prominent example is the study by Cai et al. (2011), that used a biophysical model including spatial data on soil type, topography, average air temperature and precipitation. Areas with low production potential, marginal areas, that coincided with observed low-productivity cropping were indicated as abandoned, idle or wasted, while marginal areas with observed full cropping were indicated as degraded. In other words, the extent of degradation was based on over-utilization of land with marginal productivity capability. This approach excludes lands that were previously abandoned, as it focusses on current cropping, as well as non-agricultural degradation and is thus not meant to provide a complete picture. The approach might be applicable to more contexts however. The study by Laestadius et al. (2011), in which the potential for FLR is estimated and which is discussed in section 2.1.2, is another example of this type of assessment.

Finally, degraded lands can be mapped by researching the abandonment of agricultural land. The idea is that these areas that were once cropland have been abandoned because of decreased productivity, however they can also have political or economic reasons. The advantage of this method is that a longer timeframe is captured than with the satellite approach, as data on the changes of cropland is available from 1700 onwards. A prominent database on abandoned cropland and pastures is the History Database of Global Environment 3.0 (HYDE), which is used by (Campbell et al. 2009) to estimate the total area of abandoned agricultural land over the last three centuries. A significant disadvantage of this approach is that land and soil degradation other than abandonment is not included. On the other hand, lands that are not necessarily degraded are also included.

The different studies discussed have very different results. The total extent of degraded land is estimated at 1216 Mha in GLASOD (Oldeman et al. 1991; Oldeman 1988), 2740 Mha in GLADA (Bai et al. 2008), 991 Mha in Cai et al. (2011) and 470 Mha in Campbell et al. (2008). For Africa, the estimates range between 69 Mha in Campbell et al. (2008) and 660 Mha in GLADA. As the datasets use different proxies for degradation, but do not measure degradation directly, not one of them captures all degraded lands accurately. They all have their use, however, as they contribute to the discussion on land degradation.

2.1.8 Key Messages on the Bonn Challenge

Underlying the Bonn Challenge is the concept of Forest Landscape Restoration (FLR). Different restoration options can be considered under this concept, some of these could produce feedstock for bioenergy.

Countries that pledge to the Bonn Challenge generally do this by stating the area that is to be restored, without detail on area or type of restoration. Hence for most countries only this figure is known. By conducting a study using the Restoration Opportunity Assessment Methodology (ROAM), more insight in the possible restoration strategy is given.

According to its definition, FLR is to be implemented on deforested or degraded forest landscapes. However, in the completed ROAM assessment both non-forest and non-degraded areas are considered as potential restoration areas for the Bonn Challenge. In Kenya, for example, restoration of grasslands is also considered (MENR Kenya 2016). Furthermore, land that is not seen as degraded is considered for implementing FLR. Land degradation will be described in more detail in the next section.

The ROAM reports of Rwanda and Kenya show significant potential for restoration activity that could support bioenergy feedstock production. In Rwanda, a total of 1.1 Mha of land has potential to be restored via agroforestry, while another 0.25 Mha are existing eucalyptus plantations that can be improved. In Kenya 1.8 Mha is identified for agroforestry under the conservative scenario, while another 0.4 Mha is eligible for establishment of commercial plantations.

2.2 Input Data

2.2.1 Short Rotation Woody Crop Yield

The SRWC yield map used in the analysis is a result of the integrated assessment model IMAGE 3.0 (Stehfest et al. 2014). IMAGE (Integrated Model to Assess the Global Environment) aims to shed light on the interactions between human development and the natural environment on a global scale. Part of the model is a bioenergy module, which uses the dynamic global vegetation model LPJmL (Lund-Potsdam-Jena managed Land) to calculate potential yields for bioenergy crops.

The IMAGE model is developed by the Netherlands Environmental Assessment Agency (PBL) (Stehfest et al. 2014). Its main aims are related to global environmental change: important processes and response strategies can be analysed. It is mainly used for two purposes: to model and examine a future without drastic changes, e.g. a baseline, and to see how policies and measures could limit the negative impacts on the environment and human development. As shown in Figure 2.4, the model's framework consists of the Human system and the Earth system and its interactions, which result in a set of impacts. This is influenced by the model drivers and policy responses. IMAGE is set-up with a modular structure: next to a core model, IMAGE is linked to several other models which handle different components of the overall framework.

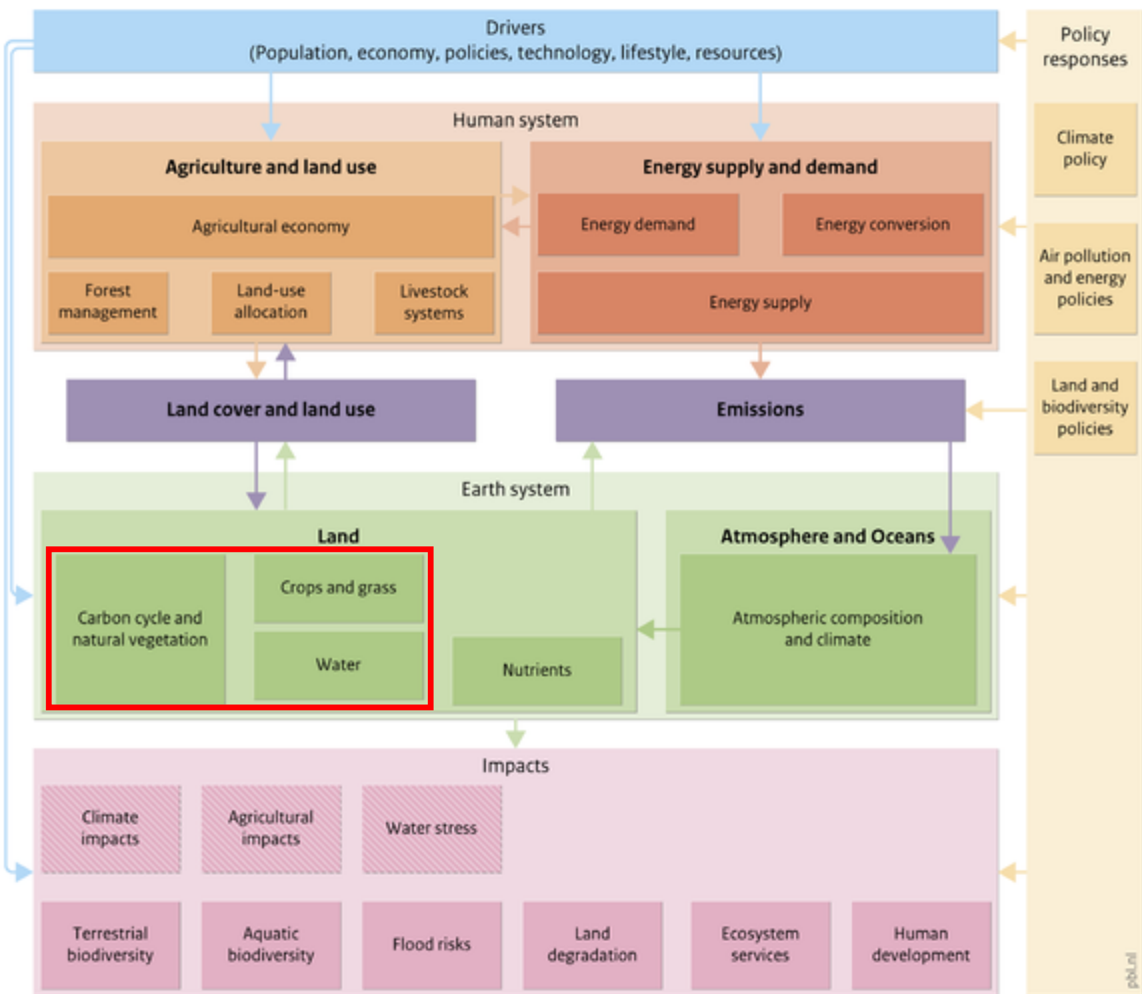

Figure 2.4 IMAGE 3.0 framework, the place of the LPJmL model is outlined in red (Stehfest et al. 2014)

LPJmL, however, is embedded in the core model. It takes care of the Carbon, vegetation, agriculture and water component of the Earth system in IMAGE, outlined in red in Figure 2.4. The bioenergy module is part of one of its subsections: Crops and grass. In this context, LPJmL is used to calculate a total of potentially available bioenergy, by calculating global bioenergy crop yields on a 0.5x0.5 degree grid. This potential supply is restricted by a set of criteria and may or may not be used in the Energy supply and demand component, depending on its economic performance.

LPJmL as a standalone model was developed by the Potsdam Institute for Climate Impact Research (PIK) (Bondeau et al. 2007). It represents both natural and managed ecosystems on a global level. Major ecosystem processes that are important for plant geography, physiology, biogeochemistry and vegetation dynamics are represented in the model, simulating the exchange of carbon and water between the atmosphere and terrestrial life. A total of 9 plant functional types (PFTs), which represent natural vegetation, and 15 crop functional types (CFTs), which represent managed vegetation, describe the global flora. Two of these CFTs represent SRWCs for dedicated biomass plantations, they were added to LPJmL after a study by Beringer et al. (2011). The first represents temperate deciduous SRWCs and is designed to match the performance of poplars and willows. The second represents tropical evergreens and it reproduces the performance of relevant eucalyptus species. Their parameter values are given in Table 2.3.

*Table 2.3 Short Rotation Woody Crop Crop Functional Type parameter values[3]. Values indicated with an * are different from original LPJmL values (adapted from Beringer et al. 2011).*

CFT	**g_{min} (mms^{-1})**	**a_{leaf} (year)**	**f_{leaf} ($year^{-1}$)**	**$f_{sapwood}$ ($year^{-1}$)**	**f_{root} ($year^{-1}$)**	**$T_{c,min}$ (°C)**	**$T_{c,max}$ (°C)**	**R (year)**	**R_{max} (year)**
Temperate tree	0.3	0.5	1	10	1	-30	8	10*	40
Tropical tree	0.2	2.0	2	10	2	7	-	10*	40

Like other parts of the model, the SRWC part has been evaluated against different types of observational data. In this case, they were compared both to existing biomass plantations and predictions of 2050 yield levels. LPJmL simulated yields were found to be in the right order of magnitude and to show a realistic spatial variability (Beringer et al. 2011).

The biophysical yield calculated by LPJmL was multiplied with a management factor generated by IMAGE to calculate the actual yield. The management factor is region and crop specific and represents the effect of multiple yield influencing elements, like the use of pesticides and fertilizers, intelligent cropping and sowing dates, integrated pest and nutrient management and improved crop varieties. The assumption is made that the plantations are non-irrigated. The yields are given in GJ ha^{-1} yr^{-1}, using a calorific heating value of 19.5 MJ kg^{-1} oven dry.

The output for the continent Africa is shown in Figure 2.5.

[3] g_{min} = minimum canopy conductance, a_{leaf} = leaf longevity, f_{leaf} = leaf turnover time, $f_{sapwood}$ = sapwood turnover time, f_{root} = fine root turnover time, $T_{c,min}$ = minimum coldest-month temperature for survival, $T_{c,max}$ = maximum coldest-month temperature for establishment, R = rotation length, R_{max} = maximum time before replanting of plantation.

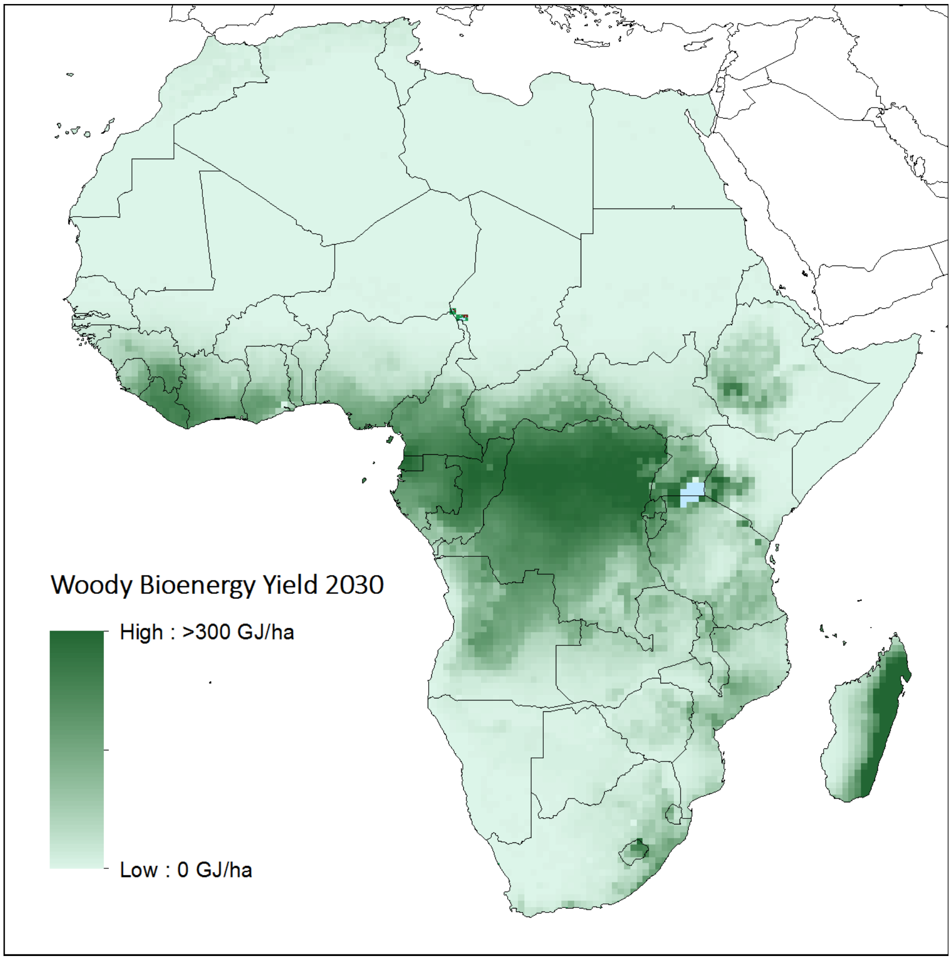

Figure 2.5 SRWC yield in 2030 as calculated by IMAGE 3.0.

2.2.2 Land Degradation

The maps used in the analysis are taken from the Global Land Degradation Information System (GLADIS), a part of FAO's Land Degradation Assessment in Drylands (GLADA) project (Nachtergaele et al. 2011). The ecosystem approach is at the core of it, seeing land degradation as a decline of ecosystem goods and services that the land can provide over a period of time. Ecosystem goods refer to actual products provided by land, e.g. food, construction materials or water, while ecosystem services include more qualitative characteristics of the land provides: regulating climate, cleansing air and water or even providing beauty, inspiration and recreation. These goods and services are grouped in six distinct components, thought to be tangible and measurable: biomass, soil health, water quantity, biodiversity, economic services and social services. So, whereas GLADA focussed on biomass and GLASOD on soil health, GLADIS uses a differentiated approach to cover the subject of land degradation, thereby portraying the complexity of the topic of land degradation.

First, the method to correct the SRWC yield from IMAGE for land degradation, is treated. In this method, the soil health map from GLADIS is used. Then GLADIS' biophysical land degradation status map is discussed, used in the analysis to select the area for bioenergy production in the *Restoration* and *Restricted* scenarios.

2.2.2.1 *Soil Health Status and Correction of the Short Rotation Woody Crop Yield*

The SRWC yields from IMAGE do not take the effect of land degradation into account (Bondeau et al. 2007). This effect can be added with the use of a different database, different studies use degradation data from GLASOD and a simple yield reduction calculation (Beringer et al. 2011; Schueler et al. 2013). After extensive literature research, no yield reduction method was found that uses land degradation data from GLADIS. Therefore, the method used here is adapted from the one presented by Nijsen et al. (2012). This method was designed to derive yield reduction from GLASOD degradation data, one of the predecessors of GLADIS, and therefore needs to be adapted to be applicable to the present study.

As described in section 2.1.7, GLASOD is based on expert opinion (Oldeman et al. 1991; Oldeman 1988). It assessed human-induced soil degradation in the period of 1945 to 1990 and provides data on severity of degradation, in five qualitative degrees, and the area affected in percentage. This is done for each mapping unit, units based on physiographic features ranging in size up to a country the size of Kenya, and for the two most important types of degradation in each unit. The types of degradation considered are compaction, erosion, waterlogging, subsidence and chemical.

Crosson (1997)estimated generic yield reduction percentages that are valid for C_3 annual food crops (crops that fixate CO_2 using only the C_3 pathway, i.e. via 3 phosphoglyceric acid), providing a high and low yield reduction percentage for each degree of degradation. These were later used by the developers of GLASOD as well (Oldeman 1998). Nijsen et al. (2012) adapted these for perennial bioenergy crops, including SRWCs, based on a literature review. Perennial bioenergy crops are thought to be less susceptible to soil degradation, mainly for two reasons: they have certain characteristics that give them a higher stress tolerance, resulting in higher survival rates and therefore higher yields, and they can increase soil organic matter, improving soil quality and yield as a result. The research focused on determining a difference in yield reduction for five different soil degradation induced limitations: nutrients, water, toxicity, agronomy and gaseous exchange. These were translated into the different degradation types mapped in GLASOD, giving a high and low degradation related yield reduction per type.

The axis in the GLADIS framework that corresponds with the GLASOD database is that of soil health, shown in Figure 2.6. The soil health map of GLADIS is based on the Global Agro-Ecological Zones study (Fischer et al. 2002). It is important to note that soils under natural vegetation are not considered degraded, but only when used for cropped agriculture or presence of livestock.

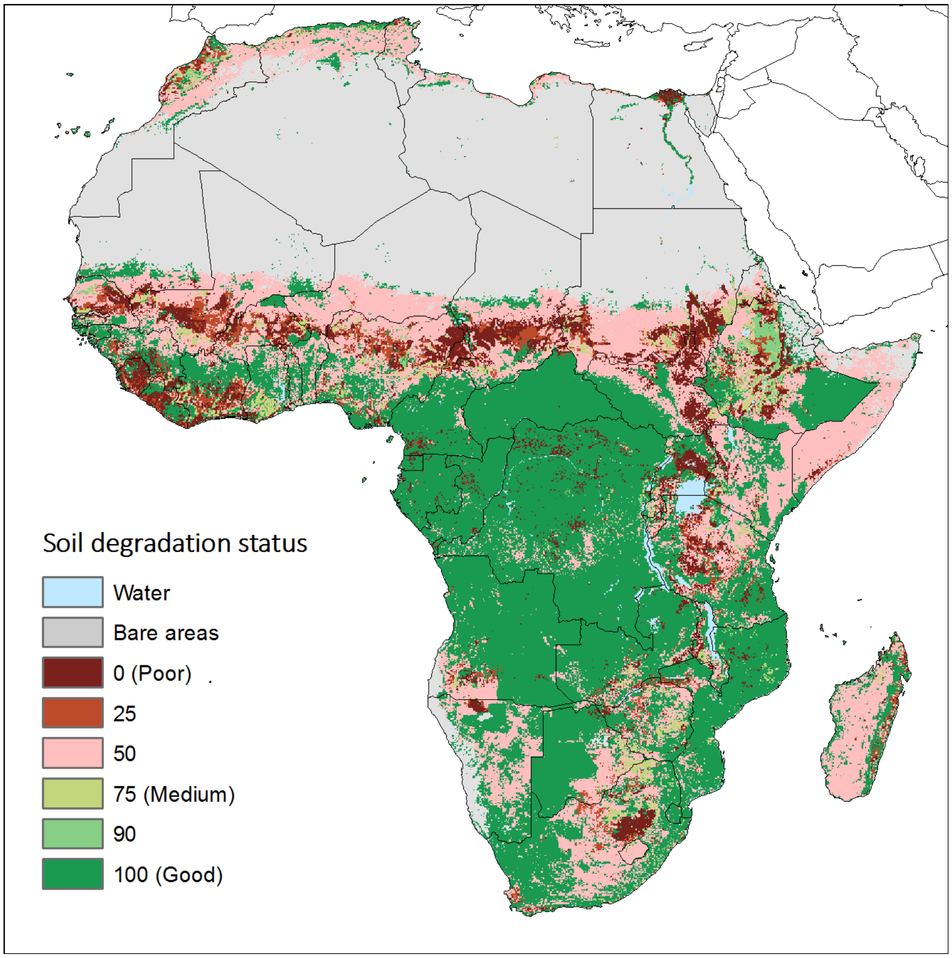

Figure 2.6 Soil health status from GLADIS.

The GLADIS soil health status layer does not contain data on the type of soil degradation. Therefore, the yield reductions per degradation type from Nijsen et al. (2012) are brought back to one value, te lowest for each degree of degradation. This does not greatly affect the level of detail since differences between the degradation types are relatively low. The GLADIS soil health status is divided in 5 equal parts to match the severity classes of GLASOD. Table 2.4 shows the resulting yield reduction method.

Table 2.4 Yield reduction range for GLADIS soil health status range and the equivalent GLASOD degradation degree.

GLASOD degree of degradation	GLADIS soil health status	Perennial energy crop yield reduction range (in %)
No degradation	100 (Good), 90	0
Light degradation	75 (Medium)	4.7
Moderate degradation	50	16.4
Strong degradation	25	44.5
Extreme degradation	0 (Poor)	84.3

2.2.2.2 Biophysical Land Degradation Status

The biophysical land degradation status map is used in the scenarios *Restoration* and *Restricted*. It considers the state of four biophysical ecosystem factors included in the GLADIS study: biomass, soil, water and biodiversity. These factors are weighted according to the main land use of a certain area such that it highlights the importance of each service for that land use (Nachtergaele et al. 2011).

2.2.3 Land Use Systems

In the present study, the global land use systems map from FAO's GLADIS database is used (Nachtergaele & Petri 2013). Constructing this map was included in the GLADIS project, since land use is seen as an important factor in land degradation. For example, land use includes the way the land is managed by farmers, which can have a positive or negative or negative impact on its status. For the construction of this map, data from a number of sources was combined, including the land cover dataset GLC-2000, irrigation data from a study by Siebert et al. (2007), urban areas from the Global Rural Urban Mapping Programme database and protected areas from World Conservation Monitoring Centre data. The land use systems map for Africa is shown in Figure 2.7 with a simplified legend.

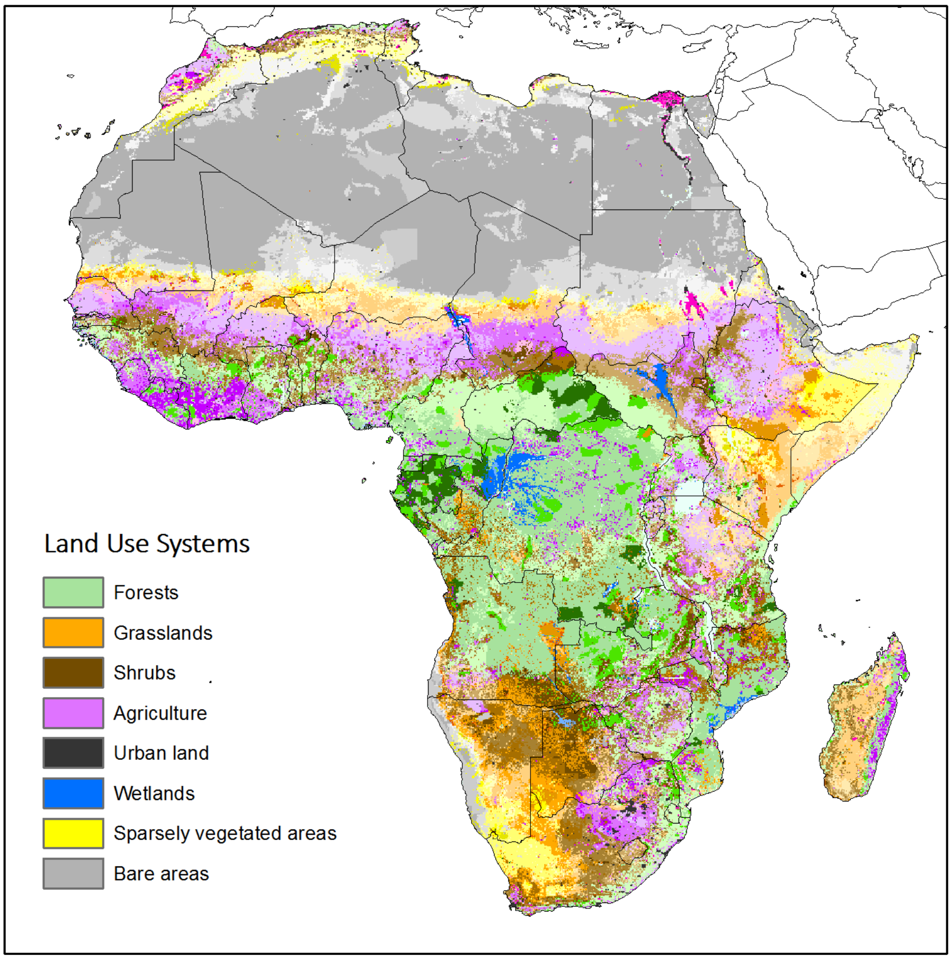

Figure 2.7 Land use systems from GLADIS.

2.2.4 Area of the Pledges

The size of each pledge in million hectares (Mha) is documented on the Bonn Challenge website (IUCN 2016b). Although some pledges are made for a specific region or province, most pledges are countrywide and have no additional spatial constraints. This applies to all African restoration pledges, which are listed in Table 2.5.

Table 2.5 Pledges made to the AFR100 initiative (IUCN 2016b)

Country	2020 pledge (in Mha)	2030 pledge (in Mha)	Total pledge (in Mha)
Benin	0.2	0.3	**0.5**
Burundi	2		**2**
Cameroon		12.06	**12.06**
Central African Republic	1	2.5	**3.5**
Cote d'Ivoire		5	**5**
DR Congo	8		**8**
Ethiopia	15		**15**
Ghana		2	**2**
Guinea		2	**2**
Kenya		5.1	**5.1**
Liberia	1		**1**
Madagascar	2.5	1.5	**4**
Malawi	2	2.5	**4.5**
Mozambique		1	**1**
Niger	3.2		**3.2**
Republic of the Congo		2	**2**
Rwanda	2		**2**
Uganda	2.5		**2.5**
Total	**39.4**	**35.96**	**75.36**

2.2.5 Detailed Restoration Potential Rwanda and Kenya

In section 2.1.4 and 2.1.5, the ROAM assessment results of Rwanda and Kenya are treated. A number of restoration options are identified as interesting for bioenergy production. These have been reclassified into either agroforestry or plantation as shown in Table 2.6.

Table 2.6 Reclassification of the ROAM restoration options

Country	Restoration option ROAM	Reclassified to
Rwanda	New agroforestry on steeply sloping land	Agroforestry
	New agroforestry on flat and gently sloping land	Agroforestry
	Improve management of existing woodlots	Plantation
Kenya	Agroforestry on cropland with under 10% tree canopy cover	Agroforestry
	Agroforestry on cropland with 10-30% tree canopy cover	Agroforestry
	Commercial plantations on marginal cropland	Plantation
	Commercial plantations on un-stocked plantations	Plantation

The resulting maps are shown in Figure 2.8 and 2.9.

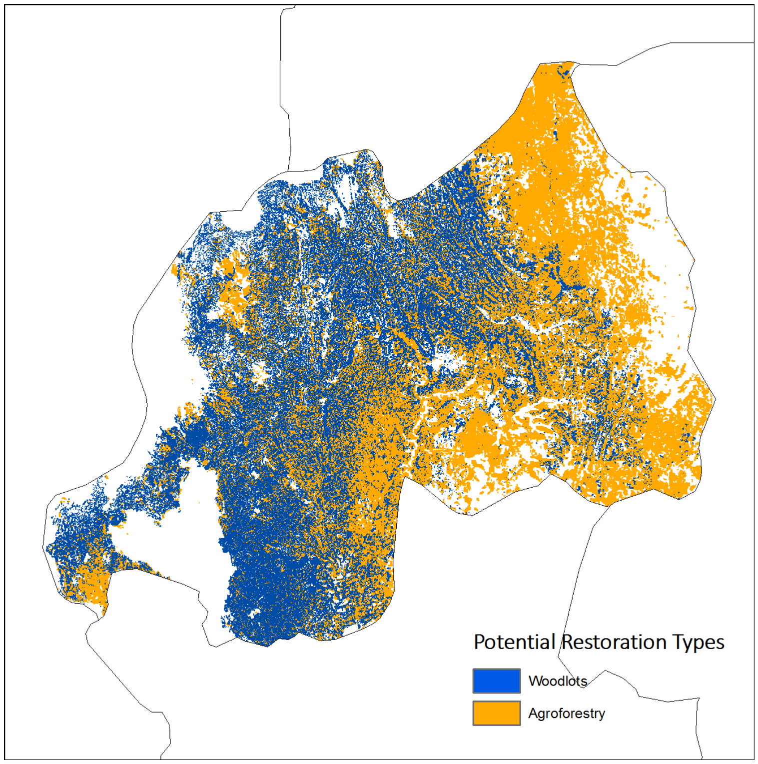

Figure 2.8 Potential restoration options interesting for bioenergy in Rwanda (adapted from MNR Rwanda 2014)

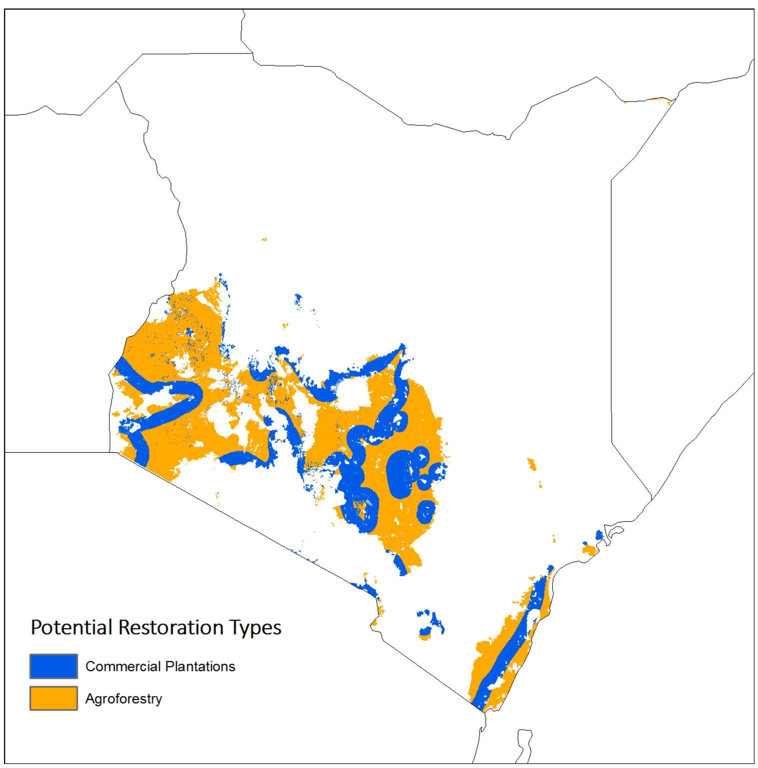

Figure 2.9 Potential restoration options interesting for bioenergy in Kenya (adapted from MENR Kenya 2016)

3 Method

For this thesis, the environmentally sustainable bioenergy potential from the restoration of degraded land in Africa was estimated. Specifically, the opportunity for short rotation woody crops (SRWCs) from pledges made to the African Forest Landscape Restoration Initiative (AFR100) was examined. Two analyses have been done:

1. A method has been developed and carried out to estimate the potential for all 18 pledges using the area pledged by a country in hectares as input. Different scenarios show the effect of different strategies that countries could use for carrying out their restoration commitments.
2. Restoration potential studies for Rwanda and Kenya have been used to give a more detailed image of the potential for these countries. The results of the Restoration Opportunities Assessment Methodology (ROAM) studies show the potential area for different restoration types, which allows for a more precise potential estimate. This method could be applied to other countries once a ROAM assessment is completed there.

A spatially explicit method is used for the analyses, which allows for location specific factors to be taken into account. The geographical information system software ArcGIS from ESRI is used to accommodate this.

The structure of this methodology is as follows:

- 3.1 On the geographical and temporal scope of the analyses carried out.
- 3.2 On the method for estimating the potential of all African restoration pledges, treating the different scenarios examined and the analysis conducted.
- 3.3 On the method for estimating the potential of the Rwanda and Kenya restoration pledges, treating the analysis conducted.

3.1 Scope

3.1.1 Geographical Scope

Both analyses focus on Africa. In the analysis for all African restoration pledges, the following 18 countries were examined: Benin, Burundi, Cameroon, Central African Republic, Congo DRC, Congo, Côte d'Ivoire, Ethiopia, Ghana, Guinea, Kenya, Liberia, Madagascar, Malawi, Mozambique, Niger, Rwanda and Uganda. Global scale data is used on yield, land degradation and land use.

The detailed analysis focusses on Rwanda and Kenya, because the ROAM assessments have been completed for these two countries. The results of the ROAM assessment have a high resolution. However, the remaining data used is the same as for the continent-wide analysis.

3.1.2 Temporal Scope

The target year for pledges made to AFR100 is either 2020 on 2030. This does not mean that the pledged area has to be completely restored by then, but rather that it is to be brought into restoration (WRI 2016). For the present study, the assumption is made that planting of bioenergy crops is started in the target year of the pledge. With a cycle of ten years, one-tenth of the annual accumulated wood mass could be sustainably harvested each year. With a ten-year lag between initial planting and maturation, countries that have pledged land restoration by 2020 are expected to produce a sustainable output of energy wood from 2030 onwards, while those that have pledged to begin restoring land by 2030 are expected to start bioenergy production in 2040.

Since crop yields have been growing over time, typical yields on bioenergy crops can be anticipated to increase between now and the year when production starts. Future bioenergy yields are projected by IMAGE (Integrated Model to Assess the Global Environment). In this model, the increase of crop yield is caused by two factors: the improvement of management practices and the increase of CO_2 concentrations over time. The second factor will not have a major effect in the present study's time horizon, however (Vassilis Daioglou, personal communication 31/03/2017). The IMAGE results for the SSP2 scenario (Shared Socioeconomic Pathway 2) were used to model future bioenergy yields. This scenario is part of a framework set up by the climate change research community. In this framework, SSP2 is a 'middle of the road' scenario (Riahi et al. 2016). It assumes that social, economic and technological trends in the world do not change greatly from historical patterns.

The yields in the present study are based on the yields produced by IMAGE for the year of planting. Thus, for a country that made a pledge for 2020 or 2030, the IMAGE yield for respectively 2020 and 2030 were used.

3.2 Potential of All African Restoration Pledges: Africa Analysis

3.2.1 Scenarios

In this analysis, the bioenergy potential for each of the pledges made to AFR100 is determined. However, two crucial factors for the calculation are not yet available for most countries, because they are not included in the initial pledge. First, information on what share of the pledge will be used for bioenergy production, e.g. what part will be dedicated to planting or restoring SRWC plantations, is missing. Second, the location for implementing the restoration options for bioenergy production is not determined. The ROAM analysis treats both issues on a country level. However, most countries have not completed such an analysis yet. Different scenarios are used to analyse possible strategies. The chosen scenarios give different views on the potential for each pledge.

The scenarios on what share of the pledge will be used for bioenergy are based on the current ROAM assessments for African countries. Four assessments are completed, but only the reports for Rwanda and Kenya resulted in a list of restoration options and the area they could be applied to (MNR Rwanda 2014; MENR Kenya 2016; MINEDD Ivory Coast & MEF Ivory Coast 2016; MWE Uganda 2016). Three scenarios have been based on these results:

1. **100% used for bioenergy.** The results of this scenario show the total bioenergy potential of each pledge.
2. **63.2% used for bioenergy.** 63.2% is the average share of the pledge that the completed ROAM analyses assign to planting/improving plantations and agroforestry practices. The results of this scenario show the potential of each pledge if a large share of each pledge would be used for bioenergy production.
3. **12.3% used for bioenergy.** 12.3% is the average share of the pledge that the completed ROAM analyses assign to planting or improving plantations. The results of this scenario show the potential of each pledge if a low share of each pledge would be used for bioenergy production.

The scenarios on what location will be used for bioenergy production are chosen to show different strategies a country could use. Two assumptions based on ROAM reports have been made. First, non-degraded land can be considered for Forest Landscape Restoration (FLR) (MNR Rwanda 2014; MENR Kenya 2016). Second, agricultural land can be considered for FLR: for agroforestry practices, but in some cases also for plantations (MENR Kenya 2016). The scenarios on the location of bioenergy production on pledged land are:

1. **Resource focused**. Areas with the highest yields are used for bioenergy production. Although this is an unlikely strategy, this scenario shows the maximum bioenergy potential of a pledge.
2. **Restoration focused**. Areas with the highest degree of degradation are used for bioenergy production. This scenario shows the bioenergy potential of a pledge if a country decides to plant SRWCs on the most degraded land that is thought to be suitable for bioenergy production, even if these includes agricultural land.
3. **Restricted:** similar to Restoration focused, but excluding arable land. This leaves the main land categories: grasslands, shrub land and sparsely vegetated areas. By excluding arable land from bioenergy production, food, feed and material production is assumed to be unaffected.

Altogether, nine scenarios are examined as shown in Table 3.1.

Table 3.1 Scenarios in the analysis of the potential of all African pledges

	Share bioenergy: 100%	**Share bioenergy: 63.2%**	**Share bioenergy: 12.3%**
Resource focused	*Resource_100%*	*Resource_63%*	*Resource_12%*
Restoration focused	*Restoration_100%*	*Restoration_63%*	*Restoration_12%*
Restricted	*Restricted_100%*	*Restricted_63%*	*Restricted_12%*

3.2.2 Analysis

The analysis of the bioenergy potential for the African restoration pledges under each scenario is based on the formula below. The potential was calculated for each scenario separately.

$$P_x = \sum_{y=1}^{18} A_{x,y} * Y_{x,y}$$

Where:

P_x = SRWC potential of all African restoration pledges in year x (in EJ)
$A_{x,y}$ = Area selected for bioenergy production in year x and country y (ha)
$Y_{x,y}$ = Average SRWC yield on selected area $A_{x,y}$ (GJ/ha)

To determine $A_{x,y}$ and $Y_{x,y}$, a three step analysis was used:

1. ***Adjust Bioenergy Yield:*** The *degradation corrected yield* was determined by adjusting potential yield downward based on the degree of degradation.
2. ***Apply Bioenergy Spatial Constraints:*** The *area to be considered for bioenergy production* was determined by excluding areas unsuitable or undesirable for bioenergy production.
3. ***Select Bioenergy Production Area:*** The *area on which bioenergy production would take place* for each pledge was specified according to the scenario that is examined, hereby determining $A_{x,y}$ and $Y_{x,y}$.

Finally, P_x was calculated in a fourth step:

4. ***Calculate Sustainable Bioenergy Potential:*** The *potential for bioenergy* for each country ($P_{x,y}$) was determined by multiplying $A_{x,y}$ and $Y_{x,y}$. Summing $P_{x,y}$ for all countries yields P_x.

An overview of the analysis is shown in Figure 3.1, each step is described in more detail in separate sections below.

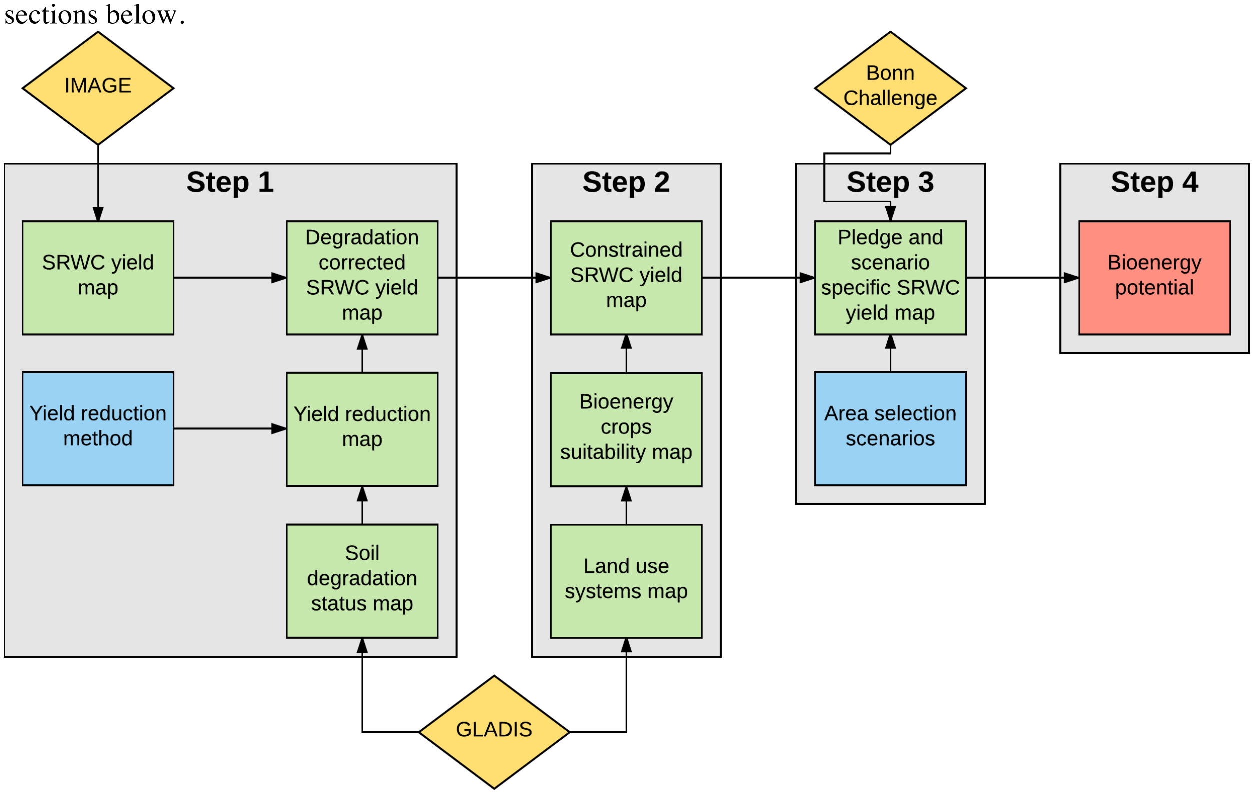

Figure 3.1 Overview of the analysis for all African restoration pledges. Sources of input data are shown in yellow, maps in green, other methods in blue and results in red.

3.2.2.1 Adjust Bioenergy Yield

In the first step, maps on the short rotation woody crop yield from IMAGE (Integrated Model to Assess the Global Environment) and the status of soil health from GLADIS (Global Land Degradation Information System) were used to generate a map of the degradation corrected SRWC yield map. A method to translate soil health to a yield reduction factor was adapted from Nijsen et al. (2012). The following formula was used to correct the yield:

$$Y_{corrected} = Y_{uncorrected} * R_{soil}$$

Where:

$Y_{corrected}$ = Corrected SRWC yield (GJ/ha)
$Y_{uncorrected}$ = Uncorrected SRWC yield as generated by IMAGE (GJ/ha)
R_{yield} = Yield reduction factor based on the soil health status data from GLADIS (%)

The resulting map shows the degradation corrected SRWC yield for the complete continent Africa. The grid cells of this map are 5 by 5 arc-minute, which is roughly 10 by 10 km. The data used for this step is described in detail in sections 2.2.1 on the IMAGE SRWC yield map and 2.2.2 on the GLADIS degradation maps.

3.2.2.2 Apply Bioenergy Spatial Constraints

In the second step, the degradation corrected SRWC yield map was constrained by excluding a number of land uses. A map on land use systems from GLADIS was used to this end. First, the following land uses were excluded as they are generally seen as unsuitable for bioenergy production:

- Urban land
- Bare areas (i.e. the categories Bare areas – unmanaged, protected, with low feedstock density, with high feedstock density)
- Open water (i.e. the categories Open water – unmanaged, protected, inland fisheries)

Next the following categories were excluded as they are seen as undesirable for bioenergy production, following the following set of sustainability criteria set up by Beringer et al. (2011):

- Protected areas (i.e. the categories Forest – protected, Grasslands – protected, Shrubs – protected, Agriculture – protected, Wetlands – protected, Sparsely vegetated areas – protected)
- Forests (i.e. the categories Forest – virgin, with agricultural activities, with moderate or higher livestock density)
- Wetlands (i.e. the categories Wetlands – unmanaged, mangrove, with agricultural activities)

Finally, under the scenarios not that exclude arable land for bioenergy production (*Restricted*), also the following categories were excluded:

- Rainfed crops (subsistence/commercial)
- Crops and moderately intensive livestock density
- Crops and high livestock density
- Crops, large-scale irrigation, moderate or higher livestock density
- Agriculture – large scale irrigation

A map was created that contains only the area with land uses that are not excluded. This map was combined with the degradation corrected SRWC yield map. Together, they were used to generate a map of Africa showing the yield only on areas that were considered for bioenergy production: the constrained SRWC yield map. Note that the map for the *Restricted* scenarios is different from the one for the others, because agricultural land is not considered suitable for bioenergy production under the *Restricted* scenarios. The input data for this step is treated in section 2.2.3.

3.2.2.3 Select Bioenergy Production Area

In the third step, the area used for bioenergy production under the scenario was determined for each pledge ($A_{x,y}$), and when applied to the yield map this resulted in the average SRWC yield on this area ($Y_{x,y}$).

This was done in two substeps. First, the **size** of the area that would be used for bioenergy production in country y, $A_{x,y}$, was determined using the formula below. The input data in this step, the size of the area pledged, is treated in section 2.2.4.

$$A_{x,y} = A_{pledge,y} * BES$$

Where:

$A_{pledge,y}$ = Area pledged for restoration by country y (ha)
BES_x = Share of pledge that will be used for bioenergy (%)

Second, the **location** for bioenergy production in country y was determined. This was done differently for each scenario. For the *Resource* scenarios, bioenergy production would take place on the locations with the highest yield. This was achieved by selecting the appropriate number of hectares with the highest values on the constrained SRWC yield map, which together make up $A_{x,y}$.

For the *Restoration* and *Restricted* scenarios, bioenergy production would take place on the land with highest status of degradation. The map of biophysical land degradation status from GLADIS is used, treated in section 2.2.2.2. The appropriate area with the highest land degradation status was selected. Note that for the *Restricted* scenarios, the constrained yield map which also excluded agricultural land was used.

If the suitable area for bioenergy production in country y according to the constrained SRWC yield map was lower than the size determined in the first substep, the full suitable area is used.

3.2.2.4 Calculate Sustainable Bioenergy Potential

The fourth step was to multiply the hectares that are selected by the average yield on those hectares. The overall potential was found by summing the potential of all pledges:

$$P_x = \sum_{y=1}^{18} A_{x,y} * Y_{x,y}$$

To clarify above steps, as an example the analysis for Kenya under scenario *Restoration_12%* for each step was as follows:

1. The degradation corrected SRWC yield map was generated based on the SRWC yield map from IMAGE.
2. Unsuitable areas were excluded in this step (agricultural land is not excluded for this scenario), generating a constrained SRWC yield map.
3. The area that would be used for bioenergy is selected. The size of the area used for bioenergy in Kenya under this scenario is 5.1 (size of Kenya pledge) * 0.123 (share bioenergy in scenario *Restoration_12%*) = 0.63 Mha. The 0.63 Mha in Kenya on the constrained SRWC yield map with the highest biophysical land degradation status, according to GLADIS, was selected.
4. By multiplying the average yield of this area with the size of the area selected, the SRWC potential for Kenya under scenario *Restoration_12%* was calculated.

3.2.2.5 Overview of Data Used

In section 2.2, the input data for this analysis is treated in detail. An overview of all data used in this analysis is shown in Table 3.2.

Table 3.2 Data used in the analysis for all African restoration pledges.

Data	Type	Source	Details
		Step 1	
SRWC yield 2020	Map	IMAGE	2.2.1
SRWC yield 2030	Map	IMAGE	2.2.1
Soil health status	Map	GLADIS	2.2.2.1
Soil degradation to yield reduction	Method	Based on Nijsen et al. (2012)	2.2.2.1
Yield reduction	Map	Present study	
Degradation corrected SRWC	Map	Present study	
		Step 2	
Land use systems	Map	GLADIS	2.2.3
Suitable area for bioenergy crops	Map	Present study	
Constrained SRWC yield	Map	Present study	
		Step 3	
Area pledged for restoration	Parameter	Bonn Challenge	2.2.4
Year pledge to be brought into restoration	Parameter	Bonn Challenge	2.2.4
Scenarios for area selection	Scenarios	Present study	3.2.1
Biophysical land degradation status	Map	GLADIS	2.2.2.2
Pledge and scenario specific SRWC yield	Map	Present study	
		Step 4	
Area selected for bioenergy production	Parameter	Present study	
Average SRWC yield on selected area	Parameter	Present study	
SRWC potential of pledge	Result	Present study	

3.3 Potential of the Rwanda and Kenya Restoration Pledges: Country Analysis

Next to the general analysis of the African restoration pledges, the pledges of Rwanda and Kenya were examined in more detail. In the analysis of all African pledges, different scenarios were used to determine the possible bioenergy production area. Here, this area was based on the results of the ROAM analysis, which are described in section 2.1.4 and 2.1.5. The input data is treated in detail in section 2.2.5.

In both countries, two general restoration types were identified as interesting for bioenergy production: establishment/improvement of plantations and implementation of agroforestry. The SRWC data used in this analysis is suitable for SRWC plantations. To account for the lower yield in an agroforestry system, a yield reduction factor of 0.1 was applied. The potential of each pledge was calculated with the following formula:

$$P_y = A_{y,plantation} * Y_{y,plantation} + A_{y,agroforestry} * Y_{y,agroforestry} * R_{agroforestry}$$

Where:

P_y = SRWC potential of the restoration pledge of country y (in EJ)
$A_{y,plantation}$ = Area identified by ROAM to be suitable for plantations in country y (ha)
$Y_{y,plantation}$ = Average SRWC yield on area $A_{y,plantation}$ (GJ/ha)
$A_{y,agroforestry}$ = Area identified by ROAM to be suitable for agroforestry in country y (ha)
$Y_{y,agroforestry}$ = Average SRWC yield on selected area $A_{y,agroforestry}$ (GJ/ha)
$R_{agroforestry}$ = Yield reduction factor due to agroforestry (%)

To determine P_y a three step analysis was used. Note that step 1 and 3 are essentially the same as in the analysis for all African restoration pledges:

1. ***Adjust Bioenergy Yield:*** The *degradation corrected yield* was determined by adjusting potential yield downward based on the degree of degradation.
2. ***Determine Bioenergy Production Area with ROAM Results:*** The *area on which bioenergy production would take place* for each pledge was specified using the ROAM results, hereby determining $A_{y,plantations}$, $Y_{y,plantations}$, $A_{y,agroforestry}$ and $Y_{y,agroforestry}$.
3. ***Calculate Sustainable Bioenergy Potential:*** The *potential for bioenergy* for each country (P_y) was determined with the abovementioned formula.

The overview of the analysis is shown in Figure 3.2. The extra input data used for this analysis, the pledge specific restoration potential map from the ROAM analysis, is described in the next section.

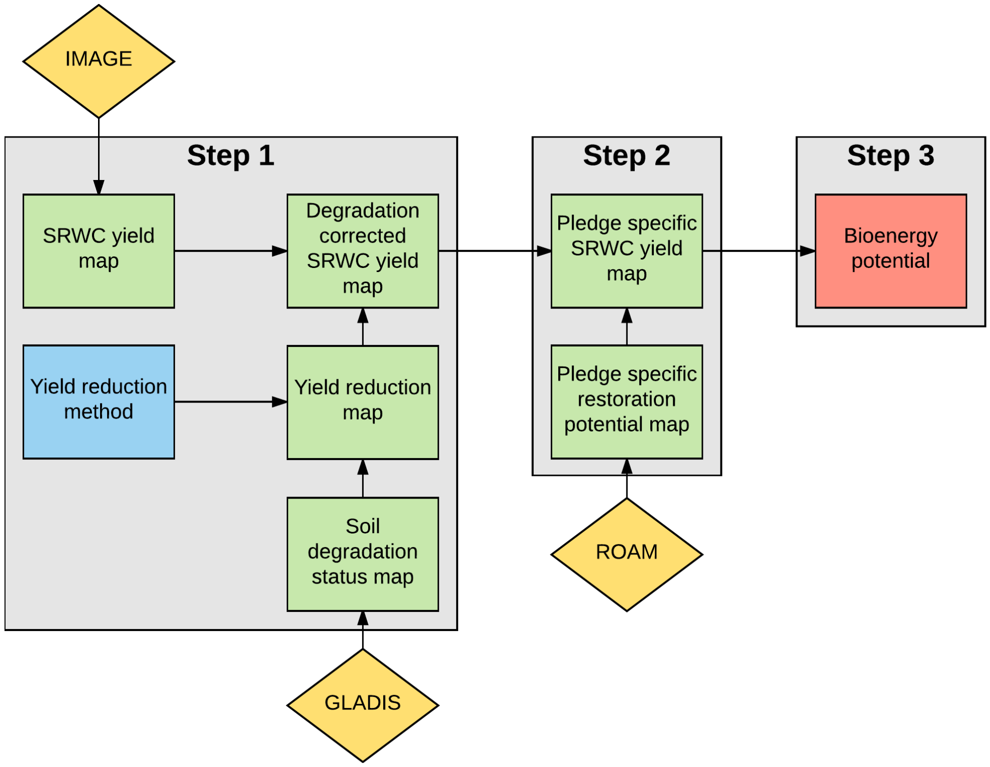

Figure 3.2 Overview of the analysis for the Rwanda and Kenya restoration pledges. Sources of input data are shown in yellow, maps in green, other methods in blue and results in red.

4 Results

First the results of the analysis on the potential of all African restoration pledges are treated, starting with the combined results for all pledges under the different scenarios, followed by the results per country. Then, the outcomes of the country level analysis are discussed.

4.1 Potential of All African Restoration Pledges

The total results for this analysis are summarized in Figure 4.1 for the short rotation woody crop (SRWC) potential under each scenario, Figure 4.2 for the bioenergy production area used for each scenario and Figure 4.3 for the average SRWC yield on that area. The results show a wide range of outcomes for the different scenarios, as a result of the range of input parameters.

The *Resource_100%* scenario yields the highest potential, 6.01 EJ yr^{-1}. Under this scenario, where 100% of the pledge is used for bioenergy and the areas with the highest yield in each country are used first, bioenergy is produced on an area of 72.7 Mha, 96% of all the area pledged for restoration. The fact that not 100% is used means that in some countries the pledge is larger than the land available under the constraints. The average yield on this area is 90.9 GJ ha^{-1} yr^{-1}. The *Restoration_100%* scenario has the same size of bioenergy production area, since no extra spatial constraints are applied. However, because the areas with the highest degree of degradation are used for bioenergy production in this scenario, the yield is less than half of the *Resource_100%* scenario: 41.5 GJ ha^{-1} yr^{-1}, resulting in a potential of 2.79 EJ yr^{-1}. Finally, the *Restricted_100%* scenario again has a slightly lower potential of 2.59 EJ yr^{-1}. The area on which bioenergy is produced is significantly lower, 59.6 Mha, but the yield is slightly higher than in the *Restoration* scenario. This is caused by the relatively high degradation of agricultural land, which makes the yield on those areas lower than on non-agricultural land.

The same overall trends can be seen in the set of *63%* and *12%* scenarios. The difference is that in both sets, the *Restricted* scenario has a higher potential than the *Restoration* scenario. In both cases the lower area in the *Restricted* scenario is compensated by the higher yield. Furthermore, note that for the *Resource* scenario set the average SRWC yield increases with a lower share of the pledge used for bioenergy, while it decreases in the other two sets. This is because the highest yielding areas are used first under the *Resource* scenario: in the *12%* scenario, bioenergy is only produced on the area with the highest yields. In the *63%* scenario, the areas with a slightly lower yield are also included, in the *100%* scenario even more land is included. For the *Restoration* and *Restricted* scenario this trend is reversed. Since the areas with the highest degradation, which generally have a lower yield, are chosen first, the average SRWC yield decreases with a lower share of the pledge used for bioenergy.

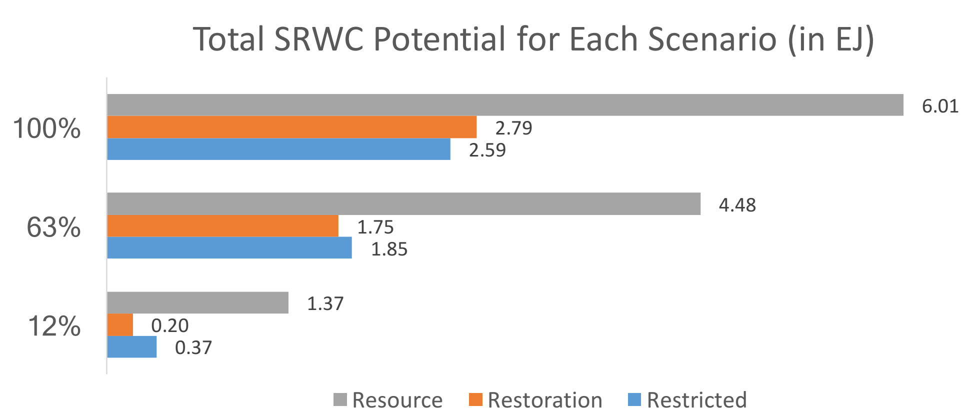

Figure 4.1 Total SRWC potential of all African restoration pledges for each scenario

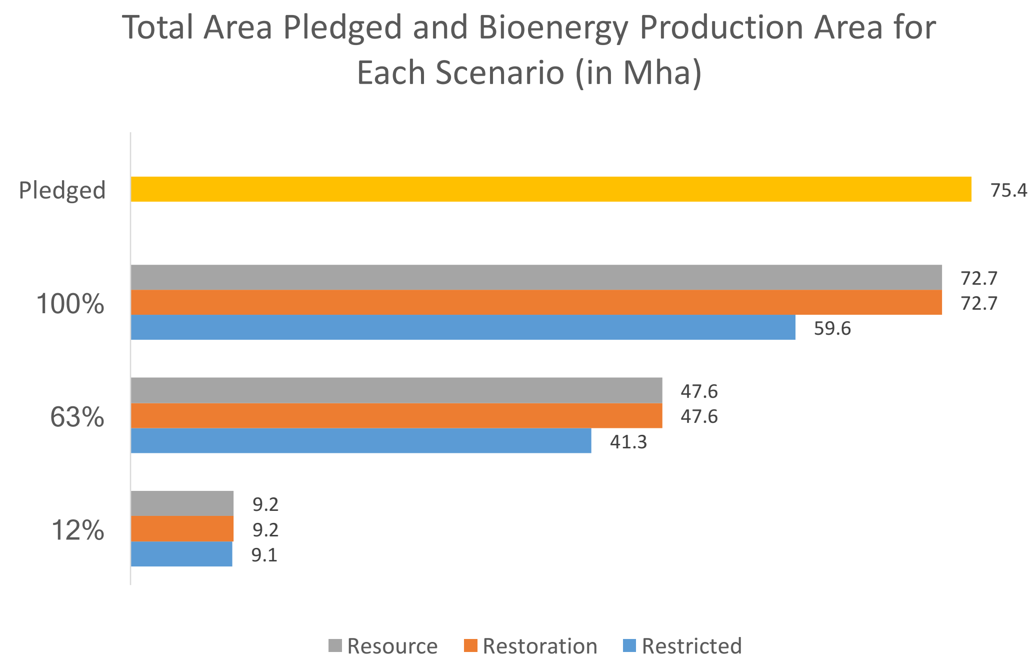

Figure 4.2 Total area of all African restoration pledges and the bioenergy production area for each scenario

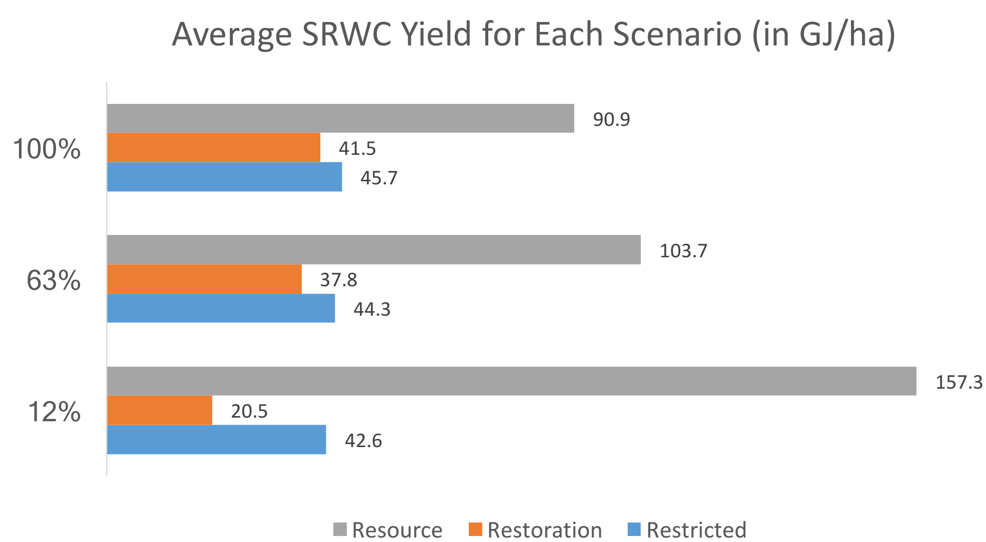

Figure 4.3 Average SRWC yield of all African restoration pledges for each scenario

These findings can be further examined by looking at the results per country. The choice is made to focus on the *Restoration_63%*, *Restricted_63%*, *Restoration_12%* and *Restricted_12%* scenario. The *100%* and *Resource* scenarios are meant to see the total potential for each pledge, but they are not seen as realistic restoration strategies.

Figure 4.4 shows the SRWC potential per country, compared to the Total Primary Energy Consumption (TPEC)[4] of each country. As the TPEC is expected to change from now until the period that bioenergy production is expected to start in 2030 to 2040, the TPEC is merely shown to give a sense of the size of the potential. Figure 4.5 shows the bioenergy production area that would be used for the four different scenarios, as well as the total area that is considered available under the spatial constraints also taking agricultural land into account. Finally, 4.6 shows the average SRWC yield on the selected area.

The country with the highest potential in all four scenarios is Congo DRC (the Democratic Republic of the Congo). Even when only 12.3% of the pledge is used for bioenergy production on the most degraded land, as is done in the *12%* scenarios, the country has a substantial potential of around 0.1 EJ. This is due to the relatively big pledge of 8 Mha, but also due to a very high average SRWC yield on the selected areas of over 100 GJ ha^{-1}. When looking at the current TPEC, using the restoration strategies as examined with these scenarios could provide a substantial part of the energy supply of Congo DRC.

Congo (Republic of the Congo) is the second country on the list, with a potential of over 0.2 EJ in the *63%* scenarios and a potential of 0.01-0.05 in the *12%* scenarios. This is a substantial potential, especially given the fact that the country's pledge of 2 Mha is much smaller than that of Congo DRC. This is due to a higher average SRWC yield on the selected areas. Note that the average SRWC yield of the *Restoration_12%* scenario is relatively low, which means that the most degraded areas in Congo are relatively unsuitable for bioenergy production.

All other countries have much lower yields, however most countries do still have a potential that makes considering bioenergy production from their restoration pledge an interesting option. Notable exceptions are the countries at the bottom of Figure 4.4: Ghana, Mozambique, Niger and Benin all have very low potentials, especially compared to their current TPEC. These countries all have relatively small pledges, and especially in Niger the SRWC yield on the selected areas is nearly 0 GJ ha^{-1}.

The total area that is considered available under the spatial constraints is shown in Figure 4.5. Note that in both Rwanda and Burundi this area is almost completely used in the *63%* scenarios. This is caused by the fact that both countries made a pledge that is nearly as large as their country size itself. Using such a substantial share of the country for bioenergy production is unrealistic given current land use characteristics in these countries.

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[4] These statistics are taken from International Energy Statistics from the U.S. Energy Information Administration and represent the TPEC in 2014 (EIA 2017).

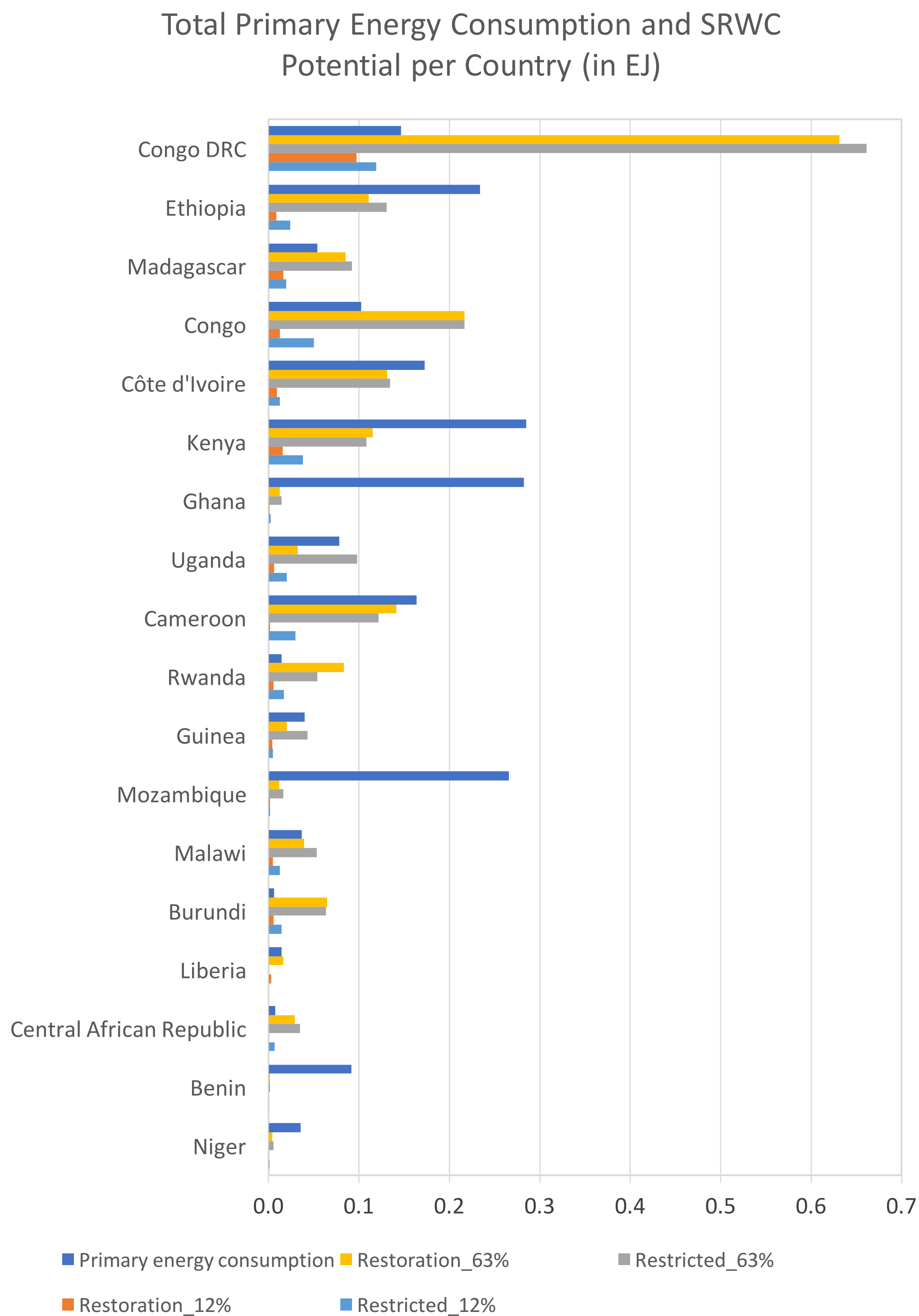

Figure 4.4 Total primary energy consumption for each country and SRWC potential for different scenarios per pledge

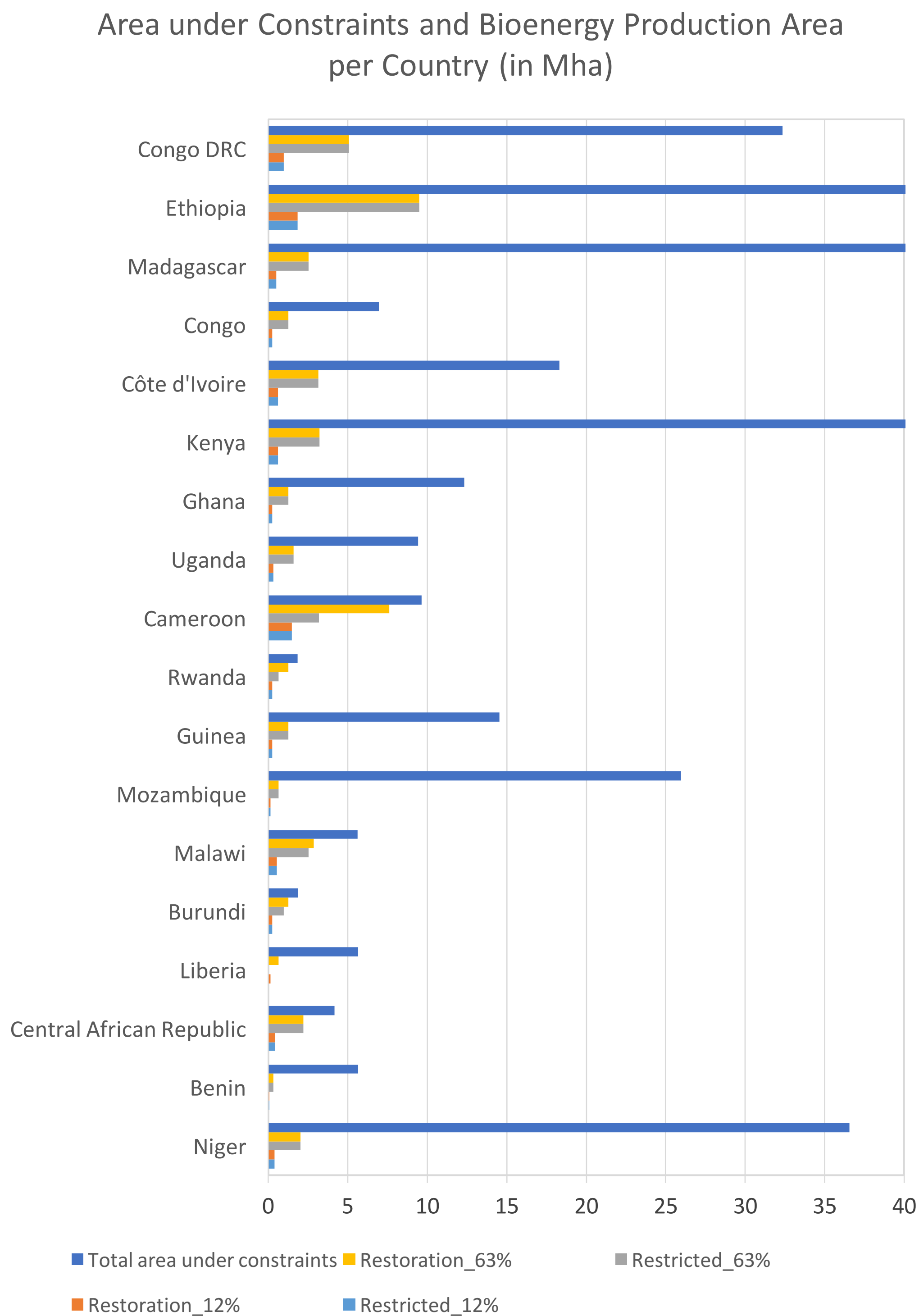

Figure 4.5 Total area that could be used for bioenergy under the spatial constraints[5] for each country and the bioenergy production area for different scenarios per pledge

[5] The following land uses are excluded under these spatial constraints: urban areas, bare areas, open water, protected areas, forests and wetlands.

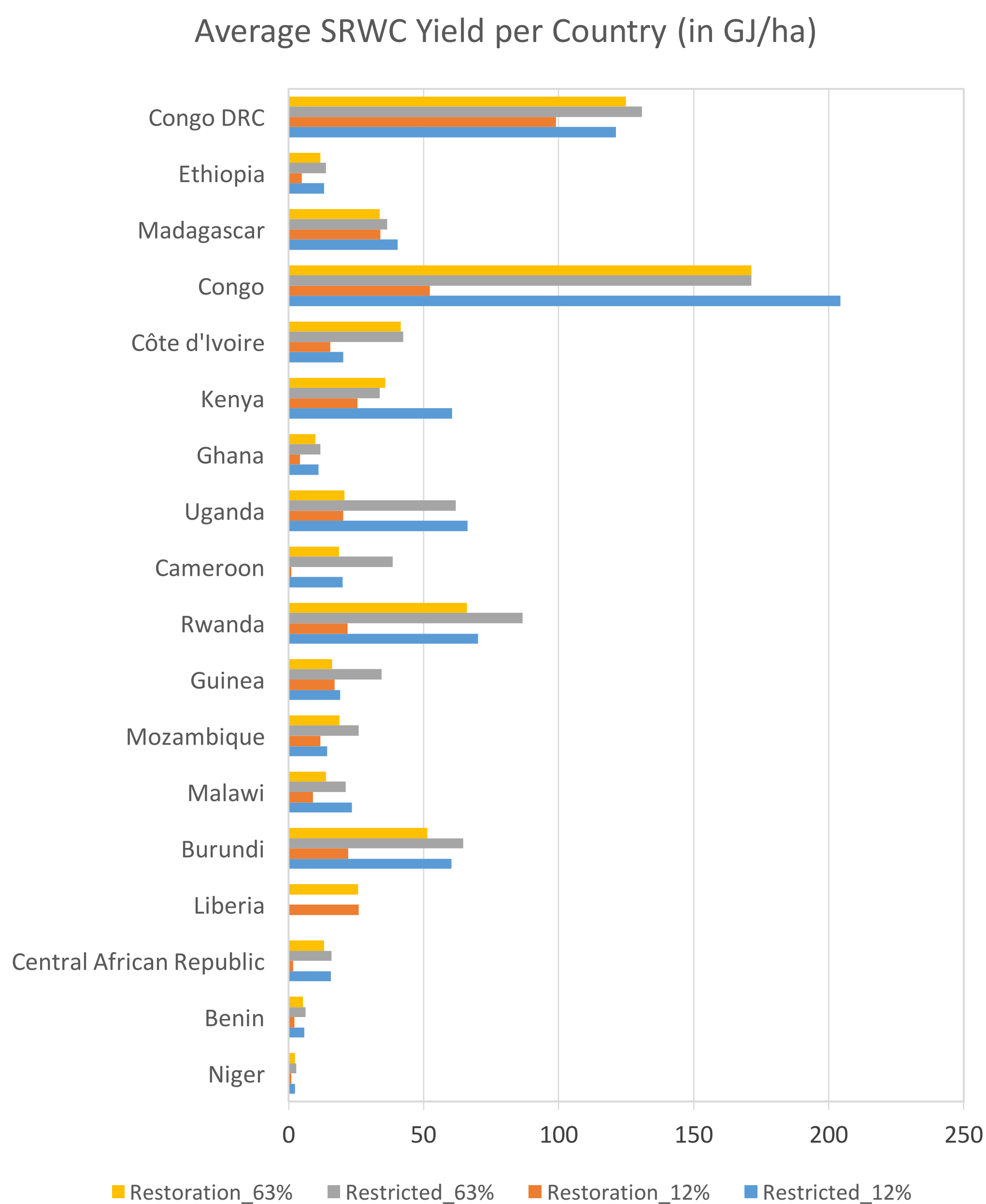

Figure 4.6 Average SRWC yield for different scenarios per pledge

4.2 Potential of the Rwanda and Kenya Restoration Pledges

The results of this analysis are summarised in Table 4.1 and 4.2. Table 4.1 shows that Rwanda has a potential of 45 PJ yr^{-1} on 1.4 Mha when the restoration strategy as proposed by the ROAM assessment is executed. The largest share of this, 34 PJ yr^{-1} on 0.256 Mha, comes from the proposed SRWC plantations. This potential is higher than estimated by the *Restoration_12%* and *Restricted_12%* scenarios: 5-17 PJ yr^{-1} on 0.245 Mha. This is not surprising, as in these scenarios the use of the most degraded land is prioritised. The plantations as proposed by the ROAM study are not necessarily on highly degraded land, resulting in a higher mean yield.

Table 4.1 Results country analysis Rwanda

Class	Mean yield (GJ/ha)	Area (Mha)	Potential (EJ)
Plantation	131.1	0.256	0.034
Agroforestry	10.5	1.110	0.012
Total		**1.366**	**0.045**

Kenya has a lower potential of 28 PJ yr^{-1} on a larger area of 2.2 Mha, due to the significantly lower yields as shown in Table 4.2. Plantations and agroforestry contribute equally to this potential, 18 PJ yr^{-1} on 0.4 Mha and 10 PJ yr^{-1} on 1.8 Mha. The potential of the proposed plantations lies in the lower end of the range estimated by the *Restoration_12%* and *Restricted_12%* scenarios, 16-38 PJ yr^{-1}. This might be explained by the fact that the proposed location of plantations is on marginal crop land, on which a low yield can be expected.

Table 4.2 Results country analysis Kenya

Class	Mean yield (GJ/ha)	Area (Mha)	Potential (EJ)
Plantation	43.9	0.4	0.018
Agroforestry	5.8	1.8	0.010
Total		**2.2**	**0.028**

5 Discussion

The aim of the present study was to estimate the sustainable potential of short rotation woody crops (SRWC) plantations from restoring degraded land pledged to the Bonn Challenge in Sub-Saharan Africa (SSA). The Bonn Challenge is a global initiative to restore an area of 350 Mha by 2030 using forest landscape restoration. Some of the restoration activities considered could offer an opportunity for growing dedicated bioenergy crops. The size of this opportunity in terms of potential is estimated here in an analysis using different scenarios. The scenarios are used to see the effect of different restoration strategies that countries could deploy and vary in the share of each pledge used for SRWCs and the location on which restoration is applied.

The findings show that a total of 6.01 EJ yr^{-1} of primary energy from SRWCs could be extracted when all pledges are completely focused on growing SRWC plantations on land with the highest yield available, under the spatial constraints taken into account. The slightly more conservative scenarios, using the land with the highest degree of degradation first, have a total of 2.59-2.79 EJ yr^{-1}. It is however highly unlikely that the full pledge can be used for growing SRWC. The scenarios that are seen as most feasible, where a relatively small share (12.3%) of the pledge is used for bioenergy crop production, have a potential of 0.20-0.37 EJ yr^{-1} when using the most degraded land, and 1.37 EJ yr^{-1} when cultivation of SRWC is prioritised on land with the highest yield.

In all scenarios however, the bioenergy potential from restoring the area currently pledged to AFR100 is substantial, considering a total SSA primary energy demand of 23.9 EJ yr^{-1} in 2012, and a biomass demand of 14.6 EJ yr^{-1} (IEA 2014). The large range in the estimated potential (0.20-6.01 EJ yr^{-1}) indicates the large related uncertainties. Since for most countries only the total area committed to restoration is known, it is not feasible to provide more precise estimates. The type of restoration and location that will be restored have a very large impact on the actual bioenergy production potential. The uncertainty of these parameters is reflected by the scenarios, which are chosen to show the impact of a wide bandwidth of possible restoration strategies. The bioenergy strategies in the scenarios do therefore not necessarily reflect the most realistic strategies, but rather the extremes. Note also that in particular in developing countries, the future biomass potential is highly dependent on future (socio-economic) developments (Smeets 2008; IPCC 2011).

Several studies assessing the potential for bioenergy crops in SSA exist (Wicke et al. 2011; Dasappa 2011). This analysis however specifically focusses on the potential from the restoration pledges made, making a comparison with other studies impossible. On a country level, Wicke et al. (2011) estimate the technical potential for woody crops in Kenya to be 1.14 EJ yr^{-1} from an available area of 5.6 Mha. This is an average yield of 203 GJ ha^{-1}, significantly higher than the average of 110 GJ ha^{-1} average found in the country level analysis of the present study. This could be explained by the older yield database of IMAGE used in Wicke et al. (2011), which uses a different model to estimate crop yields. The integration of the LPJmL allowed for more interlinkages and added a global hydrology module to IMAGE, improving its results (Stehfest et al. 2014).

With respect to the method, one of the main uncertainties is the **chosen timeframe**. Although the pledges state in which year the pledged area should be in the process restoration, it is unclear what is meant by this. Furthermore, whether countries will indeed make their restoration targets on time remains to be seen, as the Bonn Challenge is not a binding agreement. The assumption that planting of SRWCs starts in the year the pledge is made, is therefore highly uncertain.

Next to uncertainties related to the method, the quality and availability of input data used to determine the potential varied. This causes additional uncertainties, the first of these is found in the **future yields** for SRWCs. These yields are generated by IMAGE 3.0 (Integrated Model to Assess the Global Environment) using the Shared Socioeconomic Pathway 2 (Vassilis Daioglou, personal communication 09/01/2017). A yield increase is expected due to the improvement of management practices and the increase of CO_2 concentrations over time. It is unclear whether the chosen scenario is realistic, however. This has an impact on the future yields, although the difference might not be large on the assessed time frame.

Furthermore, it was required to correct the yield generated by IMAGE for **land degradation**. This was done using GLADIS (Global Land Degradation Information System) in combination with a yield reduction method. Two uncertainties are associated to this process. First, assessing land degradation is still seen as a major challenge, with large uncertainties in both the size of the degraded area and exact location (Gibbs & Salmon 2015). All global databases that exist today are affected by this, and all face challenges on data quantity and quality (Caspari et al. 2015). This is the case for GLADIS as well, which has been criticized by Nkonya et al. (2011) for its approach of combining multiple factors into aggregated indicators, lacking a description of how these factors affect land degradation. Furthermore, the focus on managed land is seen as a weakness: soils under natural vegetation are not considered as degraded (Caspari et al. 2015). An expert peer review conducted by FAO (2011) shows a similar picture: 7 of 18 experts qualified the soil health status map as satisfactory, another 7 as partially satisfactory and 4 as unsatisfactory. The other map used in this analysis, biophysical land degradation, scores slightly better with two third of the experts qualifying it as satisfactory. Finally, because of the use of aggregated indicators, the type of land degradation is not included, although this has a major impact on yields (Blanco-Canqui 2016).

Different assessments on land degradation are currently underway. The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) is conducting a global assessment on land degradation and restoration, to be completed by 2018 (IPBES 2017). The IPBES study will provide improved insights in the global status and trends by region and land cover type, as well as its effect on biodiversity, ecosystem services and human health and finally the state of knowledge. Another promising project is the compiling of a third edition of the World Atlas of Desertification by the Joint Research Centre (JCR) of the European Commission and UNEP, to be completed shortly (Cherlet et al. 2015). Finally, the Status of the World's Soil Resources report of the Intergovernmental Technical Panel on Soils (ITPS) assesses soil and related issues globally, and is updated on a five year basis (FAO & ITPS 2015). Unfortunately, the findings of the ITPS report are not yet incorporated in the present study due to time limitations.

Next to mapping of land degradation, the **yield reduction method** applied in the present study is uncertain. The effect of land degradation on annual food crop yields is generally well understood. For example, global crop suitability is modelled in the Global Agro-Ecological Zone study by FAO (Fischer et al. 2002). This is not the case for perennial bioenergy crops. Very little experimental data exist on the effect of the type and degree of land degradation on their yields, especially for SRWCs (Blanco-Canqui 2016). More empirical research is therefore needed, the result of which can be used to calibrate and validate models to estimate the bioenergy potential of degraded land (Qin et al. 2016). This, together with improved data on land degradation could greatly improve the SRWC yield data and, as a result, the estimate of the bioenergy potential.

A different source of uncertainty in the input data comes from the **availability of land**. In the analysis, different land uses are excluded because they are either unsuitable for bioenergy crop production or undesirable for sustainability reasons. The remaining land is thought to be available and can be used for bioenergy production in the present analysis. Several issues still exist with this area however. In the scenarios using the land with the highest yield, this is obvious: non-degraded agricultural land is used, conflicting with food, feed and material production. The more realistic restoration focused scenarios also face some issues. An important assumption in using degraded land for bioenergy crop production is that the land is not or hardly in use (Wicke 2011). However, it is shown that this assumption is not always true, since in reality it is often in use and it can be a crucial resource for poor communities (Berndes 2002; Gallagher 2008; Schubert et al. 2009).

The **lack of data with sufficiently high resolution** is a final source of uncertainty. The data used are all meant for analysis on a large, i.e. global, scale (Nachtergaele et al. 2011; Stehfest et al. 2014). While these may support conclusions on a continental scale, the data is not meant to assess the potential of smaller regions (e.g. a single country). Furthermore, using data with a higher level of detail could allow for more factors to be taken into account, e.g. the slope of the terrain. Therefore, the data needs a higher resolution to be able to provide a more accurate country level estimate.

6 Conclusion

The Bonn Challenge is a global restoration effort aiming to restore 150 Mha of deforested and degraded land by 2020 and another 200 Mha by 2030. This initiative might be an opportunity for perennial bioenergy crops, as they can grow on non-prime agricultural land and could provide multiple benefits. The potential of dedicated energy crops cultivated on the 350 Mha that the Bonn Challenge aims to restore was estimated to be 33-67 EJ in a previous study (IRENA 2016a). This is seen as a first order estimate, assuming an average yield in combination with a rough possible yield reduction due to land degradation. Because the Bonn Challenge has various aims, using full pledges for bioenergy is not realistic. In order to better understand the opportunity the Bonn Challenge might provide for bioenergy, a more precise estimate was needed.

The present study addresses part of this need, by estimating the sustainable potential of biomass for energy from restoring degraded land pledged to the Bonn Challenge in Sub-Saharan Africa (SSA). This was done with a geographic explicit method using data from different sources: short rotation woody crop (SRWC) yields from IMAGE (Integrated Model to Assess the Global Environment), land degradation and land use data from the GLADIS database (Global Land Degradation Information System) and pledge characteristics from the Bonn Challenge site. Environmental constraints were incorporated by excluding different land uses with high biodiversity or high carbon storage. A total of 9 scenarios were used to see the effect of different management strategies a country could use to restore their pledged area. These scenarios varied in the share of the pledge used for SRWC plantation (12.3%, 63.2% or 100%) and in the location that is used (prioritising the use of land with a high yield, a high degree of degradation or a high degree of degradation while excluding agriculture).

The results of the SSA analysis show a total potential of 6.01 EJ yr^{-1} of primary energy from SRWCs could be cultivated, using 72.7 Mha of the 75.4 Mha pledged land by assuming that the most productive land will to be used. However, this restoration strategy is considered infeasible. The scenarios using a lower share of the pledges and focussing on the use of land with a high degree of degradation are thought to give more realistic estimates. They result in a potential of 1.75-1.85 EJ yr^{-1} on 41.3-47.6 Mha when 63.2% of the pledges is used and 0.20-0.37 EJ yr^{-1} on 9.1-9.2 Mha when 12.3% of the pledges is used.

Next to the SSA analysis, a country level analysis was conducted for Rwanda and Kenya. This analysis used ROAM outputs (Restoration Opportunity Assessment Methodology) on the potential areas suitable for restoration and the potential restoration options on these areas. The results show that Rwanda has a potential of 45 PJ yr^{-1} on 1.4 Mha when the restoration strategy as proposed by the ROAM assessment is executed. Kenya has a potential of 28 PJ yr^{-1} on 2.2 Mha.

Considering the present study it is clear that bioenergy could play a role in the Bonn Challenge. The underlying principle behind the initiative, forest landscape restoration, includes restoration activities in which growing bioenergy crops could be envisioned. Sustainable bioenergy production could give a boost to the Bonn Challenge, by providing extra economic incentives and possibly additional greenhouse gas emission mitigation by replacing fossil fuels. What part of the pledge is feasible to use for bioenergy crop production, is country dependent. In Rwanda and Burundi for example, due to the fact that the restoration pledge is almost as large as the country size itself, the share that can be used for bioenergy will be small. Countries with a considerable potential and sufficient area available, like Kenya or Ethiopia, could use a larger part. The goals a country wants to achieve by restoring will also play a big role.

To look into the potential for bioenergy on a country level in more detail, studies should be done when ROAM assessments become available. However as mentioned above, more accurate and detailed input data is required in order to conduct meaningful country level studies. This will involve field research as not all data is available. Next to environmental sustainability, economic and social factors should also be included. Involving local stakeholders in the process is important, as land restoration should respect their rights and provide them with benefits (IUCN & WRI 2014). Incorporating bioenergy potential assessment in future ROAM studies is an interesting option, as these studies involve engagement with local stakeholders.

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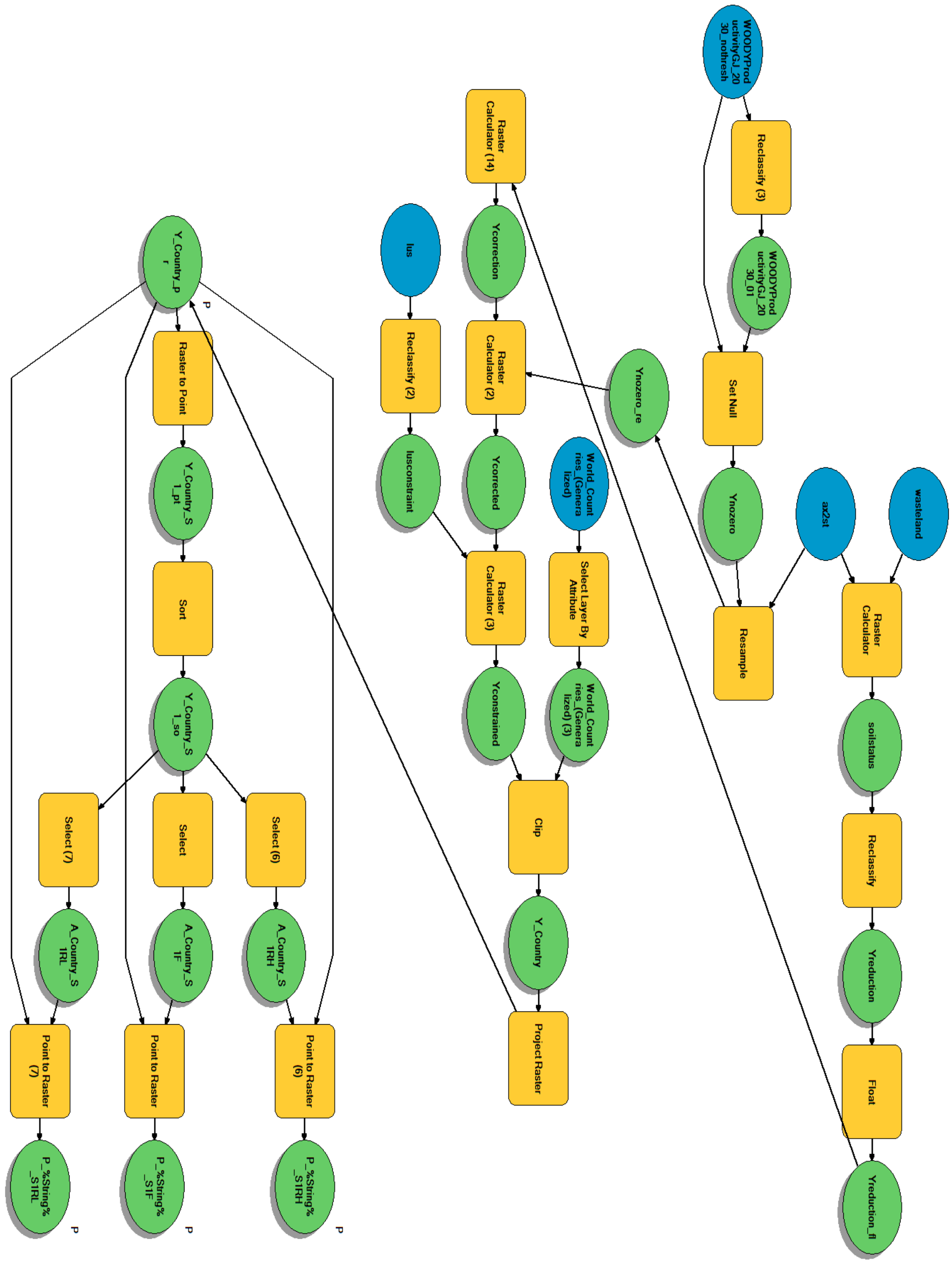
Appendix: ArcGIS Models

Africa Analysis

An example of the model used to generate results for the *Resource* scenario:



Country Analysis

The model used to generate results for Rwanda: