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BIOENERGY FROM DEGRADED LAND IN AFRICA

Sustainable and technical potential under Bonn Challenge pledges

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DISCLAIMER

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ABBREVIATIONS

AFR100	African Forest Landscape Restoration Initiative
CAR	Central African Republic
DRC	Democratic Republic of the Congo
EJ	exajoule
FLR	forest landscape restoration
GHG	greenhouse gas
GJ	gigajoule
GLADA	Global Assessment of Land Degradation and Improvement
GLADIS	Global Land Degradation Information System
GLASOD	Global Assessment of Soil Degradation
IRENA	International Renewable Energy Agency
IUCN	International Union for Conservation of Nature
km^2	square kilometre
MENR	Ministry of Environment & Natural Resources, Kenya
Mha	million hectares
MNR	Ministry of Natural Resources, Rwanda
PJ	petajoule
ROAM	Restoration Opportunities Assessment Methodology
SRWC	short rotation woody crops
TPES	Total Primary Energy Supply
WRI	World Resources Institute

EXECUTIVE SUMMARY

Biomass plantations on degraded lands can help restore and reclaim such lands while supplying significant amounts of bioenergy. They can also provide employment opportunities, ecosystem services and carbon storage. As degraded land can be challenging and economically unattractive for food crop cultivation, planting it with high-yielding wood or grass species can allow bioenergy to be extracted without conflicting with food production. When degraded land has relatively little planted on it, introducing bioenergy crops that absorb carbon as they grow can also enhance removal of carbon from the atmosphere. Growing wood on degraded land can further serve to curb unsustainable wood extraction from local forests.

The Bonn Challenge provides a great opportunity to unlock the potential of degraded land. This is a global endeavour to restore 150 million hectares (Mha) of deforested and degraded land by 2020, and another 200 Mha by 2030.

In this context, restoration is the long-term process of re-establishing the ecological functionality of an area and enhancing human well-being. Within the Bonn Challenge timeframe, 18 sub-Sahara African countries have pledged to restore some 75 Mha through AFR100, the African Forest Restoration initiative aiming to regenerate 100 Mha. This study finds that these pledges could yield around six exajoules (EJ) per year of primary bioenergy, assuming that the entire amount of land pledged were dedicated to bioenergy crops, and these pledges were fulfilled on land with the highest potential yield.

If a smaller share of pledged land were devoted to bioenergy, and crops were instead grown on the most degraded land, the yield would be much lower. Further investigation could clarify which degraded land is most likely to be selected for bioenergy plantations. A key consideration is whether other uses of the more productive lands

are more attractive from economic, social and environmental points of view. Whatever lands are chosen, bioenergy could strengthen the economic case for restoration.

A more detailed country-level analysis was conducted for Kenya and Rwanda. Both these countries have applied a Restoration Opportunities Assessment Methodology (ROAM) to evaluate restoration options in suitable areas. Assuming restoration strategies are aligned with their ROAM assessments, Kenya has a bioenergy potential of around 28 petajoules (PJ) per year on 2.2 Mha, while Rwanda has a potential of approximately 45 PJ per year on 1.4 Mha. These potentials reflect relatively low yields per hectare compared to the broader analysis of all AFR100 pledges as the two countries have selected low-quality land for restoration. Such analysis could be applied to other countries that complete ROAM assessments.

The restoration strategy pursued and bioenergy obtained will depend on the goals and opportunities in each country. Country-level studies are needed to better understand a range of issues including the alternative uses of degraded land (such as bioenergy, food and nature conservation), possible synergies among these uses (such as agroforestry to produce a high-yielding mix of food and fuel crops while enhancing biodiversity), the technical resource potential of each alternative use, and the share of this potential likely to be realised in different contexts.

Bioenergy potential would be useful to examine more closely in future ROAM studies. Significantly, such studies engage with local stakeholders, whose initiative is key to reaping this potential.

1 INTRODUCTION

The worldwide use of bioenergy has increased greatly in recent 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 at just over 50 EJ per year (Creutzig *et al.*, 2015). In future, especially in ambitious climate change mitigation scenarios, bioenergy is expected to play an even more important role in the energy mix (Intergovernmental Panel on Climate Change, 2014). The large-scale use of bioenergy could cut greenhouse gas (GHG) emissions, reduce reliance on fossil fuels and increase opportunities to develop the agricultural sector (Intergovernmental Panel on Climate Change, 2011; Nijsen *et al.*, 2012).

However, bioenergy, viewed from the broader sustainability perspective, reveals potential negative impacts. Using land for energy crops could, directly or indirectly, lead to the conversion of natural vegetation to agricultural land, thereby lowering biodiversity and raising GHG emissions (Searchinger *et al.*, 2008). It can also lead to emissions from different greenhouse gases, such as nitrous oxide, due to fertiliser use (Smeets *et al.*, 2009). Finally, bioenergy crops grown on productive land may compete with food, animal feed and materials production requirements for land, water, capital and labour (Eickhout *et al.*, 2008; Rosegrant, 2008). Many of these disadvantages are related to direct land use change and implied indirect land use change.[1]

Using degraded land to produce bioenergy may avoid problems related to land use change because this type of land is usually unsuited to and economically unattractive for food crops. Degraded land is defined as land that has suffered from a long-term loss of ecosystem services caused by disturbances from which the system cannot recover unaided (United Nations Environmental Programme [UNEP], 2007). Growing bioenergy crops on degraded land – especially perennial crops – could significantly increase the productivity of the land and would have little negative impact on biodiversity and GHG balance (Nijsen *et al.*, 2012; Immerzeel *et al.*, 2014). Using land with zero or little previous productivity can contribute to social and economic development in rural regions.

However, several possible disadvantages are associated with the use of degraded land. Difficult growing conditions mean that establishing perennial energy crops on such land will require sustained effort over many years. Even then, the expected yields in these areas will be lower than on high-quality land. Furthermore, these degraded sites are often an essential resource for poor rural communities (Öko-Institut and UNEP, 2009; Schubert *et al.*, 2009; Dornburg *et al.*, 2010; van Dam *et al.*, 2010). Though degraded, land may still produce useful amounts of food and animal feed that could be displaced by wood crops, which are often considered an alternative. Restoration with wood crops should be planned in such a way that supplements rather than displaces more important uses with higher market or other value. In addition, prioritising the restoration of land with relatively low yield potential could divert attention from other action that could more effectively improve the overall efficiency of land use. Examples include increasing the yields on existing cropland and reducing the demand for land-intensive products (Gibbs and Salmon, 2015).

However, degraded lands clearly do offer a potential source for growing bioenergy crops. The Bonn Challenge may reveal possible solutions for unlocking this potential. This is a global effort to restore 150 Mha of deforested and degraded land by 2020, and 350 Mha by 2030. The first target was issued by civic, business and government leaders at a meeting hosted by the German Federal Ministry for the Environment, Nature Conservation,

1. Direct land use change means clearing forests or grasslands for bioenergy crops. Indirect land use change could occur when farmland is used for bioenergy crops, causing food prices to rise and leading farmers to clear forests or grasslands for food crops. Land use change can largely be avoided through sustainable intensification of land use.

Building and Nuclear Safety, and the International Union for Conservation of Nature (IUCN) in 2011. In 2014, this target was extended by the New York Declaration on Forests, which calls for the restoration of another 200 Mha by 2030. The Bonn Challenge is overseen by the Global Partnership on Forest Landscape Restoration. By March 2017, 40 pledges had been made in 35 countries spread across four continents: Africa, Asia, North and South America. This amounts to 148.38 Mha intended for restoration (IUCN, 2016b).

Africa accounts for the largest share of global degraded land (Nachtergaele *et al*., 2011), making it especially suitable for restoration under the Bonn Challenge. Not surprisingly, therefore, 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 by March 2017. This accounts for over half 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 have finished this assessment are Kenya and Rwanda, both of which have also published their findings (Ministry of Environment & Natural Resources [MENR Kenya], 2016; Ministry of Natural Resources [MNR Rwanda], 2014).

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 and World Resources Institute [WRI], 2014). Sustainable bioenergy production that does not conflict with food, animal feed and materials production, could play a part in this process. The momentum created by the Bonn Challenge thus offers an opportunity to develop this role. Conversely, sustainable biomass production for energy could also stimulate the Bonn Challenge and could improve the economic sustainability of projects undertaken while mitigating more GHG by replacing fossil fuels. Furthermore, the extra financial incentive arising from bioenergy crop production could increase the likelihood that the Bonn Challenge succeeds. In Africa, additional bioenergy production could generate further benefits by lightening the burden of energy insecurity so typical of the region while generating employment and income, thereby reducing poverty.

Degraded land is usually unsuited to, and economically unattractive for, food crops

Energy crops can be subdivided into oil-bearing crops (such as jatropha and oil palm), carbohydrate-rich crops (such maize and sugarcane), and lignocellulosic crops (such as wood and grasses). The latter category includes rapidly growing grasses like miscanthus and switchgrass, and short rotation woody crops (SRWC) like poplar, willow and eucalyptus (Vis and van den Berg, 2010). Analysis has shown that current practices for converting crops rich in oil or carbohydrates to biofuels may have limited ability to lower emissions (Crutzen *et al*., 2008; Fargione *et al*., 2008).

Moreover, such crops do not grow well on degraded land and compete with food production if grown on non-degraded land (Searchinger *et al.*, 2008). This shifts the weight of expectation to lignocellulosic crops. Given that FLR aims to increase the health and/or number of trees in an area, SRWC is ideal for restoration. SRWC is especially well suited to landscape restoration because it can grow on non-prime agricultural land and could provide different ecosystem services. For example, SRWC could increase soil carbon sequestration (Matos *et al*., 2012; Qin *et al.*, 2016), reduce soil degradation processes such as water and wind erosion (Blanco-

Canqui, 2016), and improve wildlife habitat (Haughton *et al*., 2016)

In a recent report, IRENA provides a rough global estimate of SRWC potential from the Bonn Challenge. Assuming yields of five to ten tonnes per hectare, restoring 350 Mha would produce 33-67 EJ of primary biomass per year (IRENA, 2016a). This is in line with the range published in studies calculating the global potential for dedicated bioenergy crops on degraded land and estimating 5-147 EJ per year (Hoogwijk *et al*., 2005; van Vuuren *et al*., 2009). There are several reasons for the breadth of this range. Firstly, different studies have different goals, different scope and system boundaries, and evaluate different timeframes (Thrän *et al.*, 2010). Secondly, they focus on different biomass resource types and different types of biomass potentials. Thirdly, different methodologies and approaches are used to estimate the bioenergy potential. Finally, a variety of datasets and assumptions are employed for yields, conversion factors and sustainability criteria (Batidzirai *et al*., 2012).

This report attempts to give a more precise estimate of the bioenergy potential from land pledged to the Bonn Challenge, concentrating on the pledges made so far in Africa. It poses the following research question: **What is the sustainable potential of biomass for energy from restored degraded land pledged to the Bonn Challenge by African countries?** It takes an overall view of the pledges in this light but considers Kenya and Rwanda in more detail because more data are available for these countries.

2 BACKGROUND

The Bonn Challenge is based on FLR, defined as "the long-term process of regaining ecological functionality and enhancing human well-being across deforested or degraded forest landscapes" (IUCN and WRI, 2014).

2.1 Bonn Challenge and forest landscape restoration

The *Forest Landscape Restoration Handbook* describes the four key features of FLR in the following definition (Rietbergen-McCracken *et al.*, 2007).

1. FLR is a participatory process based on adaptive management of the landscape, and 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 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 the forest to its original state. It should be seen as a forward-looking approach to help strengthen the forests while keeping future options open (Rietbergen-McCracken *et al.*, 2007). Combining this with the attention paid to the landscape as a whole generates a balance of different land uses across the landscape after restoration (IUCN and WRI, 2014). Activities that can be included in FLR are listed below (Rietbergen-McCracken *et al.*, 2007):

- rehabilitation and active management of degraded primary forest
- active management of secondary forest growth
- restoration of primary forest-related functions in degraded forest land
- promotion of natural regeneration on degraded/marginal land
- ecological restoration
- plantations and planted forests
- agroforestry and other trees on farms.

Finally, FLR aims to increase the number and/or health of trees in the area of implementation (IUCN and WRI, 2014).

Degraded land has been topical lately due to rising demand for food, animal feed and fuel, combined with a diminishing agricultural land base in many world regions. Projections show that increasing population and growing meat consumption will double global demand for agricultural products by 2050 (Food and Agriculture Organization [FAO], 2006). Energy policies adopted by many countries to encourage more bioenergy production create additional pressure on land (World Energy Council, 2011). Increasing the yield of existing cropland will make a significant contribution to increasing food production. However, this will not be sufficient in itself (Ray *et al.*, 2013).

The expansion of agricultural areas 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 because they are thought to be more resistant to less favourable conditions (*e.g.* low nutrient, erodible and droughty soils) than most food crops (Tilman *et al.*, 2006; Gelfand *et al.*, 2013).

There are many different definitions of degraded land. Wiegmann *et al.* (2008) present a set of comprehensive definitions for degraded land and related terms. Degraded land is defined as land that has 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 costeffective food and animal feed production is not possible under given site conditions and cultivation techniques (Schroers, 2006). Waste land is characterised by natural physical and biological conditions that are inherently unfavourable to human activities associated with the land (Oldeman *et al.*, 1991). The above definitions are not used in all the available literature, especially the terms degraded and marginal land, which are often used interchangeably (Lewis and Kelly, 2014). For this reason, this report refers to several studies in which marginal land is considered almost the same as degraded land.

The Bonn Challenge provides a possible route to fulfilling the potential of degraded land. However, the challenge is not only about restoring degraded land. The official goal is to restore deforested and degraded land (IUCN, 2016b). Deforested areas are not necessarily viewed 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 options for FLR (MENR Kenya, 2016; MNR Rwanda, 2014). Nevertheless, land degradation is an important consideration in the present study because degraded lands will make up a large share of restoration and may make a significant impact on the biomass yields (Blanco-Canqui, 2016).

The present study aims to provide a methodology to estimate the yields of all Bonn Challenge pledges, preferably incorporating land degradation and the associated yield loss using globally consistent data. There is no technique for assessing land degradation at the national level (Bruinsma, 2003), so that we only rely on a method for mapping global land degradation. The FLR concept underpins the entire Bonn Challenge. Different restoration options can be considered within this concept, and some of these could produce feedstock for bioenergy.

Countries that make pledges to the Bonn Challenge usually do this by stating number of hectares to be restored without providing details on the location or type of restoration. This means that most countries only know the number of hectares to be restored. Conducting a study using ROAM provides more insight into the possible restoration strategy. The ROAM analysis is discussed in section 2.3.

As indicated by its definition, FLR takes place on deforested or degraded forest landscapes. However, the ROAM assessment additionally considers both non-forest and non-degraded areas as targets for potential restoration within the Bonn Challenge. The ROAM assessment for Kenya, for example, also takes restoration of grasslands into consideration (MENR Kenya, 2016). Moreover, it also considers land not viewed as degraded for FLR. Land degradation will be described in more detail in the next section.

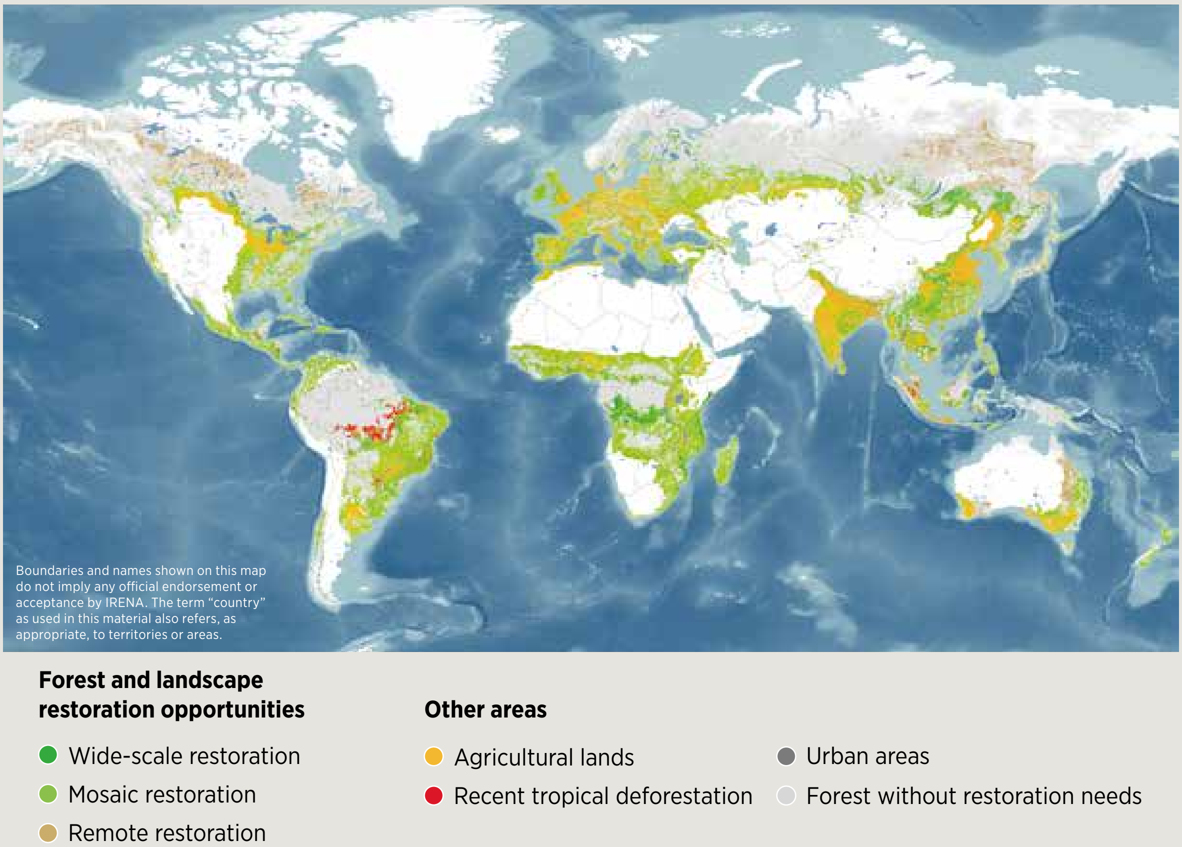
The ROAM reports of Kenya and Rwanda show significant potential for restoration activity that could support bioenergy feedstock production. Kenya identifies 1.8 Mha for agroforestry under a conservative scenario, while another 0.4 Mha is eligible for commercial plantations. Rwanda identifies 1.1 Mha to be restored through agroforestry, while another 0.25 Mha consists of existing eucalyptus plantations with the potential to be improved.

2.2 Mapping landscape restoration at global scale

The first assessment of the global opportunity for FLR was commissioned by the Global Partnership on Forest Landscape Restoration before the Bonn Challenge started. This research estimated that more than 2 billion hectares of land across the world could be subject to FLR, as shown in Figure 2.1 (Laestadius *et al.*, 2011). This is about 15% of the total global land surface area.

Laestadius *et al.* (2011) first estimated locations where forests could grow if there were no human interventions, *i.e.* the potential forest cover. Data on climate, soil type and elevation were used, as well as the current and historical forest extent. The map of **potential** forest cover was then compared with a map of **current** forest cover to identify areas that have been **deforested**. Next, **degraded** areas were identified as land where tree cover is lower than its potential. Finally, areas subject to high pressure from human activity were excluded. These include densely populated areas with more

Figure 2.1 Forest landscape restoration opportunities worldwide



Source: Laestadius et al., 2011

than 100 inhabitants per square kilometre (km²), as well as cultivated areas and intensively used areas.

In the Laestadius assessment, the restoration opportunity is divided into three different categories outlined below.

1. Wide-scale restoration is suitable on 0.5 billion hectares of land. This is land with a population density of less than ten inhabitants per km² and the potential to support a closed forest (more than 45% canopy).

2. Mosaic restoration is appropriate in 1.5 billion hectares, making it the biggest opportunity in terms of area. Mosaic restoration is assumed to be the most likely option in an area with moderate human pressure (10-100 inhabitants per km²). In such areas, forests are combined with other land uses that incorporate trees. Examples are agroforestry, smallholder agriculture and buffer planting around water courses or settlements.

3. Remote restoration is an opportunity in 0.2 billion hectares. These areas are unpopulated and far from human settlement – mainly northern boreal forests that have been degraded by fire. While these would be difficult (*i.e.* costly) to deliberately restore, they could resume functioning naturally and become healthy again.

Estimates by Laestadius are similar to estimates in global land degradation studies (Gibbs and Salmon, 2015). However, the goal of Laestadius was not to map degraded land but rather to map the opportunity for FLR.

There are various reasons why forest cover may be lower than its potential, so this land is not necessarily degraded. In addition, land may be degraded in regions where no FLR potential exists.

Degraded lands show productive potential, but this is often overestimated, particularly in terms of bioenergy crops, due to highly uncertain degradation datasets (Gibbs and Salmon, 2015). This poses a severe risk of misinforming policymakers. The location, area and condition of degraded land is not well understood, and this obstructs a realistic strategy. There is no clear consensus on the entire area of degraded land either globally or at the 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 series of processes *e.g.* desertification, salinisation, erosion and compaction. But it sometimes refers to only some of these processes (Gibbs and Salmon, 2015). Further, some studies include degradation due to natural causes while others only include degradation caused by humans (Wiegmann *et al.*, 2008), and idistinguishing between the two is often difficult.

In addition, there are differences in the timeframe and spatial scope of studies. Some estimates focus on the current status of land, due to past degradation, while others consider ongoing degradation processes or the risk of future degradation. Land with natural low productivity is sometimes treated as degraded. Finally, some studies have concentrated on soil degradation while more recent research views land degradation in a broader sense by also including vegetation (Gibbs and Salmon, 2015).

There are four different main methods for quantifying degraded land: expert opinion, satellite-derived net primary productivity, biophysical models and maps of abandoned cropland. Each provides an insight on one aspect of the situation but they all have their weaknesses too (Gibbs and Salmon, 2015).

Expert opinion is the oldest method for assessing degraded land. Although subjective, it is widely used, and this will likely continue since degradation will remain a subjective concept with location-specific benchmarks (Sonneveld and 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 relatively old is still in use (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 and Salmon, 2015).

Satellite assessments, biophysical modelling and maps of abandoned cropland give different insights

The second approach is satellite-based. This has the potential to improve the spatial representation of degraded land in a consistent way, and is both quantitative and repeatable. However, this method has a number of drawbacks: it has a tendency to neglect soil degradation, can only measure degradation after 1980 and does not easily distinguish between naturally low productive and (human-induced) degraded areas.

An example of this approach is the FAO project known as the Global Assessment of Land Degradation and Improvement (GLADA) (Bai *et al.*, 2008). One aspect of this project is to quantify degradation between 1981 and 2003 using the Normalized Difference Vegetation Index, which assesses vegetation condition and productivity.

Deviations from the Normalized Difference Vegetation Index could indicate land degradation if other factors like rainfall, climate and land use are taken into account. The methods underlying GLADA received criticism (Wessels *et al.*, 2012), and the satellite-based assessments will never capture the full degradation picture. However, this 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 datasets 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), which used a biophysical model including spatial data on soil type, topography, average air temperature and precipitation. Marginal areas with low production potential, which coincided with observed low-productivity cropping, were designated as abandoned, idle or wasted. Meanwhile, marginal areas with observed full cropping were designated as degraded. In other words, the extent of degradation was based on overutilisation of land with marginal productivity. This approach excludes land that has been previously abandoned because its focus is on current cropping as well as non-agricultural degradation; it is thus not meant to provide a complete picture. This approach may be applied to a greater number of settings, however. The study by Laestadius *et al.* (2011) discussed above, which estimates the potential for FLR, is another example of this type of assessment.

Finally, degraded lands can be mapped by identifying abandoned agricultural land. The idea is that areas that were once cropland have been abandoned because of decreased productivity. However, they may well have been abandoned for political or economic reasons too. This method captures a longer period of time than does the satellite approach – an advantage because in many places data on cropland changes are available from as long ago as 1700. A prominent database on abandoned cropland and pastures is the History Database of Global Environment 3.0 (HYDE), employed to estimate the total area of abandoned agricultural land over the last three centuries (Campbell *et al.* 2009). It excludes land and soil degradation other than abandonment, which is a significant disadvantage of this source. On the other hand, land that is not necessarily degraded is included. The different studies discussed provide very different results. The total extent of degraded land is estimated at 1 216 Mha in GLASOD (Oldeman *et al.*, 1991; Oldeman, 1988), 2 740 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. The datasets use different proxies for degradation but do not measure degradation directly, so not one of them captures all degraded land accurately. They all have their uses, however, as they contribute to the discussion on land degradation.

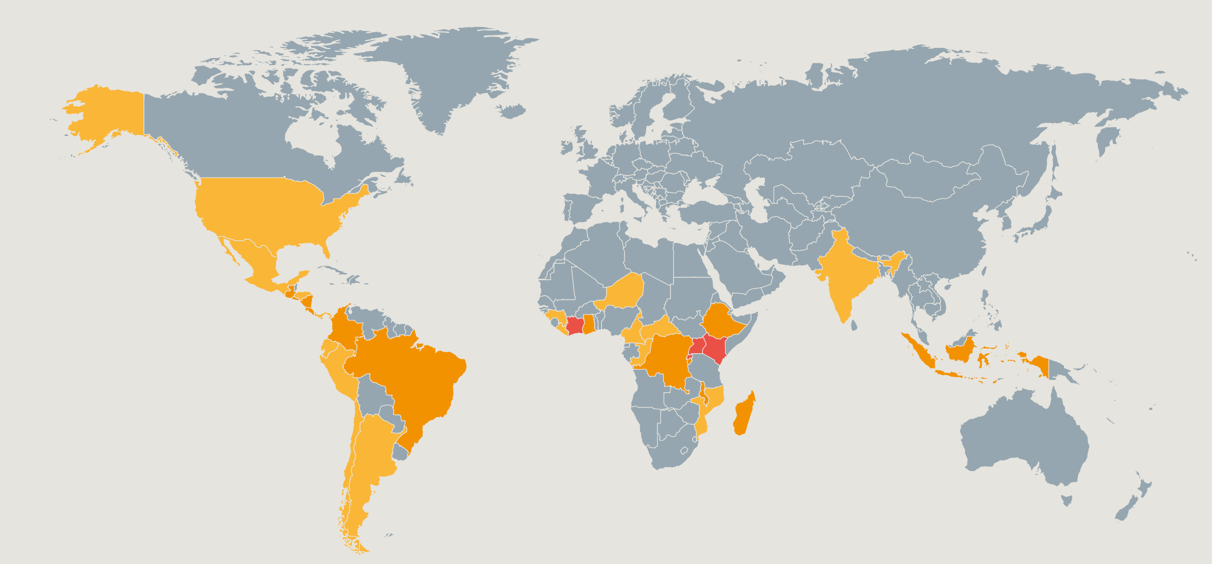
2.3 Landscape restoration opportunity at country level

While the study by Laestadius *et al.* (2011) presents the big picture on FLR potential, its low resolution (*i.e.* level of detail) and lack of country-specific input data means it is of little use for national decisions. The ROAM methodology was devised 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 can serve as a starting point by identifying areas most suitable for restoration (IUCN and WRI, 2014).

During a ROAM assessment, different facets of the restoration opportunity are explored. The total magnitude of restoration opportunity in an area is calculated taking social, economic and ecological factors into consideration. The assessment ascertains the different types of restoration and specific sites in a particular country. The costs and benefits of different restoration strategies are evaluated. Finally, ROAM identifies the important stakeholders and the policy, financial and social incentives in place or required to support restoration efforts (IUCN and WRI, 2014).

The ROAM method was initially tested in four countries: Ghana, Guatemala, Mexico and Rwanda (IUCN and WRI, 2014). By February 2017, ROAM assessment reports had been completed for four African countries: Kenya, Rwanda, Cote d'Ivoire and Uganda (MENR Kenya, 2016; MNR Rwanda, 2014; Côte d'Ivoire Ministry of Environment and Sustainable Development, 2016; Ministry of Water and Environment Uganda, 2016). Furthermore, assessments were being carried out in Brazil, Colombia, Costa Rica, Democratic Republic of the Congo (DRC), El Salvador, Ethiopia, Ghana, Guatemala, Indonesia, Madagascar, Malawi and Nicaragua (Mawoko, 2017; IUCN, 2016b).

Figure 2.2 Overview of countries making Bonn Challenge pledges and ROAM assessments



Source: IUCN, 2016b; IRENA review of ROAM reports

Rwanda

Rwanda was the first African country to make a pledge to the Bonn Challenge and the first to complete a ROAM assessment (MNR Rwanda, 2014). One of Rwanda's policy objectives is to achieve border-to-border forest and landscape restoration, reversing resource depletion across the whole country. 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 border-to-border restoration goal is reflected in the pledge to restore 2 Mha by 2020, which is around 75% of the country's total surface area.

Rwanda's ROAM assessment was carried out by a team of government professionals and experts from WRI and IUCN. They mapped the assessment areas with the most urgent restoration needs, the most immediate benefits and the greatest chance of success. Relevant stakeholders contributed to the process through workshop consultations. Landscape restoration opportunities were evaluated by conducting a geospatial analysis and a cost-benefit analysis. Success factors for FLR were ascertained using a Rapid Restoration Diagnostic created by IUCN and WRI.

The assessment identified four types of land use that could benefit most from restoration by tree planting and site management: traditional agriculture, poorly managed woodlots, poorly managed timber plantations and deforested land. This process generated six restoration interventions as follows:

1. Agroforestry on steeply sloping land (3°-30°) currently used for traditional agriculture and applying soil conservation measures such as terracing.
2. Agroforestry on flat or gently sloping land currently used traditionally. This includes both cropland and pasture/rangeland.
3. Rehabilitating existing eucalyptus woodlots currently managed in a sub-optimal way.

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, riverside zones and wetland buffer zones.

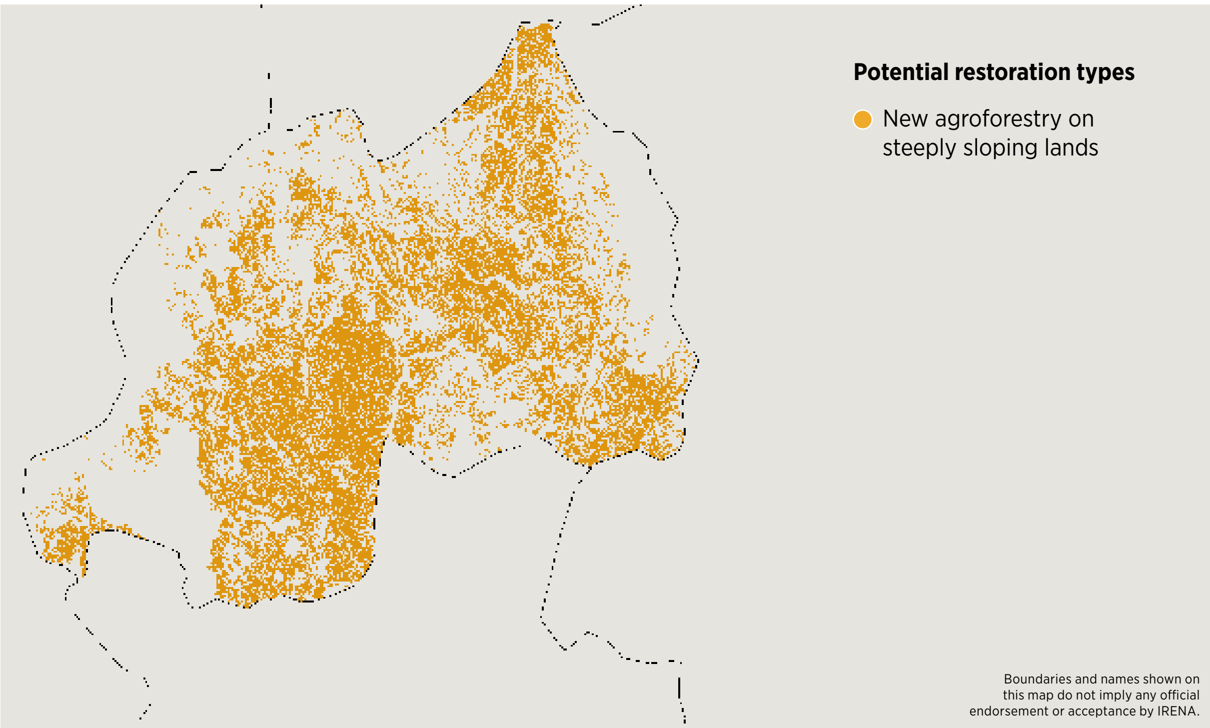
The assessment indicated the first three restoration options are relevant to feedstock production for bioenergy. Since data for these options are used as an input to the assessment, selection criteria for land targeted by these options are critical.

The applicable area for all restoration interventions was selected on the basis of 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. Geographic Information System (GIS) software was used to collect and analyse these data.

The researchers worked out the potential areas for agroforestry on steeply sloping land by identifying land with a slope of 3°-30°, isolating areas shown to be cropland from the land cover dataset, and non-forested areas from the forest cover dataset. Areas for agroforestry on flat or gently sloping land were located using the same datasets but this time also including grassland/shrubland from the land cover dataset and land with a slope of less than 3°. No land degradation criterion was included in the selection for agroforestry. Areas that could benefit from the third option above were chosen by isolating the eucalyptus plots in the forest cover dataset. No data on the management status of these plots were available, so it was assumed that all plots could benefit from this restoration intervention.

The analysis shows a total restoration opportunity of 1.52 Mha, of which 1.37 Mha is worth considering for bioenergy, shown in green in Table 2.1. The restoration options considered unsuitable for bioenergy production are shown in red.

Figure 2.3 Opportunities for agroforestry on steeply sloping lands in Rwanda



Source: MNR Rwanda, 2014

Table 2.1 Potential surface area for each restoration option in Rwanda

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

Source: MNR Rwanda, 2014

Kenya

The Kenya ROAM assessment is still in progress. However, a tree-based landscape restoration potential map has been published along with a technical report describing the methodology used (MENR Kenya, 2016). Forest restoration is a high priority in Kenya as indicated by several policies such as the pledge to the Bonn Challenge and AFR100 to restore 5.1 Mha land by 2030, and the plan in the 2010 Constitution to reforest and maintain tree cover in at least 10% of the country.

To support these goals, a working group was formed to assess the landscape use challenges in Kenya, as well as the corresponding landscape restoration options. It was also tasked with mapping the locations in which the different options could be implemented. The resulting maps intend to identify priority landscapes; additional mapping is still to be carried out at the landscape level to meet the specific needs of particular areas (MENR Kenya, 2016).

The study identified several land use challenges: 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, seven restoration options were selected and are listed below (MENR Kenya, 2016):

1. Reforestation of natural forests in protected areas that have had recent forest cover, or afforestation of protected areas 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. Agroforestry on cropland, subdivided into areas with currently less than 10%, and areas with 10%-30% tree canopy cover. Tree canopy cover of 10% on agricultural land is required by law in Kenya (Government of Kenya, 2009), so areas with currently less than 10% could be prioritised. However, some areas might benefit from a higher tree canopy cover, especially if they have degraded

soil. The upper threshold for regenerating degraded land without negatively affecting agricultural production was found to be 30%. The selection criteria for this option are discussed in detail below.

4. Commercial tree and bamboo plantations on potentially marginal cropland and unstocked plantation forests. For cropland with low productivity, it could be more beneficial to switch to plantations, while designated plantations with very low tree canopy cover can be restored. The selection criteria for this option are discussed in detail below.
5. Tree-based buffer zones along water bodies and wetlands.
6. Tree-based buffer zones along roads.
7. Restoration of degraded rangelands. This was not one of the original restoration options but was selected after stakeholder consultation because of the large areas concerned 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 seven restoration options, the assessors found the third and fourth to be appropriate for producing feedstock for bioenergy. Selection criteria were chosen for each option and aligned with corresponding national-level spatial datasets. For the third option – agroforestry on cropland – agricultural land was included from a current land cover dataset. However, large-scale irrigation agriculture was excluded because it was assumed that this type of agriculture would not benefit from higher tree cover. Next, areas with less than 10%, and with 10%-30% tree cover, were selected from the tree canopy cover dataset for the two different options. Slopes exceeding 35% (~20°)

were excluded, as well as protected areas. As in Rwanda, the areas identified for restoration with agroforestry are not necessarily degraded.

For the fourth option – commercial tree and bamboo plantations on marginal cropland and unstocked plantations – the marginal cropland and unstocked plantations had to be defined. Marginal cropland included cropland 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) according to moisture availability, with 1 being humid at 1100-2700 millimetres (mm) annual rainfall and 7 being very arid (150-350 mm). This zoning method is different from the agro-ecological zoning method used by FAO. Agriculture areas in these buffers can have marginal yields due to ecological stress and low precipitation. From this definition of these marginal croplands, only areas with annual precipitation of more than 400 mm were included because trees need this to have acceptable survival rates (Hijmans *et al.*, 2005). In addition, only areas within 10 km of a road were included because it was assumed that areas further away than this were too isolated to be easily accessible, and that this is an important consideration for these commercial plantations. As with the third option, protected areas and areas with a slope exceeding 35% (~20°) were excluded. Unstocked plantations were simply defined as plantations with less than 15% tree canopy cover.

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

Table 2.2 Potential surface area and 2030 target for each restoration option in Kenya

Restoration option	Restoration potential (Mha)	Restoration target 2030, conservative scenario (Mha)
Reafforestation 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 unstocked 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

Source: MENR Kenya, 2016

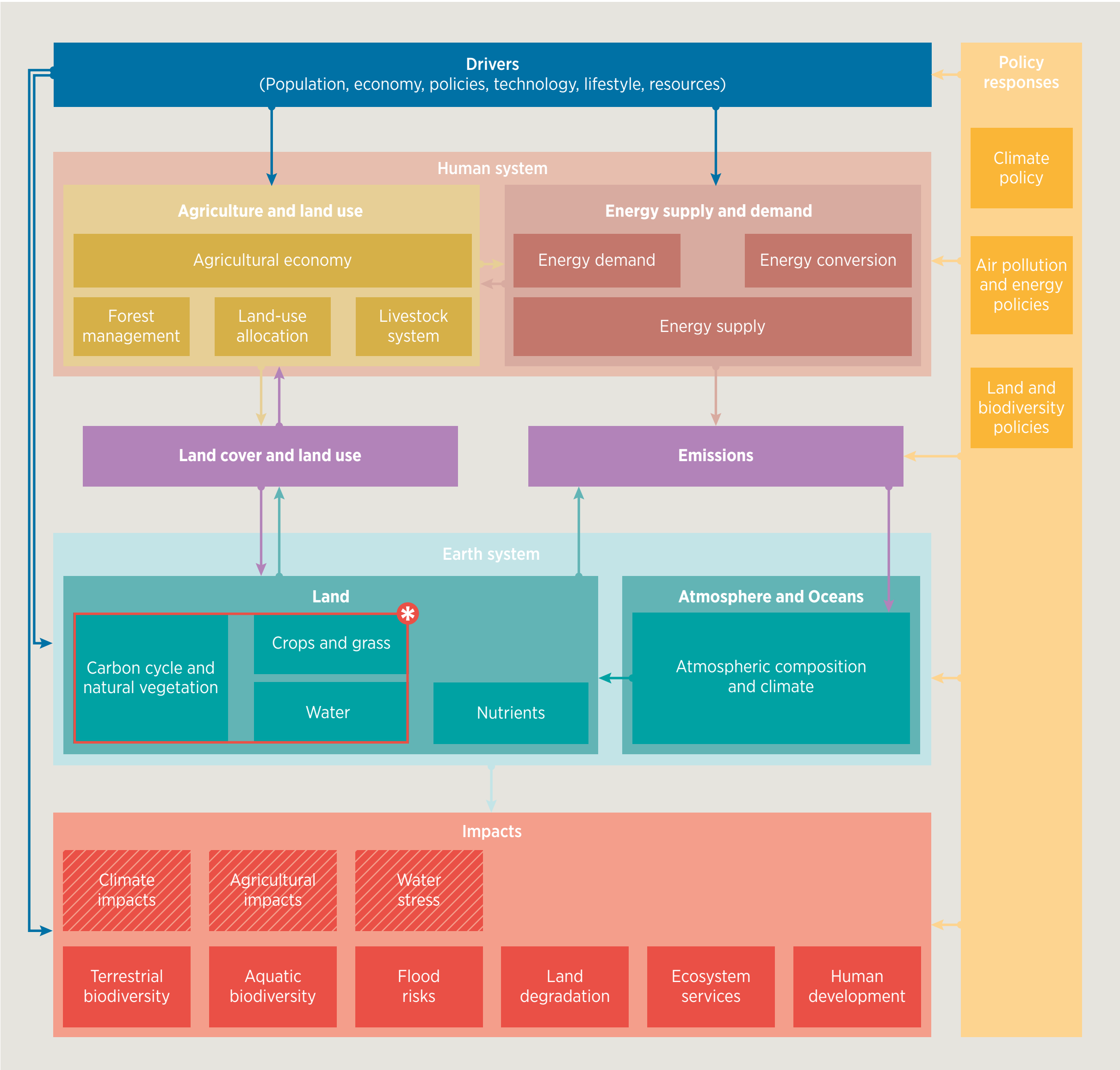
3 INPUT DATA

The SRWC yield map used in the analysis results from the integrated assessment model IMAGE 3.0 (Stehfest *et al.*, 2014). This model, standing for 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 that uses the dynamic global vegetation model LPJmL (standing for Lund-Potsdam-Jena managed Land) to calculate potential yields for bioenergy crops.

3.1 Data on yields of short rotation woody crops

The IMAGE model is developed by the Netherlands Environmental Assessment Agency (Stehfest *et al.*, 2014). The main aims of IMAGE relate to global environmental change and the analysis of important processes and response strategies. IMAGE is mainly used for two purposes: to model and examine a future without drastic change *e.g.* a baseline, and to see how policies and measures

Figure 3.1 IMAGE 3.0 framework



** Role of LPJmL model is outlined in red*

Source: Stehfest et al., 2014

could limit negative impacts on the environment and human development. As shown in Figure 3.1, the model's framework consists of the Human system and 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.

However, LPJmL is embedded in the core model and takes care of the carbon, vegetation, agriculture and water component of the Earth system in IMAGE, outlined in red in Figure 3.1. The bioenergy module is part of one of its subsections: crops and grass. In this context, LPJmL is employed to calculate a total of potentially available bioenergy by calculating global bioenergy crop yields on a 0.5 x 0.5 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.

As a standalone model, LPJmL was developed by the Potsdam Institute for Climate Impact Research (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. Nine plant functional types, which represent natural vegetation, and 15 crop functional types, which represent managed vegetation, describe the global flora. Two of these crop functional types represent SRWC for dedicated biomass plantations. These two crop functional types were added to LPJmL following a study by Beringer *et al.* (2011). The first represents temperate deciduous SRWC and is designed to match the performance of poplars and willows. The second represents tropical evergreens and reproduces the performance of relevant eucalyptus species. Their parameter values are given in Table 2.3.

Like other parts of the model, the SRWC component has been evaluated against different types of observational data. In this case, it was 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 specific to the region and crop, and represents the effect of multiple variables that influence yield, such as the use of pesticides and fertilisers, intelligent cropping and sowing dates, integrated pest and nutrient management, and improved crop varieties. The plantations are assumed to not be irrigated. The yields are given in gigajoules (GJ) per hectare per year, using a calorific heating value of 19.5 megajoules per oven dry kilogramme.

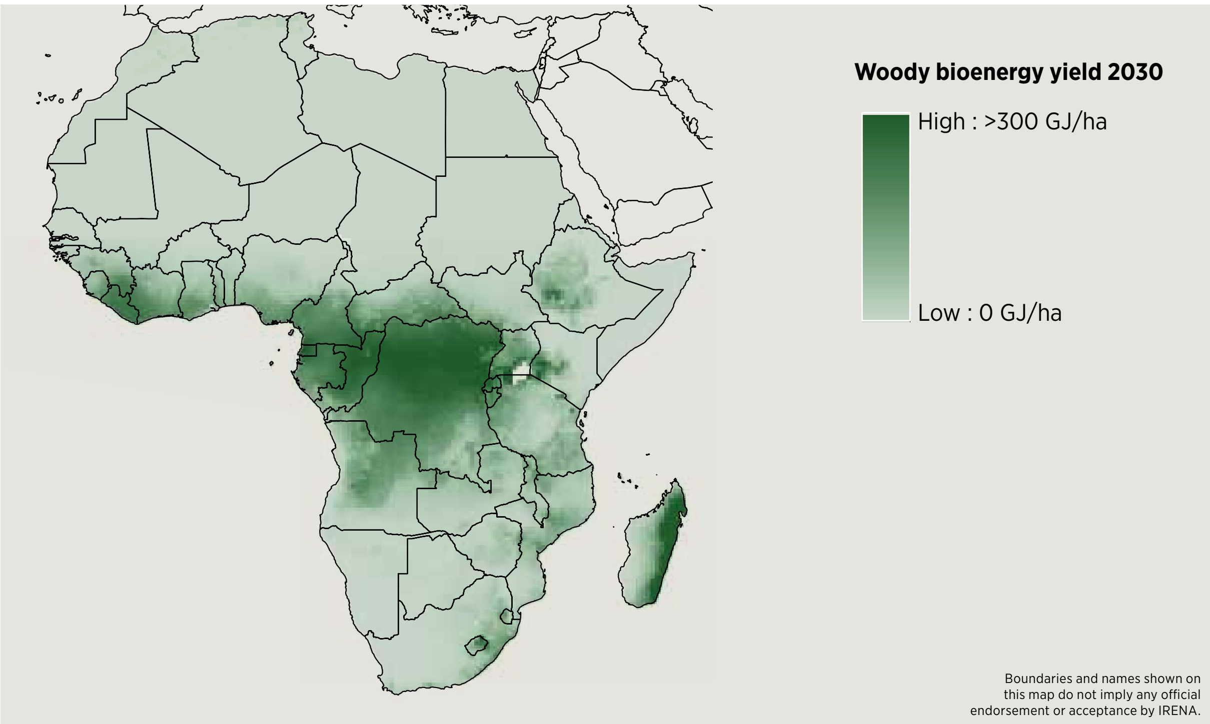
Table 3.1 Short rotation woody crop functional type parameter values[2]

Crop functional type	g_{min} per mm per second	a_{leaf} in years	f_{leaf} per years	$f_{sapwood}$ per years	f_{root} per years	$T_{c,min}$ (ºC)	$T_{c,max}$ (ºC)	R in years	R_{max} in years
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

*(values indicated with * differ from original LPJmL values)*
Adapted from Beringer et al., 2011

2. *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.*

Figure 3.2 Short rotation woody crop yield in 2030 as calculated by IMAGE 3.0.



Source: Stehfest, 2014

3.2 Data on land degradation

The maps used in the analysis are taken from the Global Land Degradation Information System (GLADIS), part of FAO's land degradation assessment for drylands, known as the GLADA project (Nachtergaele *et al.*, 2011). The ecosystem approach is at its core, viewing land degradation as a decline of ecosystem goods and services available from the land over a period of time. Ecosystem goods refer to actual products provided by the land, *e.g.* food, construction materials or water, while ecosystem services include more qualitative characteristics provided by the land: regulating climate, cleansing air and water or even providing beauty, inspiration and recreation. These goods and services are grouped in six distinct components considered tangible and measurable: biomass, soil health, water quantity, biodiversity, economic services and social services. Thus, whereas GLADA focuses on biomass and GLASOD on soil health, GLADIS uses a differentiated approach to cover the subject of land degradation. It thereby portrays the complexity of the topic of land degradation.

First this section deals below with the method to correct the SRWC yield from IMAGE for land degradation. This method makes use of the soil health map from GLADIS. Then the GLADIS biophysical land degradation status map is discussed. This is used in the analysis to select the area for bioenergy production in a range of scenarios as described in section 4.2.

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 in 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 employed here is adapted from the method 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 adjusted in order to be applicable to the present study.

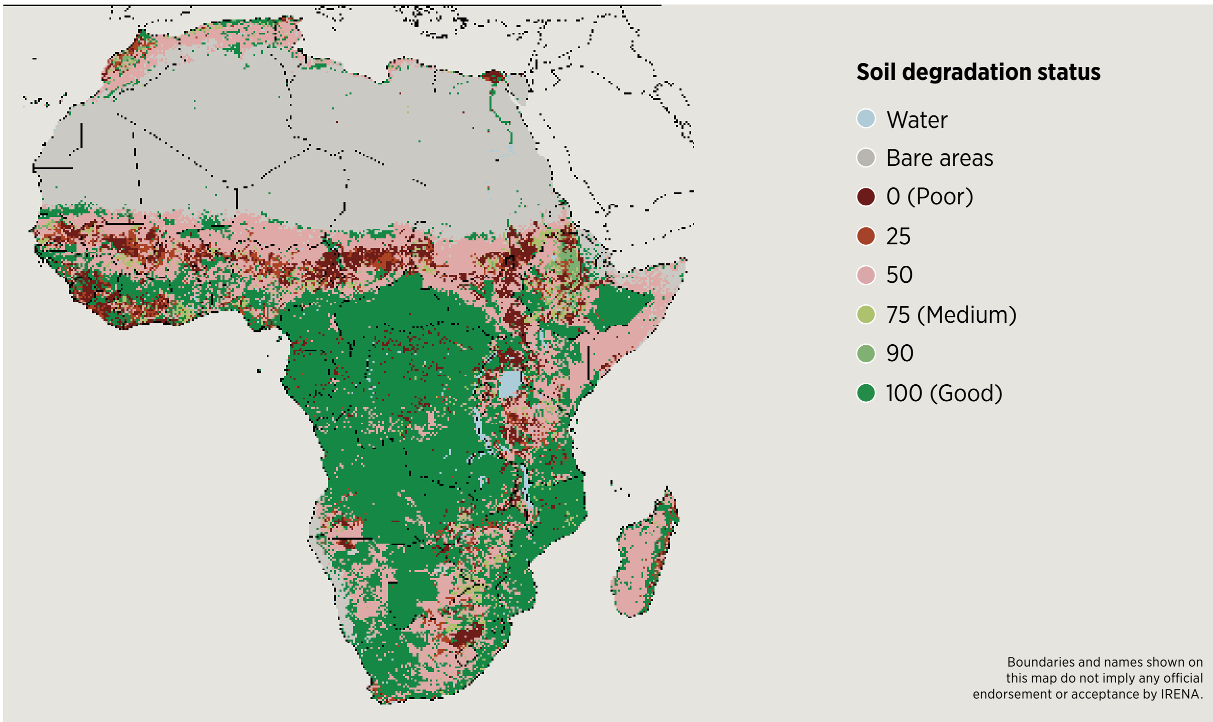
As described in section 2.7, GLASOD is based on expert opinion (Oldeman *et al.*, 1991; Oldeman, 1988). It assessed human-induced soil degradation in 1945-1990 and provides data on severity of degradation in five qualitative degrees as well as the area affected as a percentage. This is worked out for each mapping unit, which is based on physiographic features. It is then worked out for the two most important types of degradation in each unit. Compaction, erosion, waterlogging, subsidence and chemical are the types of degradation considered.

Crosson (1997) estimated generic yield reduction percentages valid for C_3 annual food crops (crops that fixate carbon dioxide in photosynthesis using only the C_3 pathway (*i.e.* via 3-phosphoglyceric acid). This provided a high and low yield reduction percentage for each degree of degradation. These percentages were later also used by the GLASOD developers (Oldeman, 1998). Nijsen *et al.* (2012) adapted these for perennial bioenergy crops, including SRWC on the basis of a literature review. Perennial bioenergy crops are considered less susceptible to soil degradation for two main reasons.

First, they have characteristics that give them higher stress tolerance, resulting in higher survival rates and higher yields. Second, they can increase soil organic matter, improving soil quality and yield. The research aimed to determine a difference in yield reduction for five different limitations induced by soil degradation: nutrients, water, toxicity, agronomy and gaseous exchange. These were translated into the different degradation types mapped in GLASOD, giving a high and low yield reduction per type related to degradation.

The axis of the GLADIS framework that corresponds with the GLASOD database is soil health, shown in Figure 3.3. A difference between the two is that soils under natural vegetation are not considered degraded in GLADIS. The GLADIS soil health map is based on the Global Agro-Ecological Zones study (Fischer *et al.*, 2002).

Figure 3.3 Soil health status in GLADIS



Source: Nachtergaele et al., 2011

The GLADIS soil health status axis does not contain data on the type of soil degradation. The yield reductions per degradation type according to Nijsen *et al.* (2012) are thus brought back to one value, the 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 into five equal components to match the severity categories in GLASOD. Table 3.2 shows the resulting yield reduction method.

Biophysical land degradation status

The biophysical land degradation status map is used in the RESTORE and RESTRICT scenarios. 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 in order to highlight the importance of each service for that land use (Nachtergaele *et al.* 2011).

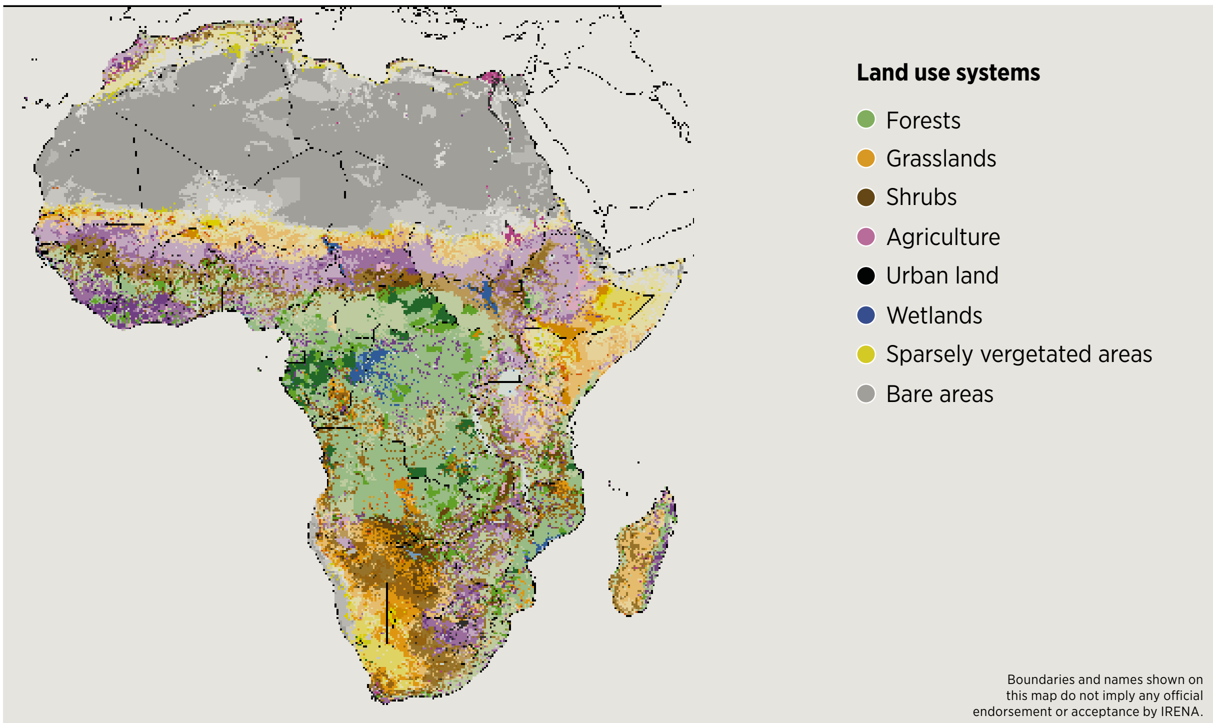
Table 3.2 Crop yield reduction versus land degradation and soil health

GLASOD degree of degradation	GLADIS soil health status	Perennial energy crop yield reduction
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%

3.3 Data on land use systems

The present study uses the global land use systems map from the FAO GLADIS database (Nachtergaele and Petri, 2013). The GLADIS project constructed this map because land use is considered 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 impact on its status. To construct this map, data from a number of sources were 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 3.4 with a simplified legend.

Figure 3.4 Land use systems in GLADIS



Sou rce: Nachtergaele et al., 2011

3.4 Data on land area associated with AFR100 pledges

The size of each AFR100 pledge is documented on the Bonn Challenge website (IUCN, 2016b). Although some pledges are made for a specific region or province, most pledges are spread across the whole country and have no additional spatial constraints. The AFR100 pledges are listed in Table 3.3.

The Bonn Challenge provides a great opportunity to unlock bioenergy potential

Table 3.3 Pledges made to the AFR100 initiative

Country	2020 pledge (Mha)	2030 pledge (Mha)	Total pledge (Mha)
Benin	0.2	0.3	0.5
Burundi	2		2
Cameroon		12.06	12.06
Central African Republic	1	2.5	3.5
DRC	8		8
Republic of the Congo		2	2
Cote d'Ivoire		5	5
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
Rwanda	2		2
Uganda	2.5		2.5
Total	39.4	35.96	75.36

Source: IUCN 2016b

3.5 Data on land restoration potential in Kenya and Rwanda

The ROAM assessment results for Kenya and Rwanda are discussed in section 2.3. They identify a number of restoration options worth considering for bioenergy production. These have been reclassified into either agroforestry or plantation as shown in Table 3.4.

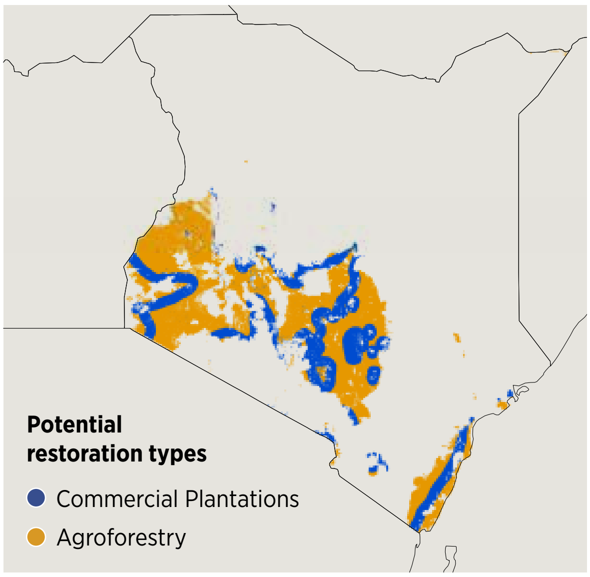
The resulting maps are shown in Figures 3.5 and 3.6.

Country-level studies are needed to understand the range of uses for degraded land

Table 3.4 Reclassification of ROAM restoration options

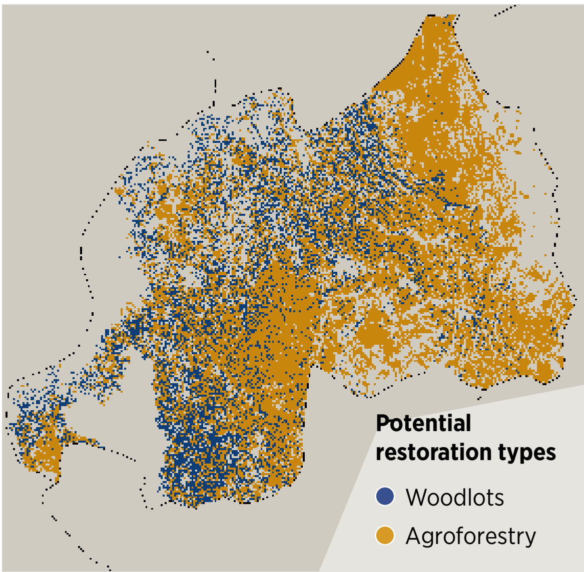
Country	Restoration option ROAM	Reclassified
Kenya	Agroforestry on cropland with less than 10% tree canopy cover	Agroforestry
	Agroforestry on cropland with 10%-30% tree canopy cover	Agroforestry
	Commercial plantations on marginal cropland	Plantation
	Commercial plantations on unstocked plantations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

Figure 3.5 Potential restoration options relevant to bioenergy in Kenya



Adapted from MENR Kenya 2016

Figure 3.6 Potential restoration options relevant to bioenergy in Rwanda



Adapted from MNR Rwanda 2014

Boundaries shown in these maps do not imply any official endorsement or acceptance by IRENA.

4 METHODOLOGY

In the present study, two different methods were employed to examine the environmentally sustainable bioenergy potential from restored degraded land in Africa using SRWC following pledges made to AFR100. One method estimates the potential for all 18 pledges under the initiative, using data available for each. A more precise method is employed to estimate the potential for Rwanda and Kenya, building on the studies these countries have carried out using ROAM. This method could be applied to other countries once they have completed a ROAM assessment.

4.1 Geographical scope and timeframe of study

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

The detailed analysis focuses on Kenya and Rwanda 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 are the same as for the analysis of the African continent.

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

Since crop yields have been rising over time, it can be anticipated that typical yields on bioenergy crops will increase between now and the year when production starts. Future bioenergy yields are projected by IMAGE. In this model, the increase in crop yield is due to two factors: the improvement in management practices and the increase in carbon dioxide concentrations over time. However, the second factor will not have a major effect in the time horizon of this study (Daioglou, 2017).

The IMAGE results for the Shared Socioeconomic Pathway 2 (SSP2) scenario 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 diverge greatly from historical patterns.

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

4.2 General method for evaluating restoration pledges in Africa

Scenarios

This analysis determines the bioenergy potential for each of the pledges made to AFR100. However, most countries still lack two critical factors required to calculate this because these factors are not included in the initial pledge. First, there is no information on the share of the pledge to be used for bioenergy production *e.g.* how much surface area will be dedicated to planting or restoring SRWC plantations. Second, the sites targeted for restoration for bioenergy production are not identified. The ROAM analysis deals with both these issues at the national level. However, most countries have not completed such an analysis yet. Different scenarios are used to analyse possible strategies. The scenarios chosen give different views on the potential for each pledge.

The scenarios for share of pledge to be used for bioenergy are based on the current ROAM assessments for African countries. Four assessments are complete but only the reports for Kenya and Rwanda have resulted in a list of restoration options and the area they could be applied to (MENR Kenya, 2016; MNR Rwanda, 2014; Ministry of Environment and Sustainable Development Côte d'Ivoire and Ministry of Economy and Finance Côte d'Ivoire, 2016; Ministry of Water and Environment Uganda, 2016). These results are the basis for three scenarios, outlined below.

- **100% used for bioenergy.** The results of this scenario show the total bioenergy potential of each pledge.
- **63.2% used for bioenergy.** This percentage is the average share of 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 were used for bioenergy production.
- **12.3% used for bioenergy.** This percentage 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 were used for bioenergy production.

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

A. **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.

B. **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 SRWC on the most degraded land considered suitable for bioenergy production, even if this includes agricultural land.

C. **Restricted.** Similar to "restoration-focused" but excludes arable land. This leaves the main land categories: grasslands, shrubland and sparsely vegetated areas. By excluding arable land from bioenergy production, the assumption is that food, animal feed and materials production are not affected.

Altogether, nine scenarios are examined as shown in Table 4.1.

Analysis

The bioenergy potential for the African restoration pledges under each scenario is calculated using the following formula:

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

Table 4.1 Scenarios in the analysis of the potential from all African pledges

	Bioenergy share: 100%	Bioenergy share: 63.2%	Bioenergy share: 12.3%
Resource-focused	RESOURCE-100	RESOURCE-63	RESOURCE-12
Restoration-focused	RESTORE-100	RESTORE-63	RESTORE-12
Restricted	RESTRICT-100	RESTRICT-63	RESTRICT-12

Where:

P_x = SRWC potential from all African restoration pledges in year x (in EJ)

$A_{x,y}$ = area selected for bioenergy production in year x and country y (hectares)

$Y_{x,y}$ = average SRWC yield on selected area $A_{x,y}$ (GJ per hectare)

A three-step analysis was employed to determine $A_{x,y}$ and $Y_{x,y}$:

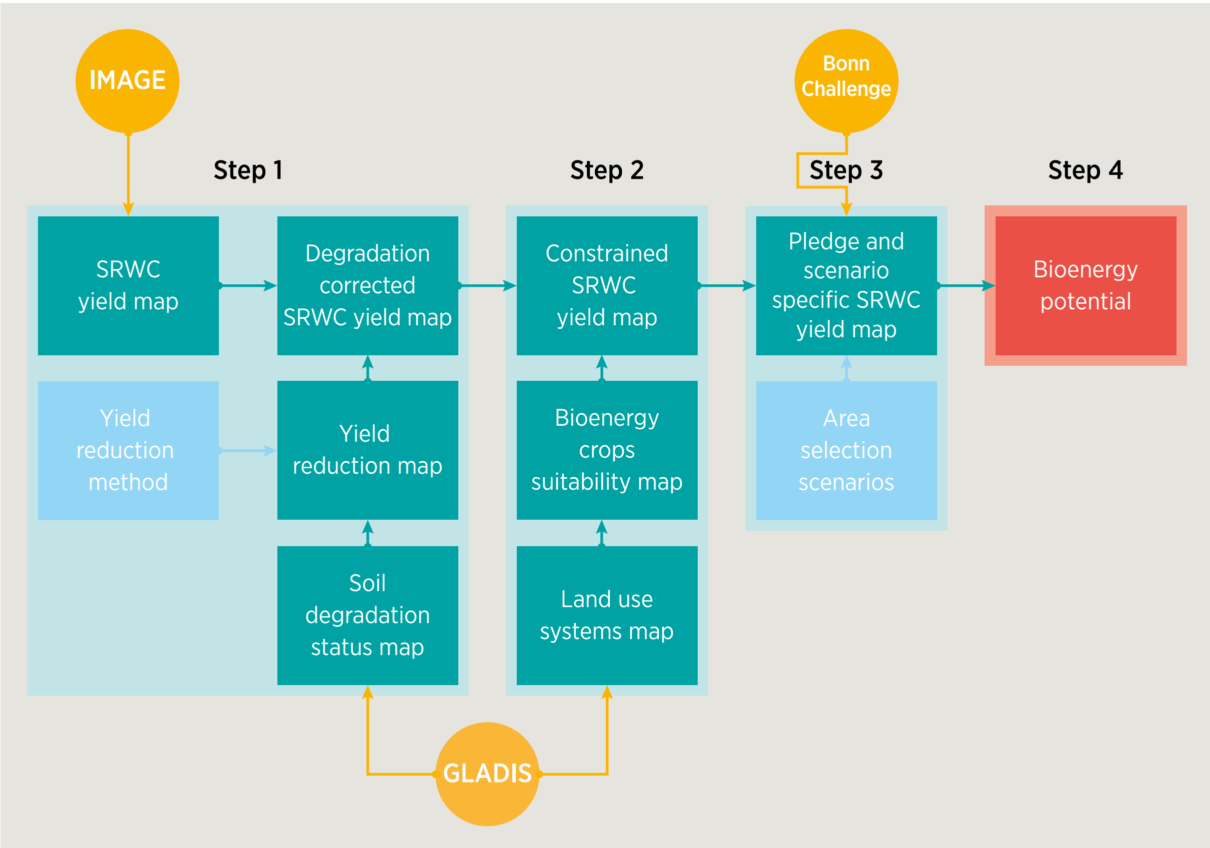
1. **Adjust bioenergy yield:** the **degradation corrected yield** was determined by adjusting potential yield downward based on degree of degradation.
2. **Apply bioenergy spatial constraints:** the area to be considered for bioenergy production was determined by excluding areas unsuitable or undesirable for bioenergy production.
3. **Select bioenergy production area:** the **area in which bioenergy production would take place** for each pledge was specified according to the scenario examined, thereby 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 $Y_{x,y}$. The sum of $P_{x,y}$ for all countries yields P_x.

An overview of the analysis is shown in Figure 4.1, and details of each step provided in separate sections below.

Figure 4.1 Overview of the analysis for all African restoration pledges



Sources of input data are shown in yellow, maps in green, other methods in blue, results in red

Adjust bioenergy yeeld

In the first step, maps on the SRWC yield from IMAGE and the status of soil health from GLADIS were employed to generate a map of the SRWC yield corrected for degradation. A method for translating 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 per hectare)

$Y_{uncorrected}$ = uncorrected SRWC yield generated by IMAGE (GJ per hectare)

R_{yield} = yield reduction factor based on GLADIS soil health status data (%)

The resulting map shows the SRWC yield corrected for degradation for the complete continent of 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 are described in detail in sections 3.1 on the IMAGE SRWC yield map and 3.2 on the GLADIS degradation maps.

Apply bioenergy spatial constraints

In the second step, the SRWC yield map corrected for degradation was constrained by excluding a number of land uses. A GLADIS map on land use systems was employed to this end. First, the following land uses (and categories within them) were excluded as they are generally viewed unsuitable for bioenergy production:

- urban land
- bare areas (unmanaged; protected; with low feedstock density; with high feedstock density)
- open water (unmanaged; protected; inland fisheries).

Next the following categories were excluded as they are considered undesirable for bioenergy production, according to the set of sustainability criteria established by Beringer *et al.* (2011):

- protected areas (categories “forest – protected” “grasslands – protected” “shrubs – protected”, “agriculture – protected”, “wetlands – protected” “sparsely vegetated areas – protected”)
- forests (categories “forest – virgin”, “with agricultural activities”, “with moderate or higher livestock density”)
- wetlands (categories “wetlands – unmanaged”, “mangrove”, “with agricultural activities”).

Finally, under the scenarios that exclude arable land for bioenergy production (RESTRICT), the following categories were also 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 then generated that excluded these land uses. This map was combined with the SRWC yield map corrected for degradation. Together, they produced a map of Africa showing the yield only on areas considered for bioenergy production: the constrained SRWC yield map. The map for the RESTRICT scenarios differs from the map for the other scenarios because agricultural land is not considered suitable for bioenergy production under the RESTRICT scenarios. The input data for this step are discussed in section 3.3.

Select bioenergy production area

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

It took two substeps to work out the area for bioenergy production. First, the **size** of the area that would be used for bioenergy production in country y, $A_{x,y}$, was calculated using the formula below. The input data for this step – size of the area pledged – are discussed in section 3.4.

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

Where:

$A_{pledge,y}$ = area pledged for restoration by country y (hectares)

BES_X = share of pledge that will be used for bioenergy (%)

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

Bioenergy will play a very important role in future

For the RESTORE and RESTRICT scenarios, bioenergy production would take place on the land with highest degradation status. For this purpose, the map of biophysical land degradation status from GLADIS is employed, as discussed in section 3.2.2. Thus the appropriate area with the highest land degradation status was selected. For the RESTRICT scenario, the constrained yield map which also excluded agricultural land was employed.

If the constrained SRWC yield map showed the area for suitable bioenergy production in country y was lower than the area identified in the first substep, the larger area is selected.

Calculate sustainable bioenergy potential

The fourth step was to multiply the hectares selected with the average yield for that surface area. The overall potential was found by adding up the potential for all pledges:

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

To clarify the steps above, the analysis for Kenya under scenario RESTORE-12 for each step follows below as an example.

The SRWC yield map corrected for degradation was generated on the basis of the IMAGE SRWC yield map.

1. Unsuitable areas were excluded in this step, generating a constrained SRWC yield map. Agricultural land is not excluded for this scenario.
2. The area that intended for bioenergy is selected. Under this scenario, the surface area used for bioenergy in Kenya is 5.1 (size of Kenya pledge) * 0.123 (share of bioenergy in scenario RESTORE-12) = 0.63 Mha. In Kenya, the 0.63 Mha on the constrained SRWC yield map with the highest biophysical land degradation status shown by GLADIS was selected.
3. Multiplying the average yield of this area with the size of the area selected generated the total SRWC potential for Kenya under scenario RESTORE-12.

Overview of data used

An overview of all data used in this analysis is shown in Table 4.2. The far right-hand column cross-references with detailed explanations of the data elsewhere in this report.

Table 4.2 Data used in the analysis for all African restoration pledges.

Data	Type	Source	Details
	Step 1		
SRWC yield 2020	Map	IMAGE	3.1
SRWC yield 2030	Map	IMAGE	3.1
Soil health status	Map	GLADIS	3.2.1
Soil degradation to yield reduction	Method	Based on Nijsen *et al.* (2012)	3.2.1
Yield reduction	Map	Present study	
Degradation-corrected SRWC	Map	Present study	
	Step 2		
Land use systems	Map	GLADIS	3.3
Suitable area for bioenergy crops	Map	Present study	
Constrained SRWC yield	Map	Present study	
	Step 3		
Area pledged for restoration	Parameter	Bonn Challenge	3.4
Year pledge to be brought into restoration	Parameter	Bonn Challenge	3.4
Scenarios for area selection	Scenarios	Present study	4.2.1
Biophysical land degradation status	Map	GLADIS	3.2.2
Pledge and scenario-specific SRWC yield	Map	Present study	
	Step 4		
Area selected for bioenergy production	Parameter	Present study	
Average SRWC yield for selected area	Parameter	Present study	
SRWC potential of pledge	Result	Present study	

4.3 Detailed method for evaluating restoration pledges in Kenya and Rwanda

Following the general analysis of the African restoration pledges, the Rwanda and Kenya pledges were examined in more detail. The overview of the analysis is shown in Figure 4.2. In the analysis of all African pledges, different scenarios were selected to ascertain the possible bioenergy production area. This area was based on the results of the ROAM analysis, which are described in section 2.3. The input data are discussed in detail in section 3.5.

In both countries, the research showed two main restoration types to be relevant to bioenergy production: (1) establishment or improvement of plantations; and (2) agroforestry implementation.

The SRWC data used in this analysis is suitable for SRWC plantations. To account for the lower yield in an agroforestry system, they applied a yield reduction factor of 0.1.

The potential of each pledge was calculated through 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 as suitable for plantation in country y (hectares)

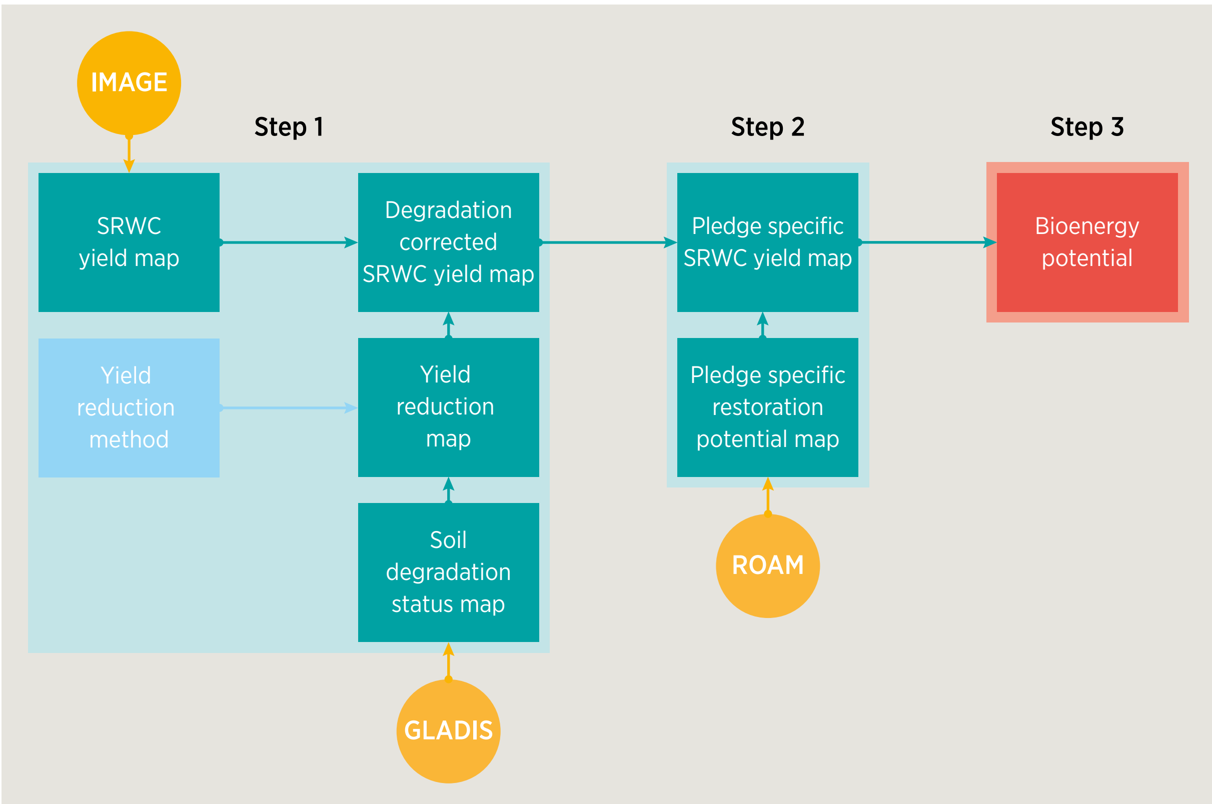
$Y_{y,plantation}$ = average SRWC yield on area $A_{y,agroforestry}$ (GJ per hectare)

$A_{y,agroforestry}$ = area identified by ROAM as suitable for agroforestry in country y (hectares)

$Y_{y,agroforestry}$ = average SRWC yield on selected area $A_{y,agroforestry}$ (GJ per hectare)

$R_{agroforestry}$ = yield reduction factor due to agroforestry (%)

Figure 4.2 Overview of analysis for Rwanda and Kenya restoration pledges



Sources of input data are shown in yellow, maps in green, other methods in blue and results in red

A three-step analysis was employed to determine P_y. Steps 1 and 3 are the same as for the analysis for all African restoration pledges:

1. **Adjust bioenergy yield:** the *degradation-corrected yield* was calculated by adjusting potential yield downwards on the basis of degree of degradation.
2. **Calculate bioenergy production area using ROAM results:** the area intended for bioenergy production for each pledge was specified using the ROAM results, thus calculating $A_{y,plantations}$, $Y_{y,plantations}$, $A_{y,agroforestry}$ and $Y_{y,agroforestry}$.
3. **Calculate sustainable bioenergy potential:** the potential for bioenergy for each country (Py) was worked out through the formula above.

4.4 Related uncertainties

In addition to uncertainties related to the method, variations in the quality and availability of input data employed to estimate the potential caused further uncertainties. The first of these is the **future yield** for SRWC. These yields are generated by the IMAGE 3.0 model using the Shared Socioeconomic Pathway 2 (SSP2) (Daioglou, 2017). A yield increase is expected due to improved management practices and the rise in carbon dioxide concentrations over time. Whether the chosen scenario is realistic is not clear. However, the impact on future yields modelled may not be great for the timeframe assessed.

Furthermore, it was necessary to correct the yield generated by IMAGE for **land degradation**. This was achieved using GLADIS in combination with a yield reduction method. Two uncertainties are associated with this process. First, assessing land degradation is still seen as a considerable challenge associated with major uncertainties on both size and exact location of degraded area (Gibbs and Salmon, 2015). All global databases in existence today are affected by this problem, and all need significant improvements in both data quantity and quality (Caspari *et al.*, 2015). GLADIS is no different, and has been criticised (Nkonya *et al.*, 2011) both for combining multiple factors into aggregated indicators and for lacking a description of how these factors affect land degradation. Moreover, its focus on managed land is viewed as a weakness: it does not consider soils under natural vegetation ever to be degraded (Caspari *et al.*, 2015). For example, a peer review by 18 experts conducted by FAO (2011) reflects this view, with seven experts qualifying the soil health status map as satisfactory, another seven as partially satisfactory and four as unsatisfactory. The other map in this analysis – biophysical land degradation – scores slightly better, with two-thirds of the experts qualifying it as satisfactory. The use of aggregated indicators means type of land degradation is excluded even though it has a major impact on yields (Blanco-Canqui, 2016).

Another uncertainty arises from the **yield reduction method** applied in the present study. 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) but this excludes perennial bioenergy crops. Very little experimental data exist on the effect of land degradation type and degree on bioenergy crop yields, especially for SRWC (Blanco-Canqui, 2016).

5 RESULTS

The results of this analysis are summarised below. The area used for bioenergy production is shown in Figure 5.1 for the countries as a group, and in Table 5.1 for each individual country. The average SRWC yield on a particular area is displayed in Figure 5.2 in total, and in Table 5.2 by country. The SRWC potential, a product of area and yield, is shown in Figure 5.3 and Table 5.3. Table 5.4 displays the SRWC potential as a percentage of the Total Primary Energy Supply (TPES) in each country.

5.1 Potential of all African restoration pledges

Figure 5.1 shows that in the RESOURCE-100 and RESTORE-100 scenarios, bioenergy is produced on 72.7 Mha – 96% of the entire area pledged for restoration. This figure falls short of 100% because in some countries (Burundi, Cameroon and Rwanda) the pledge is greater than the land available under the constraints. The area on which bioenergy is produced in the RESTRICT-100 scenario is significantly lower, namely 59.6 Mha, or 79% of the pledged area. Excluding arable land reduces the capacity available for bioenergy production to an area lower than the pledge in additional countries (Central African Republic, Cote d'Ivoire, Liberia, Malawi and Uganda). Similarly, less land is used in the 63% and 12% scenarios, given that a lower share of the pledge is dedicated to bioenergy in these scenarios.

Table 5.1 shows the bioenergy production area that would be used under the different scenarios, as well as the total area considered available under the spatial constraints examined, taking arable land into account. In most countries, this total area is higher than the bioenergy production area even under the 100% scenarios, which are limited to the size of the pledge. Exceptions are Burundi, Cameroon and Rwanda, where the bioenergy production area is limited by area available under spatial constraints. In Burundi and Rwanda this is because they made a pledge nearly as large as the country itself. Note that the bioenergy production area is equal for the RESOURCE and RESTORE scenarios, which are limited by the same spatial constraints and cover an identical area within each of these three countries.

Figure 5.2 shows that the average SRWC yield for the selected bioenergy production area is highest in the RESOURCE scenarios. This is to be expected, since the areas with the highest yield are selected for bioenergy production under this scenario.

Figure 5.1 Area of African restoration pledges compared to bioenergy production area by scenario (Mha)

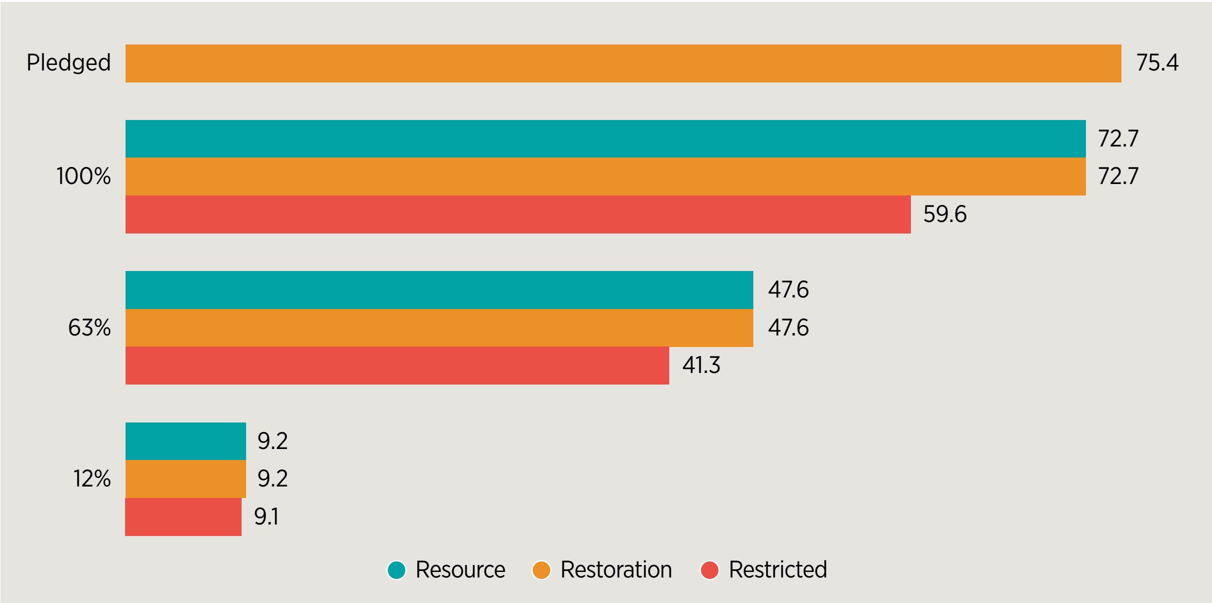


Table 5.1 Bioenergy production area by country under different scenarios (Mha)[3]

Country	Total area under con-straint	Bioenergy production area in scenario								
		RESOURCE			RESTORE			RESTRICT		
		100%	63%	12%	100%	63%	12%	100%	63%	12%
Benin	5.67	0.50	0.32	0.06	0.50	0.32	0.06	0.50	0.32	0.06
Burundi	1.89	1.89	1.26	0.25	1.89	1.26	0.25	0.99	0.99	0.25
Cameroon	9.65	9.65	7.62	1.48	9.65	7.62	1.48	3.17	3.17	1.48
CAR*	4.16	3.50	2.21	0.43	3.50	2.21	0.43	3.15	2.21	0.43
DRC**	32.37	8.00	5.06	0.98	8.00	5.06	0.98	8.00	5.06	0.98
Congo***	6.96	2.00	1.26	0.25	2.00	1.26	0.25	2.00	1.26	0.25
Côte d'Ivoire	18.32	5.00	3.16	0.61	5.00	3.16	0.61	4.34	3.16	0.61
Ethiopia	80.72	15.00	9.48	1.84	15.00	9.48	1.84	15.00	9.48	1.84
Ghana	12.33	2.00	1.26	0.25	2.00	1.26	0.25	2.00	1.26	0.25
Guinea	14.52	2.00	1.26	0.25	2.00	1.26	0.25	2.00	1.26	0.25
Kenya	46.54	5.10	3.22	0.63	5.10	3.22	0.63	5.10	3.22	0.63
Liberia	5.64	1.00	0.63	0.12	1.00	0.63	0.12	0.00	0.00	0.00
Madagascar	44.84	4.00	2.53	0.49	4.00	2.53	0.49	4.00	2.53	0.49
Malawi	5.63	4.50	2.84	0.55	4.50	2.84	0.55	2.52	2.52	0.55
Mozambique	25.98	1.00	0.63	0.12	1.00	0.63	0.12	1.00	0.63	0.12
Niger	36.56	3.20	2.02	0.39	3.20	2.02	0.39	3.20	2.02	0.39
Rwanda	1.84	1.84	1.26	0.25	1.84	1.26	0.25	0.63	0.63	0.25
Uganda	9.43	2.50	1.58	0.31	2.50	1.58	0.31	1.96	1.58	0.31

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RESOURCE-12 has the highest yield, followed by RESOURCE-63 and RESOURCE-100.

Again, this is a consequence of the way the scenarios are set up: under the RESOURCE-12 scenario, the area with the highest yield is used for bioenergy production. The bioenergy production area is bigger in RESOURCE-63 and RESOURCE-100, and land with a relatively low yield is included, lowering the average yield.

For both the RESTORE and RESTRICT scenarios, this trend is reversed: the highest average yield is found in the 100% scenarios, and the lowest in the 12% scenarios. In the RESTORE and RESTRICT scenarios, the land with the highest degree of

3. As reflected in the table, land use in the analysis is spatially constrained to exclude land of several types ill-suited to crop production: urban areas, bare areas, open water, protected areas, forests and wetlands.

degradation is prioritised. Hence, the 12% scenarios use the most degraded land, which results in the lowest average yield. The average yield difference between the RESTORE scenarios is higher than the average yield difference between the RESTRICT scenarios.

This is caused by the relatively high degradation of agricultural land, which makes the yield on those areas lower than on non-agricultural land. In the RESTORE scenarios, this highly degraded agricultural land will be used, resulting in a low average yield. However, agricultural land is excluded from bioenergy production in the RESTRICT scenarios due to the spatial constraints, which results in a higher average yield.

Table 5.2 below shows the average SRWC yield for the selected area by country. In general, the yields in RESOURCE scenarios are higher than in RESTORE and RESTRICT scenarios. For every country, the highest yield is in the RESOURCE-12 scenario, and the lowest yield is in the RESTORE-12 scenario.

Figure 5.2 Average short rotation woody crop yield of all African restoration pledges by scenario (GJ per hectare)

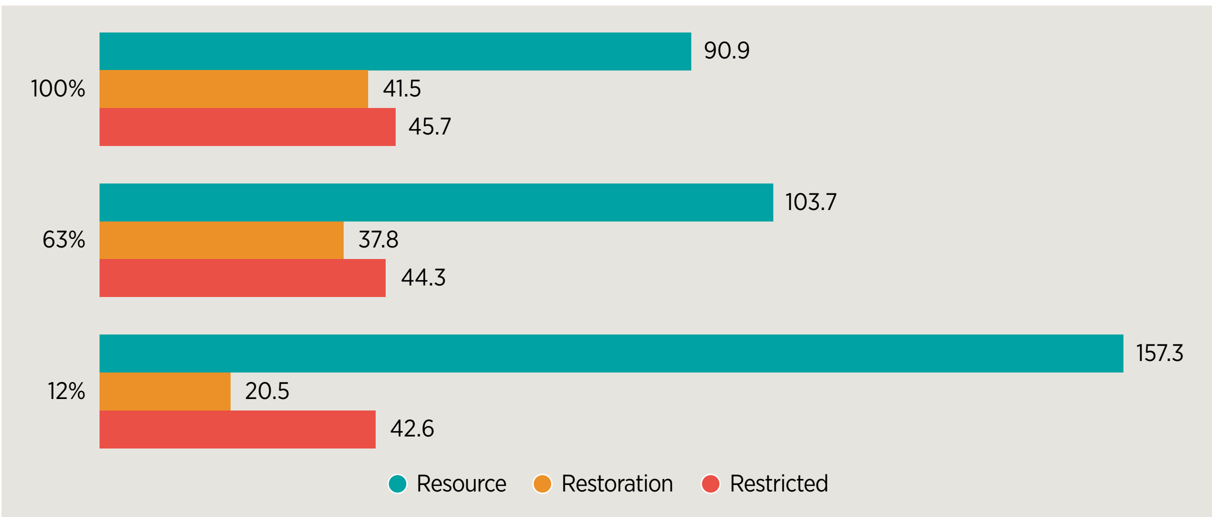

Table 5.2 Average short rotation woody crop yield by country under different scenarios (GJ per hectare)

Country	Average short rotation woody crop yield under different scenarios								
	RESOURCE			RESTORE			RESTRICT		
	100%	63%	12%	100%	63%	12%	100%	63%	12%
Benin	47	57	96	5	5	2	6	6	6
Burundi	61	73	132	61	51	22	65	65	60
Cameroon	23	29	80	23	19	1	38	38	20
CAR*	18	23	44	14	13	2	16	16	16
DRC**	190	213	257	111	125	99	117	131	121
Congo***	267	275	297	179	171	52	200	171	204
Côte d'Ivoire	99	118	157	33	41	15	40	42	20
Ethiopia	59	72	121	12	12	5	10	14	13
Ghana	129	138	174	20	10	4	21	12	11
Guinea	73	86	146	26	16	17	28	34	19
Kenya	68	88	177	30	36	25	23	34	61
Liberia	91	100	164	25	26	26	0	0	0
Madagascar	160	187	336	53	34	34	50	36	40
Malawi	27	36	78	17	14	9	21	21	23
Mozambique	132	139	159	19	19	12	38	26	14
Niger	3	4	5	2	2	1	2	3	2
Rwanda	96	120	225	96	66	22	87	87	70
Uganda	93	109	182	21	21	20	59	62	66

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Countries with high yields in all scenarios are both DRC and Republic of the Congo. According to IMAGE data, favourable conditions give these countries a very high SRWC yield.

GLADIS shows that only small parts of these two countries are affected by degradation. Ghana, Madagascar and Mozambique are other countries with a high average yield (greater than 100 GJ per hectare) in the RESOURCE scenarios. These three countries benefit from large areas with favourable conditions for SRWC and low degradation. However, their low yield in the RESTORE and RESTRICT scenarios suggest that the most degraded areas are not suitable for SRWC.

Countries with a low average yield (less than 100 GJ per hectare) in all scenarios are Benin, Cameroon, Central African Republic, Malawi and Niger. The conditions in these countries are unfavourable for growing SRWC at a large scale, even in the highest yielding areas. Ethiopia, Ghana, Guinea, Liberia and

Mozambique are other countries with low average yields in the RESTORE and RESTRICT scenarios. The most degraded land in these five countries might not be suitable for SRWC.

Figure 5.3 shows the total SRWC potential per scenario. This is calculated by multiplying the bioenergy production area by the average SRWC yield for that area. The RESOURCE-100 scenario yields the highest annual potential – 6.01 EJ. The RESTORE-100 scenario has the same size of bioenergy production area but an annual potential of 2.79 EJ because of the lower yield. The RESTRICT-100 scenario again has a slightly lower potential – 2.59 EJ per year. The area on which bioenergy is produced is significantly lower – 59.6 Mha. However, the yield is slightly higher than in the RESTORE scenario discussed above. The same overall trends are evident in the 63% and 12% set of scenarios. The difference is that the RESTRICT scenario shows a higher potential than the RESTORE scenario in both sets. In both cases the higher yield in the RESTRICT scenario compensates for the lower area.

Table 5.3 shows the SRWC potential per country. In each scenario, DRC has the highest potential. In the RESOURCE scenarios, the DRC potential is about a quarter of the total potential. In the RESTORE and RESTRICT scenarios, this share is even higher at around one-third of the total.

This high potential is explained by DRC's relatively large pledge, amounting to 8 Mha, combined with a very high average SRWC yield on the areas selected.

Ethiopia and Madagascar are two other countries with a high potential. Under the RESOURCE scenarios, these two countries both contribute more than 10% to the total potential. This is explained by Ethiopia's large pledge, amounting to 15 Mha, while in Madagascar the SRWC yields are high under these scenarios. Both have a relatively lower share under the RESTORE and RESTRICT scenarios. In those scenarios, Republic of the Congo contributes more than 10% of the total due to its relatively high potential. Taken together, these four countries (DRC, Republic of the Congo, Ethiopia and Madagascar) hold about 60% of the total potential under all scenarios. Countries with a relatively low potential across all scenarios are Benin, Central African Republic, Ghana, Liberia, Mozambique and Niger. However, this potential can still be considered substantial compared to their energy demand.

Table 5.4 shows the SRWC potential per country as a percentage of TPES of each country (UN,2016). Given that TPES is expected to change between now and the period in which bioenergy production is expected to start (2030-2040), this percentage is shown merely to give a sense of its size.

Figure 5.3 Total short rotation woody crop potential from African restoration pledges by scenario (EJ)

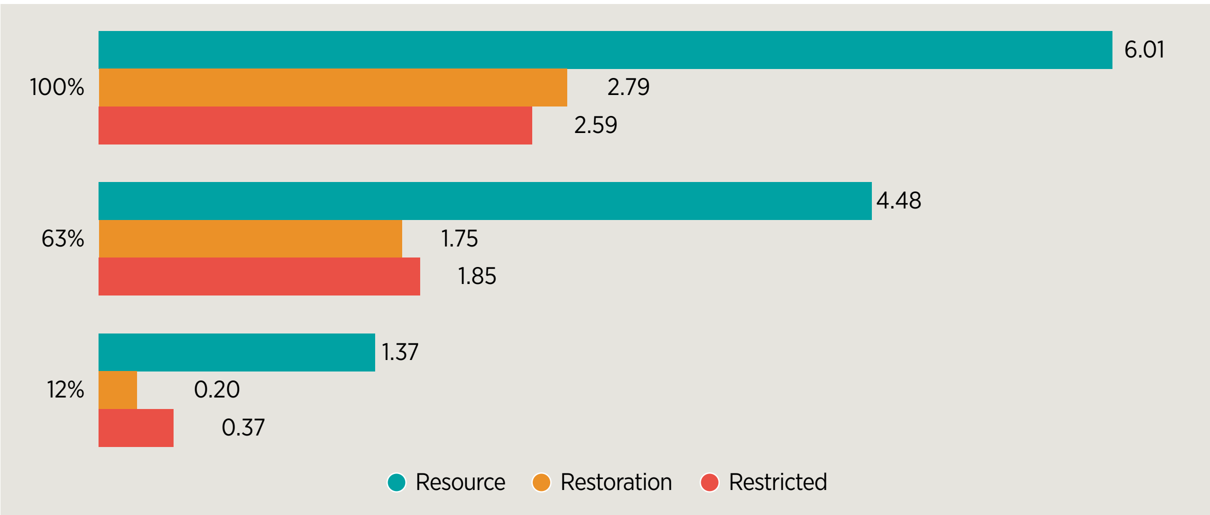

Table 5.3 Short rotation woody crop potential by country under different scenarios (EJ)

Country	Short rotation woody crop potential by country under different scenarios (EJ)								
	RESOURCE			RESTORE			RESTRICT		
	100%	63%	12%	100%	63%	12%	100%	63%	12%
Benin	0.024	0.018	0.006	0.003	0.002	0.000	0.003	0.002	0.000
Burundi	0.115	0.093	0.032	0.115	0.065	0.005	0.064	0.064	0.015
Cameroon	0.219	0.219	0.118	0.219	0.141	0.002	0.122	0.122	0.030
CAR*	0.061	0.051	0.019	0.050	0.029	0.001	0.052	0.035	0.007
DRC**	1.523	1.078	0.252	0.889	0.631	0.097	0.940	0.662	0.119
Congo***	0.534	0.348	0.073	0.358	0.217	0.013	0.400	0.217	0.050
Côte d'Ivoire	0.496	0.374	0.096	0.165	0.131	0.009	0.175	0.134	0.012
Ethiopia	0.888	0.678	0.223	0.182	0.111	0.009	0.156	0.130	0.024
Ghana	0.258	0.174	0.043	0.040	0.013	0.001	0.043	0.015	0.003
Guinea	0.146	0.109	0.036	0.052	0.020	0.004	0.056	0.044	0.005
Kenya	0.346	0.283	0.111	0.152	0.116	0.016	0.116	0.109	0.038
Liberia	0.091	0.063	0.020	0.025	0.016	0.003	0.000	0.000	0.000
Madagascar	0.641	0.474	0.165	0.210	0.085	0.017	0.199	0.092	0.020
Malawi	0.122	0.102	0.043	0.076	0.039	0.005	0.053	0.053	0.013
Mozambique	0.132	0.088	0.020	0.019	0.012	0.001	0.038	0.016	0.002
Niger	0.010	0.007	0.002	0.007	0.004	0.000	0.007	0.006	0.001
Rwanda	0.176	0.151	0.055	0.176	0.084	0.005	0.054	0.054	0.017
Uganda	0.232	0.173	0.056	0.052	0.033	0.006	0.115	0.098	0.020

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Table 5.4 Short rotation woody crop potential as share of TPES by country under different scenarios

Country	Short rotation woody crop potential as share of TPES under different scenarios								
	RESOURCE			RESTORE			RESTRICT		
	100%	63%	12%	100%	63%	12%	100%	63%	12%
Benin	13%	10%	3%	2%	1%	0%	2%	1%	0%
Burundi	186%	149%	52%	186%	105%	9%	103%	103%	24%
Cameroon	69%	69%	37%	69%	44%	0%	38%	38%	9%
CAR*	267%	221%	81%	218%	126%	3%	226%	151%	29%
DRC**	127%	90%	21%	74%	53%	8%	78%	55%	10%
Congo***	490%	319%	67%	329%	199%	12%	367%	199%	46%
Côte d'Ivoire	85%	64%	17%	28%	23%	2%	30%	23%	2%
Ethiopia	62%	47%	16%	13%	8%	1%	11%	9%	2%
Ghana	69%	47%	12%	11%	3%	0%	12%	4%	1%
Guinea	101%	75%	25%	36%	14%	3%	38%	30%	3%
Kenya	38%	31%	12%	17%	13%	2%	13%	12%	4%
Liberia	106%	74%	24%	30%	19%	4%	0%	0%	0%
Madagascar	384%	284%	99%	126%	51%	10%	119%	55%	12%
Malawi	120%	100%	42%	74%	38%	5%	52%	52%	13%
Mozambique	24%	16%	4%	3%	2%	0%	7%	3%	0%
Niger	11%	8%	2%	8%	5%	0%	8%	6%	1%
Rwanda	184%	157%	58%	184%	87%	6%	56%	56%	18%
Uganda	50%	37%	12%	11%	7%	1%	25%	21%	4%

** Central African Republic ** Democratic Republic of the Congo *** Republic of the Congo*

5.2 Potential of the Rwanda and Kenya restoration pledges

Results of the analysis are summarised in Tables 5.1 and 5.2. Table 5.1 shows Rwanda has a potential of 45 PJ per year on 1.4 Mha of land once the restoration strategy proposed by the ROAM assessment has been carried out. The proposed SRWC plantations account for the largest proportion of this potential – 34 PJ per year on 0.256 Mha of land. This potential is higher than that estimated by the RESTORE-12 and RESTRICT-12 scenarios: 5-17 PJ per year on 0.245 Mha of land. This is not surprising given that those scenarios prioritise use of the most degraded land. Not all plantations proposed by the ROAM study are on highly degraded land, so their mean yield is higher.

Kenya has lower potential – 28 PJ per year – over a larger area (2.2 Mha) due to significantly lower yields, as shown in Table 5.2. Plantations contribute 18 PJ per year on 0.4 Mha while agroforestry contributes 10 PJ per year on 1.8 Mha. The potential from the proposed plantations lies at the lower end of the range estimated by the RESTORE-12 and RESTRICT-12 scenarios – 16-38 PJ each year. This might be explained by the fact that plantations are proposed on marginal crop land, for which a low yield can be expected.

Table 5.5 Results of Rwanda analysis

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

Table 5.6 Results of Kenya analysis

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

6 DISCUSSION AND CONCLUSIONS

As the preceding analysis makes clear, bioenergy could play a role in meeting the Bonn Challenge to restore degraded landscapes to productive use. The underlying principle behind the initiative, FLR, includes restoration activities which could integrate bioenergy crops.

Sustainable bioenergy production could stimulate the Bonn Challenge by providing extra economic incentives and possibly additional GHG emissions mitigation through the replacement of fossil fuels. The extent to which bioenergy crop production can fulfil the pledge varies according to country. For example, bioenergy will contribute a minor share in Rwanda and Burundi because the restoration pledge of both these countries is almost as large as the country itself. Countries with a considerable potential and sufficient area available, like Kenya or Ethiopia, could have a larger part to play. The economic and social goals a country wants to achieve through restoration will also play a big role in their decision.

The analysis shows that around 6 EJ of primary energy per year could in theory be sustainably extracted from SRWC cultivated on land pledged for restoration under the African Forest Landscape initiative. This amounts to about three-quarters of the land ultimately to be pledged. This proportion would account for 87% of TPES projected in 2050 for the 15 countries studied. However, this assumes bioenergy crops will be planted on the entire pledged area and that the most productive (highest yielding) land will be selected to plant such crops. If bioenergy crops were planted on just 63% of the area pledged (the average intention in the current country plans), and if the most degraded land were selected instead of the highest yielding, the amount of energy extracted would amount only to around 1.8 EJ per year – 25% of TPES.

After the analysis for Sub-Saharan Africa (SSA) as a whole, a country level analysis was conducted for Kenya and Rwanda. This used ROAM outputs for the potential areas suitable for restoration and the potential restoration options in these areas. The results show that Kenya has a potential of 28 PJ per year on 2.2 Mha, and Rwanda has a potential of 45 PJ per year on 1.4 Mha, once the restoration strategies proposed in their respective ROAM assessments are complete.

The bioenergy potential from restoring the area currently pledged to AFR100 is substantial across all the scenarios when one considers that total Sub-Saharan Africa primary energy demand is at 23.9 EJ per year and biomass demand at 14.6 EJ per year in 2012 (International Energy Agency, 2014). The breadth of the range of annual estimated potential (0.20-6.01 EJ) is a sign of major uncertainties. For most countries, only the total area committed to restoration is known, which means that more precise estimates are not feasible. The location and types of restoration make a major impact on the actual bioenergy production potential. The uncertainty of these parameters is reflected by the scenarios, which are chosen to indicate the impacts of a wide bandwidth of possible restoration strategies. Thus the bioenergy strategies in the scenarios do not necessarily reflect the most realistic strategies, but rather the extremes. In developing countries in particular, the future biomass potential is highly dependent on future (socioeconomic) developments (Smeets, 2008; Intergovernmental Panel on Climate Change, 2011).

One of the main uncertainties in the method is the **chosen timeframe**. Although the pledges state the year in which restoration in the pledged area should start,what this actually means remains unclear. The Bonn Challenge is not a binding agreement, and whether countries will indeed fulfill their restoration targets on time remains to be seen. The assumption that planting SRWC starts in the year the pledge is made is therefore highly questionable.

Different assessments of land degradation are under way. The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) is conducting a global assessment of land degradation and restoration due to be completed by 2018 (IPBES, 2017). The IPBES study will improve insight into global status and trends by region and land cover type, as well as the effect of land degradation on biodiversity, ecosystem services and human health. Finally, it will provide an update on the state of knowledge in this field. Another forthcoming promising project is the third edition of the *World Atlas of Desertification* by the European Commission's Joint Research Centre and UNEP (Cherlet *et al*., 2015). Finally, the Intergovernmental Technical Panel on Soils (ITPS) assesses soil and related issues globally in its *Status of the World's Soil Resources* report, which is updated every five years (FAO and ITPS, 2015). Unfortunately, the findings of the most recent ITPS report are not yet incorporated in the present study due to time limitations.

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). Together with improved data on land degradation, this could greatly improve SRWC yield data and thus estimates of bioenergy potential.

More research is needed to calibrate models for bioenergy potential from degraded land

Availability of land is another source of uncertainty in the input data. In the analysis, different land uses are excluded either because they are unsuited to bioenergy crop production or because they are undesirable from the perspective of sustainable development. The remaining land in the present analysis is thought to be available and can be used for bioenergy production, notwithstanding several unresolved points. In the scenarios containing the land with the highest yield, these are obvious: they include non-degraded agricultural land and this conflicts with food, animal feed and materials production. But there are also problems to be solved in the scenarios concerned with restoration. The selection of degraded land for bioenergy crop production assumes the land is almost or completely out of use (Wicke, 2011). However, it has been shown that this assumption is not always true, since in reality it often is in use and can be an essential resource for poor communities (Berndes, 2002; Gallagher, 2008; Schubert *et al*., 2009).

Lack of data with sufficiently high resolution is the 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 at a continental scale, the data are not intended for assessments of the potential in smaller regions (*e.g.* a single country). What is more, data containing a greater level of detail could allow more factors to be taken into account, such as the slope of the terrain. The data used thus need a higher resolution in order to provide a more accurate country-level estimate.

Studies investigating the potential for bioenergy in more detail at a national level should be conducted when ROAM assessments become available. However, as stated above, more accurate and detailed input data on land degradation and availability are required as well in order to conduct meaningful country-level studies. This will involve primary field research. Economic and social factors should be included as well as environmental sustainability, Involving local stakeholders in the process is important because land restoration should respect their rights and provide them with benefits (IUCN and WRI, 2014). Incorporating bioenergy potential assessments into future ROAM studies is a possibility worth considering, since the ROAM studies engage with local stakeholders.

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GLOSSARY

Afforestation Establishment of forest through planting and/or deliberate seeding on land that has not been previously classified as forest.[1]

Agroforestry Land use systems or practices in which trees are deliberately integrated with crops and/or animals on the same land management unit.[2]

Boreal Relating to or characteristic of the climatic zone immediately south of the Arctic, especially the cold temperate region dominated by taiga (coniferous forests) and forests of birch and poplar.[3]

Compaction Loss of porosity in soil due to compression, usually from vehicles or animal traffic; may cause a hard layer that is impenetrable to roots, and reduces oxygen availability.

Degraded land Land that has suffered long-term loss of ecosystem function and services caused by disturbances from which the system cannot recover unaided.[3]

Desertification Reduction or loss of the biological productivity and ecological complexity of land in arid semi-arid, and dry sub-humid areas resulting from a combination of natural and human-induced processes, influenced by climate variability and change.[4]

Drylands Arid, semi-arid and dry sub-humid areas (other than polar and subpolar regions).[2]

Ecosystem Dynamic complex of plant, animal and microorganism communities, and the non-living physical components of the environment (such as air, soil, water and sunlight), interacting as a functional unit.[3]

Ecosystem services Benefits people obtain from ecosystems.[2]

Erosion Loss of soil when rain, irrigation water, wind, ice, or other natural or anthropogenic agents detach soil and deposit it elsewhere.[3]

Land rehabilitation Actions undertaken with the aim of reinstating ecosystem functionality, where the focus is on provision of goods and services, rather than re-establishing the pre-existing ecological structure and function.[5]

Land restoration The process of assisting the recovery of an ecosystem that has been degraded. Restoration seeks to re-establish the pre-existing ecological structure and function.[4]

Marginal land Land of low agricultural value due to soil, climatic or geographic constraints that limit productivity.

Protected forests Legal term for an area subject to protection by legislation, regulation or land use policy.[3]

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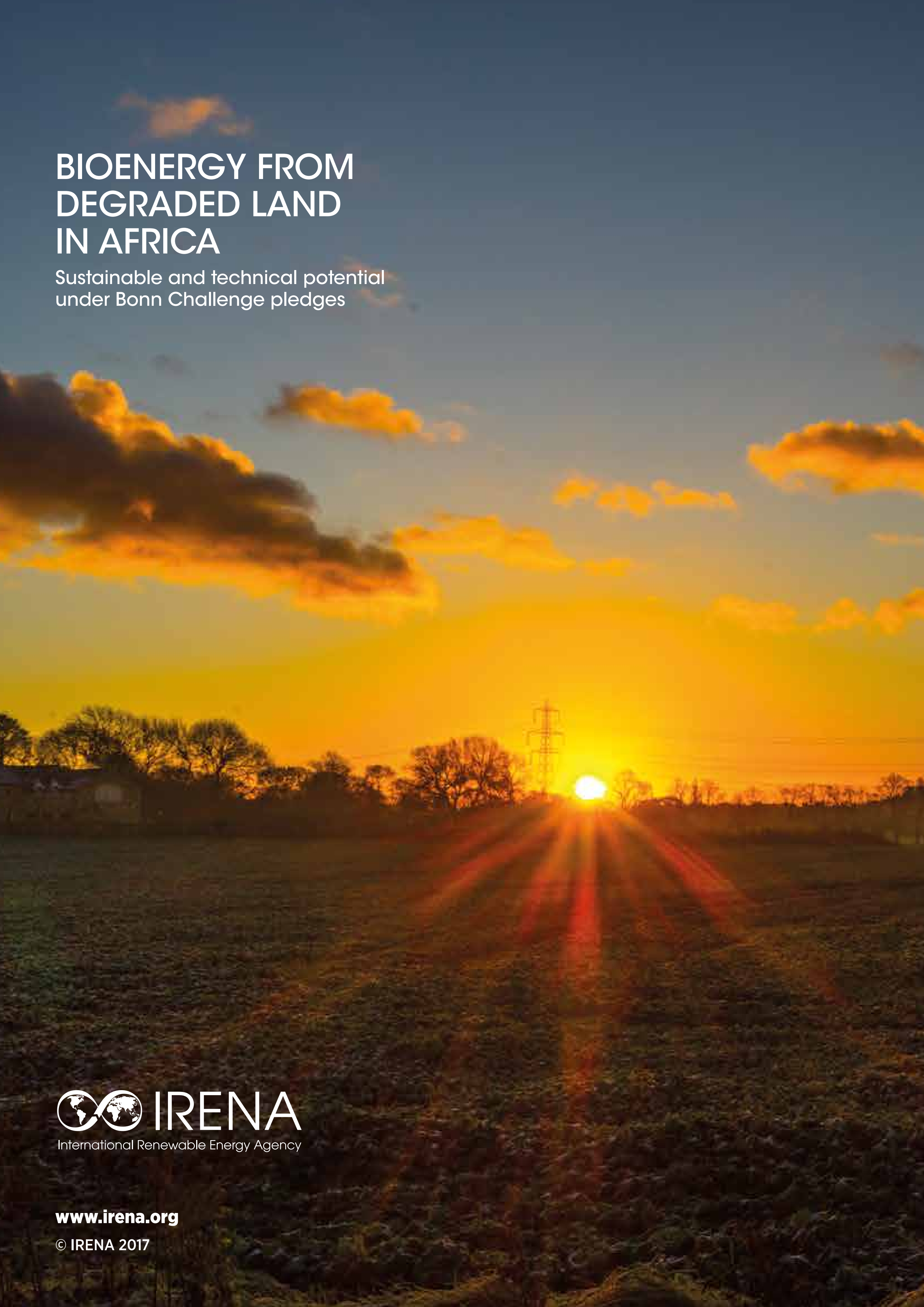
1. *http://www.fao.org/docrep/017/ap862e/ap862e00.pdf. FAO Forest Resources Assessment Programme Terms and Definitions 2015.*
2. *http://www.fao.org/docrep/017/i1688e/i1688e.pdf. FAO State of the World's Land and Water Resources for Food and Agriculture*
3. *http://www.fao.org/faoterm/en/.*
4. *http://www2.unccd.int/sites/default/files/documents/2017-09/UNCCD_Report_SLM_web_v2.pdf. United Nations Convention to Combat Desertification (UNCCD) Sustainable Land Management contribution to successful land-based climate change adaptation and mitigation, glossary p. 17.*
5. *Orr et al. (2017), Scientific Conceptual Framework for Land Degradation Neutrality. A Report of the Science-Policy Interface, UNCCD, Bonn, Germany.*

Protective forests	Plantation for the provision of ecosystem services.[3]
Rangelands	Land on which the indigenous vegetation is predominantly grasses, grass-like plants or shrubs that are grazed or have the potential to be grazed by livestock and wildlife.[2]
Reforestation	Planting of forests on land that previously contained forests but that had been converted to some other use.[6]
Salinisation	Accumulation of water-soluble salts in the soil.[7]
Sedimentation	Deposit that creates a layer.[3]
Silvo-pastoral	Land-use systems and practices in which trees and pastures are deliberately integrated with livestock components.[2]
Siltation	Deposition of silt (soil particles coarser than clay but finer than sand) carried by water.
Wetland buffer zone	A strip of land adjacent to wetland where land use is modified to reduce adverse impacts on the wetland.

6. *http://www.ipcc.ch/ipccreports/sres/land_use/index.php?idp=48. IPCC Land Use, Land Use Change and Forestry 2000*
7. *http://eusoils.jrc.ec.europa.eu/projects/SOCO/FactSheets/ENFactSheet-04.pdf.*



BIOENERGY FROM DEGRADED LAND IN AFRICA

Sustainable and technical potential under Bonn Challenge pledges

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