Analysing the potential for CAM-fed bio-economic uses in sub-Saharan Africa

Abstract

Crassulacean Acid Metabolism (CAM) plants have the potential to provide future-proof biomass growth under increasingly stressed climatic conditions. Using active cultivation and anaerobic digestion, CAM plants can be grown and fermented to produce biogas or hydrolysed to extract valuable volatile fatty acids (VFAs) which can be applied to a range of uses: energy provision, protein and bioplastic production, carbon sequestration. However, an understanding of the spatial potential for CAM plants to be actively grown and harvested for bio-economic uses across Africa is unknown. A combined conservative assessment which incorporates three key dimensions is lacking from the literature: i) where can CAM plants physiologically grow? ii) where can CAM plants be cultivated without competing with existing land use? and iii) where lies the greatest energy demand? Answering these three questions and mapping the spatial variability between these aspects is essential to the future bioplastics / protein sector and opportunity to capitalise on generating sustainable energy which can connect off-grid rural and peri-urban communities whilst also achieving climate change mitigation targets. Using *Opuntia ficus-indica* as an example, this study compares two measures of land suitability estimation based on ecophysiological requirements and social, environmental and land-use masks. Focusing on abandoned land, conservative baseline estimates suggest that c.28-55 million hectares of land may be suitable for active CAM cultivation, with the potential to repurpose degraded lands and provide alternative bio-economic livelihoods to communities across semi-arid regions of Africa.

Key words: Crassulacean Acid Metabolism (CAM), bio-economy, semi-arid, *Opuntia ficus-indica*, abandoned land, bioenergy, anaerobic digestion (AD)

Introduction

With 600 million people without access to electricity and 83% without access to clean cooking facilities (IEA, 2019a), there is a clear need to identify strategies and opportunities to improve energy security on the African continent. 60% of the population of sub-Saharan Africa live in rural areas (The World Bank, 2018), and coupled with low per capita energy consumption and low rates of electrification, there is a good opportunity for sustainable energy developments using non-grid renewable alternatives (Szabó et al., 2011).

While over 200 million people in sub-Saharan Africa have gained access to electricity since 2000, the rate of electrification is slower than the rate of population growth; resulting in a year-on-year overall increase in numbers without access. Despite renewed international and national level efforts to prioritise rural electrification, grid extension has not provided electricity access to all communities "under grid", and the costly infrastructure outlay of grid development is not viable in a continent dominated by sparsely-populated rural communities with relatively low household energy demands.

By comparison, a focus on the potential of renewable energies and mini-grid engineering opportunities could satisfy energy demands sustainably, whilst capitalising on the high-productivity of renewable energy technologies in Africa (Szabó et al., 2011; Wu et al., 2017). To stem the energy poverty in sub-Saharan Africa, analyses have identified the strategic potential of future solar PV and wind power facilities (Wu et al., 2017) as well as the coarse-scale capability of bioenergy production, both from existing biomass residues and from active cultivation of bioenergy crops (Campbell et al., 2015; Cushman et al., 2015; Gabisa and Gheewala, 2018; Shane et al., 2016). In particular, recent research has highlighted the potential of crassulacean acid metabolism (CAM) species offering sustainable bioenergy production through anaerobic digestion (AD) methods (Borland et al., 2009; Mason et al., 2015; Owen et al., 2015; Yang et al., 2015).

As global climate change is increasing the occurrence and likelihood of droughts in Africa (Marthews et al., 2019; Otto et al., 2018), and thus competition for water resources, high water-use efficient CAM bioenergy crops that can also withstand high daily temperatures (Borland et al., 2009), can allow expansion of bioenergy feedstock production into semi-arid drylands (Cushman et al., 2015). Not only can CAM plants help stem the energy gap, but cultivation of these plants specifically on degraded or abandoned land provides environmental benefits and climate change mitigation without creating food-fuel land competition (Campbell et al., 2008; Hill et al., 2006; IPCC, 2019; Tilman et al., 2006). As well as the potential to be fermented to produce biogas for electricity production, CAM plants can also be hydrolysed to volatile fatty acids (VFA) and used in biopolymer and bioplastic production (Gheribi et al., 2019; López-García et al., 2017), competing with existing soy protein production. With c.40% of the global land area comprising arid, semi-arid and dry sub-humid environments (Cherlet et al., 2018; Middleton and Thomas, 1997; United Nations, 2011), there is vast potential for CAM plants to be grown as a sustainable feedstock in regions without competing with prime ecosystems, nor with food production.

There are three key questions that need addressing in order to assess sustainable CAM plant energy potential: i) where can CAM plants physiologically grow? ii) where can CAM plants be cultivated without competing with existing land use? and iii) where lies the greatest energy demand? Research to date has sought to identify suitable zones for CAM plant growth based on species-specific environmental tolerances and field observation (e.g. *Opuntia ficus-indica, Agave tequiliana*) (Louhaichi et al., 2015; Owen et al., 2015). Equally, a series of studies have commented on the potential lands that could be used for bioenergy feedstock cultivation (Cai et al., 2011; Campbell et al., 2008; Cushman et al., 2015; Gibbs and Salmon, 2015; Watson and Diaz-Chavez, 2011; Wicke et al., 2011). Lacking is an overarching integrated spatial assessment of the three questions above, which is essential for establishing the potential of CAM plant contributions to the energy sector and the generation of sustainable AD energy that can help connect off-grid rural and peri-urban communities whilst also achieving climate change mitigation targets.

Focusing on the African continent, the purpose of this paper is two-fold: i) to identify the regions where CAM plants could potentially be grown with the purpose of being used as feedstock for biofuel energy production; and ii) to compare the output from (i) with socioeconomic dimensions – what abandoned/degraded lands could be used for CAM cultivation, and where are the zones of greatest energy demand? In doing so, this study presents the regions where CAM plants can be grown for use as bioeconomic uses without competing with prime ecosystems, nor with food production.

Methods

This study uses a composite of tools and datasets, and focuses on the potential for *Opuntia ficus-indica* growth. *O. ficus-indica* (prickly pear) is a successful invasive species having established itself across every continent (except Antarctica) (CABI, 2019) and found across all latitudes. With this in mind, *O. ficus-indica* is a suitable test species to use for this analysis – highlighting the potential that can be achieved with CAM plantation. Results from this study help map the broad trends that can be used to inform the location and potential yield of future CAM – AD energy initiatives at the continent-scale, as well as highlight the nuances of proxies to measure existing electricity access and consider the complexities that need to be explored at the individual country-scales.

Through using GIS and satellite imagery, spatially resolved analyses can be produced that can support strategic decisions about future areas of CAM cultivation and energy supply-demand dynamics. This study produces a coarse-scale continent-wide assessment of the potential for active CAM biomass production through mapping datasets which assess three key considerations of CAM cultivation for AD energy / VFA usage: physiological constraints, land use constraints and energy demand. Table 1 identifies the open access and published data used in this analysis, with overlay analysis, data transformations and maps produced in ArcGIS Pro 2.4.1.

Source	Datasets
WorldClim (version 2.0) Fick & Hijmans (2017)	Climate data (Total annual precipitation, Mean minimum temperature of coldest quarter < 1.5°C)
Owen et al. (2015)	Environmental Productivity Indices
Fischer et al. (2008)	Harmonised World Soil Database (Excess salts)
Campbell et al. (2008)	Abandoned agricultural land
LADA collections Nachtergaele & Petri (2008)	Land use classifications
WorldPop 2015 (version 2.0)	Population density
Hoffman et al. (2016)	Conservation International (CI) Biodiversity hotspots
WDPA (2019)	Protected areas
The World Bank (2017a)	Access to electricity (national urban vs rural)

Table 1. Open access and published sources of datasets used in this study.

Results

Where can CAM plants be grown?

Recent studies have explored the environmental potential for *O. ficus-indica* growth. Louhaichi et al. (2015) identified a series of environmental growth classes based on applying climatic and soil restrictions from the literature as 'masks' to eliminate areas that exceed the environmental tolerance of *O. ficus-indica* in Jordan. Areas with salt affected soils, that had less than 200 mm of precipitation per year, or that had mean minimum temperatures < 1.5°C were initially excluded. The remaining areas were then divided into a series of classes of suitability based on levels of annual precipitation. Class 1 represents zones with annual precipitation 200-250 mm and considered marginal areas for *O. ficus-indica*. Class 2 contains areas with between 250 and 505 mm of annual precipitation and was considered suitable for cacti. Class 3 groups areas with > 505 mm annual precipitation and were classified as highly suitable, but equally would encounter competition from other crops.

By comparison, Owen et al. (2015) used a refined Nobel EPI methodology (Garcia-Moya et al., 2011; Nobel, 1988; Nobel and Meyer, 1985; Nobel and Quero, 1986; Nobel and Valenzuela, 1987) to calculate global theoretical productivity scores which can be multiplied by a value of maximum above-ground dry biomass productivity to spatially analyse CAM productivity potential. As opposed to excluding zones of unsuitability as used by Louhachi et al. (2015) (Figure 1a), this alternative approach ranks the suitability of all regions across a continuous scale of theoretical productivity (Figure 1b).

Results from applying both methods show highest levels of potential CAM cultivation suitability across central Africa and into the semi-arid regions of southern Africa, in particular in the eastern remits as compared to the driest locations across coastal Namibia and South Africa. Whilst Figure 1b maps a larger potential region in comparison to the environmental tolerance approach (Figure 1a), the EPI values are particularly low in the western Cape, Namib Desert belt and the Horn of Africa suggesting that any potential yields in these locations would both be low and probably unreliable to cultivate.

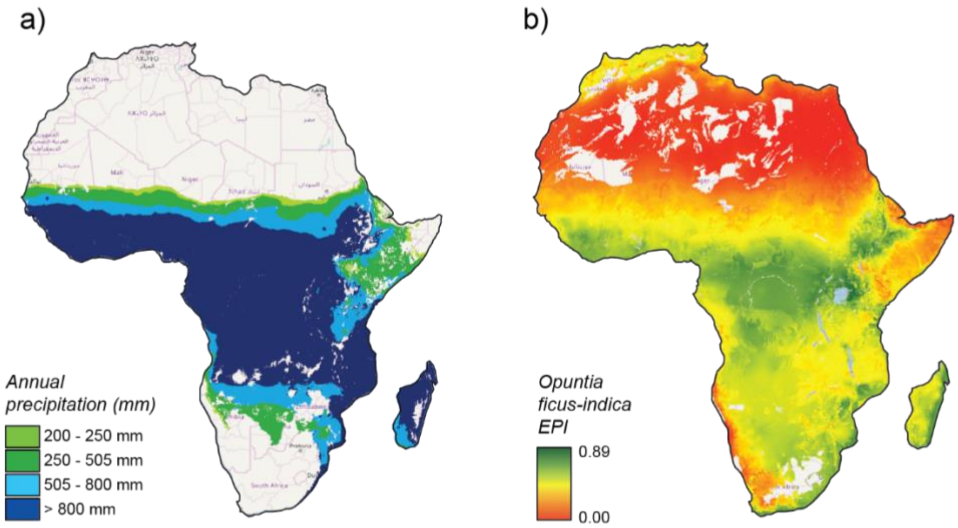

Figure 1. Maps of the environmentally suitable areas where *O. ficus-indica* could grow according to two different methods: a) Output from the method used in Louhaichi et al. (2015) producing four classes of *O. ficus-indica* suitability based on annual precipitation levels; b) Output from the method used in Owen et al. (2015) producing an *O. ficus-indica* environmental productivity index (EPI 0-1) for each individual grid cell.

What lands are available for CAM cultivation?

While the conversion of land into biofuel feedstock may contribute both towards climate change mitigation (IPCC, 2019) and energy security, it is essential to consider whether any future cultivation of plants for biofuel uses should or should not compete with existing land uses, particularly the production of food, and also areas specifically designated and protected for biodiversity or conservation reasons.

Existing studies have either tended to represent “best case” scenarios which have not taken a more conservative approach considering all existing land uses including biodiversity hotspots, conservation areas and unabandoned farmland; or are not limited specifically to those areas which are both available and suitable for CAM species in particular. Thus, whilst these studies have suggested large quantities of land suitable for bioenergy crop cultivation, the translation into the true areas which could be readily available for CAM cultivation is somewhat smaller.

One definition of potential land that could be used has commonly been cited as ‘degraded land’ (Gibbs and Salmon, 2015). Gibbs and Salmon (2015) noted significant study-to-study differences in degraded land estimates for Africa (Table 2) due to methodological contrasts that ranged from the use of expert opinion, satellite observation, biophysical models, and inventories of abandoned agricultural land.

Source	Degradation (million ha)
GLASOD	321
FAO TerraSTAT	1222
Dregne and Chou (1992)	1046
GLADA	660
Cai et al (2011)	132
Campbell et al (2008)	69
FAO Pan-tropical Landsat	9

Table 2. Synthesis of Africa-scale estimates of degradation (million ha). Data extracted from Gibbs and Salmon (2015)

Given these difficulties, we have opted to focus on the potential use of 'abandoned lands', defined in Campbell et al. (2008) as "land that was previously used for crop or pasture but has since been abandoned (and has not been converted to forest or urban areas)". By focusing on abandoned land, potential conflicts with protected lands and biodiversity hotspots are avoided. We also only register areas where over 5% of land is reported as abandoned, thereby avoiding possible competition with land used for other agricultural purposes. These abandoned lands are likely also areas that have experienced degradation, with repurposing for CAM plant growth offering other benefits of land restoration, erosion reduction and so on.

Figure 2 uses the environmental niche modelling outcomes from Figure 1 and applies the >5% abandoned land criteria of Campbell et al. (2008) to these areas (low estimate used). Additionally, further unsuitable areas were removed, including: urban areas, bare rock, sandy desert and dunes, stony deserts and water bodies as defined by the FAO land use classifications (Wicke et al., 2011). High biodiversity areas and conversation regions were excluded (CI Biodiversity Hotspots and categories 1 and 2 areas from the World Database on Protected Areas), as well as all areas classified as 'forest' or 'wetland' in an effort to protect primary ecosystems from this minimum availability calculation. Finally, areas with slope > 8% were excluded due to the potential of an increased water erosion risk following cultivation (Watson and Diaz-Chavez, 2011; Wicke et al., 2011) and logistical harvesting difficulties. Final conservative estimates of land available for CAM cultivation based on the two alternative environmental tolerance figures (Figure 1) are shown in Figure 3 and presented in Table 3.

Figure 3 shows pockets of potentially viable land for *O. ficus-indica* cultivation in southern Africa, eastern Africa and smaller patches in central Africa. The main zones of opportunity are centred on Angola, Tanzania, Namibia, Botswana, Republic of the Congo and South Africa (Table 3) where suitable growing conditions are paired with abandoned agricultural land which is equally not preserved for food production, urban development or biodiversity conservation. The top six countries with the largest potential available area provide c.80-85% of the total area suitable land for CAM cultivation across all of sub-Saharan Africa (Table 3) (i.e. 21.96 of 28.09 million hectares and 47.63 of 54.89 million hectares).

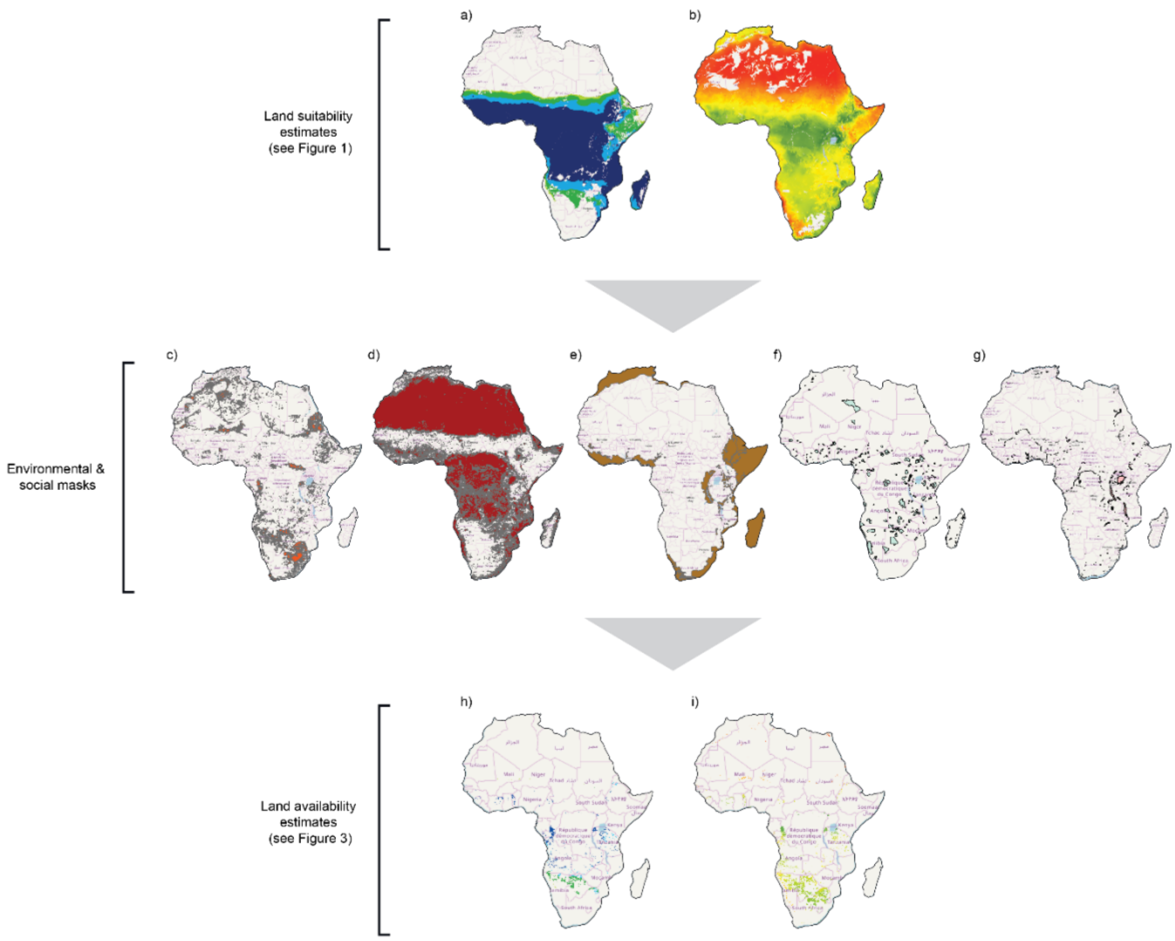

Figure 2. Environmental and social masks were applied to transition from original land suitability estimates to a conservative estimate of land available and suitable for CAM cultivation. a & b) Original land suitability estimates based on a) Louhachi et al. (2015) and b) Owen et al. (2015) methods; c – g) series of environmental and social masks: c) areas with > 5% abandoned land (Campbell et al. 2008), d) unsuitable land use / cover (forest, wetland, bare areas, open water, urban or no data – taken from LADA FAO), e) CI biodiversity hotspots, f) WDPA, g) areas > 8% slope; h & i) land available and suitable estimate.

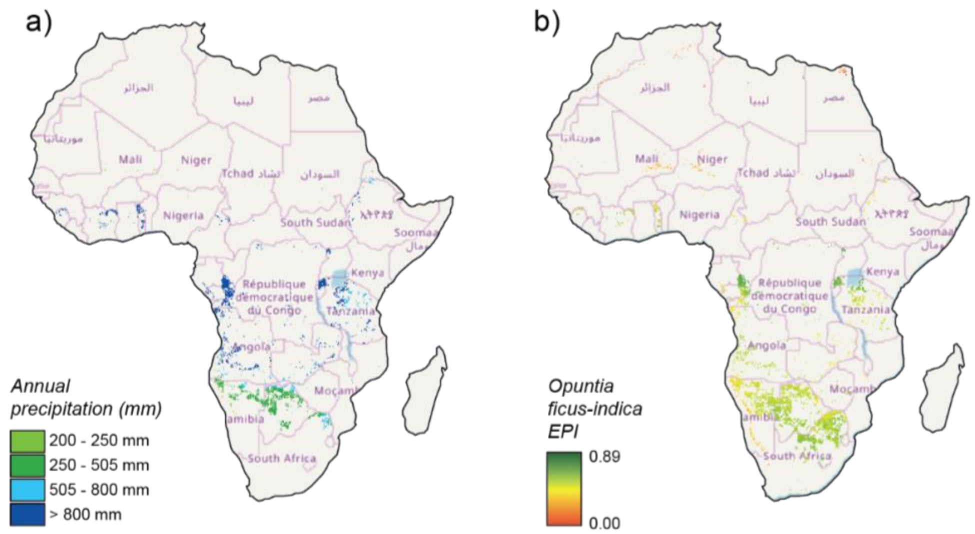

Figure 3. Map of CAM growing potential following Louhachi et al. (2015) (left) and Owen et al. (2015) (right) methods when restricted to suitable areas. Suitable areas in this study have been defined as areas with > 5% abandoned land and excluding those which include biodiversity hotspots, conservation areas and slopes > 8%.

Country	*Applied to Figure 1a (Louhaichi et al. (2015) approach)*		*Applied to Figure 1b (Owen et al. (2015) approach)*		
	Area of suitable land (million ha) [a]	***O. ficus-indica* yield / year (Mt) [c]**	**Area of suitable land (million ha) [b]**	***O. ficus-indica* yield / year (Mt) [d]**	***O. ficus-indica* yield / year (Mt) (conservative) [e]**
Angola	**2.62**	**56.51**	**3.20**	**71.89**	**4.15**
Benin	0.04	0.80	0.02	0.54	0.03
Botswana	**7.57**	**172.90**	**11.97**	**289.2**	**19.17**
Burkina Faso	0.01	0.17	0.01	0.35	0.01
Burundi	0.02	0.62	0.02	0.47	0.03
Cameroon	0.19	3.77	0.18	3.75	0.20
CAR	0.01	0.12	0.01	0.22	0.01
Chad	0.02	0.27	0.03	0.40	0.01
DRC	0.82	18.90	0.85	20.36	1.31
Eritrea	0.10	1.76	0.06	1.17	0.05
Eswatini	0.00	0.00	0.02	0.49	0.02
Ethiopia	0.45	8.71	0.51	10.05	0.58
Gabon	0.72	19.60	0.68	19.25	1.34
The Gambia	0.00	0.02	0.02	0.19	0.01
Ghana	0.02	0.39	0.05	1.14	0.04
Guinea	0.02	0.43	0.02	0.40	0.02
Guinea-Bissau	0.00	0.03	0.00	0.00	0.00
Ivory Coast	0.51	12.76	0.52	13.35	0.72
Kenya	0.02	0.46	0.02	0.62	0.02
Lesotho	0.00	0.00	0.21	6.09	0.39
Liberia	0.00	0.00	0.00	0.06	0.00
Mali	0.04	0.39	0.40	3.94	0.28
Mauritania	0.00	0.00	0.05	0.38	0.03
Mozambique	0.05	0.97	0.08	1.50	0.06
Namibia	**3.74**	**77.12**	**11.20**	**244.63**	**13.91**
Niger	0.00	0.04	0.23	1.97	0.07
Nigeria	0.01	0.18	0.03	0.71	0.03
Republic of the Congo	**2.97**	**80.36**	**2.86**	**80.67**	**8.99**
Rwanda	0.99	28.44	1.03	30.60	3.72
Senegal	0.00	0.00	0.02	0.26	0.01
Sierra Leone	0.22	5.06	0.19	4.55	0.26
South Africa	**1.47**	**33.61**	**14.87**	**372.87**	**28.57**
South Sudan	0.00	0.00	0.00	0.03	0.00
Sudan	0.01	0.18	0.09	0.59	0.01
Tanzania	**3.59**	**82.04**	**3.53**	**84.55**	**5.61**
Togo	0.82	18.63	0.77	18.00	1.32
Uganda	0.14	4.43	0.16	5.19	0.31
Zambia	0.56	10.76	0.67	13.27	0.65
Zimbabwe	0.03	0.70	0.28	6.88	0.32
Total	**28.09**	**641.2**	**54.89**	**1,310.9**	**92.48**

Table 3. Suitable land area estimates (million hectares) and yield (megatonnes) of *O. ficus-indica* to be annually cultivated based on results from Figure 3. Top 6 countries with greatest potential for cultivation highlighted in bold. [a] Area estimates (million hectares) based on Louhaichi et al. (2015) method (Figure 3a). [b] Estimated yield (megatonnes) based on Figure 3a land availability and corresponding EPI values calculated in Figure 3b. [c] Land area estimates based on Owen et al. (2015)

method (Figure 3b). [d] Estimated yield (megatonnes) based on Figure 3b EPI values. Yield estimates based on theoretical maximum above-ground dry biomass productivity: 46 Mg ha^{-1} yr^{-1} (Nobel, 1988; Owen et al., 2015). [e] Conservative estimated yield (megatonnes) based on Figure 3b EPI values. Yield estimates based on theoretical maximum above-ground dry biomass productivity: 46 Mg ha^{-1} yr^{-1} (Nobel, 1988; Owen et al., 2015). Estimated yield exclusively confined to the percentage areas of abandoned land within each cell.

In terms of yield, the corresponding EPI score (based on Owen et al. 2015) for the areas identified as suitable following either method (i.e. bioclimatic envelope – Louhaichi et al. 2015 or EPI – Owen et al. 2015) have been multiplied by the theoretical maximum above-ground dry productivity of *O. ficus-indica* which could occur under irrigated conditions with optimum planting-density. Following the method used in Owen et al. (2015), the EPI score of each grid cell was multiplied by 46 Mt (dry) ha^{-1} yr^{-1} (Nobel et al., 1992). If we were to further restrict the estimates of land availability to only the proportion considered abandoned within the >5% abandoned per hectare grid cells, Table 3 shows that the yield potential is drastically reduced to <5% of the value versus when an entire grid cell (of >5% abandoned land) is considered. Based on conservative estimates of 1 DMT = 1 MW h, the conservative yields of 92.48 million DMT (dry matter tonnes) and 641 million DMT would equate to c. 0.1-0.64 PW h of power, almost equating entirely with 2018 African electricity demand estimates of 0.7 PW h (IEA, 2019b).

Where lies the greatest energy demand?

In answering the third layer of consideration, this study looked at the proxies that could be used to determine the locations with and without access to electricity and the associated population densities. Spatially explicit information about electrification access is needed to identify where efforts should be focused and determine overlap with the regions of potential CAM cultivation. Often datasets are available at the national level, masking heterogeneity to access within the country (i.e. urban and rural without electricity statistics held at The World Bank and IEA), but a more granular level of detail is required to identify zones appropriate for comparing with bioenergy potential. As noted by Szabó et al. (2011), there is a general shortage of energy related information in Africa when compared to the rest of the world.

Whilst international agencies and governments across sub-Saharan Africa have committed to delivering rural electrification programmes and developing existing grid infrastructure, this has not necessarily translated into greater electrification rates, especially in rural areas. Grid coverage has increased in recent decades, yet this is not synonymous with access; some countries now have high grid coverage (Figure 4), but low uptake rates highlight the significance of demand-side barriers to access (Blimpo and Cosgrove-Davies, 2019). As such, grid maps for Africa do not necessarily correspond with on the ground access; representing the aerial flow of electricity from one location to another, without detailing the access to electricity between locations or those "under grid".

A recent study in Kenya, for example, showed that many households in close proximity to the grid did not have access to electricity (Lee et al., 2016a), largely due to high connection charges (Lee et al., 2016b). Similarly, high grid-connection costs beyond 30 m from electric poles was cited for the lack of uptake in Tanzanian communities (Chaplin et al., 2017), severely limiting the spatial distribution of electricity via the grid. Financial liquidity is known to be a key barrier to a household's willingness to pay for access to amenities, such as electricity (Blimpo and Cosgrove-Davies, 2019; Greenstone and Jack, 2015); "under grid" low uptake rates are often driven by these high connection costs. Meanwhile, the high initial cost of grid infrastructure construction also does not pair well with the low density, low income and low levels of demand found in the rural sub-Saharan communities (Morrissey, 2017). Alternatives to "on-grid" electricity access therefore need to be explored for both "under grid" and "far from grid" communities. With this in mind, traditional grid maps cannot be used alone to identify zones which do and do not have access to electricity as the infrastructure and supply only represent half of the supply-demand relationship.

Alternative approaches such as night-time light imagery have been used in a range of studies as a proxy for different human development indices (Amaral et al., 2005; Bruederle and Hodler, 2018; Chand et al., 2009; Doll et al., 2006; Mellander et al., 2015; Pandey et al., 2013; Townsend and Bruce, 2010) as well as to look at the relationship with access to electricity (Andrade-Pacheco et al., 2019; Min et al., 2013; Proville et al., 2017). However, whilst night-time light imagery can be used in an adapted form to look at the levels of African village electrification in terms of public amenities, it cannot be translated into a measure of household electrification (e.g. Min et al. 2013). As such, this study combined metrics of population density with country-level electrification statistics to produce a coarse-scale heatmap of the areas with greatest density of populations without access to electricity (Figure 4) – i.e. a map of electricity demand. As anticipated, the results show greatest demand in sub-Saharan Africa whilst the oil-rich and economically more-developed countries bordering the Mediterranean have high electrification rates in both urban and rural settings.

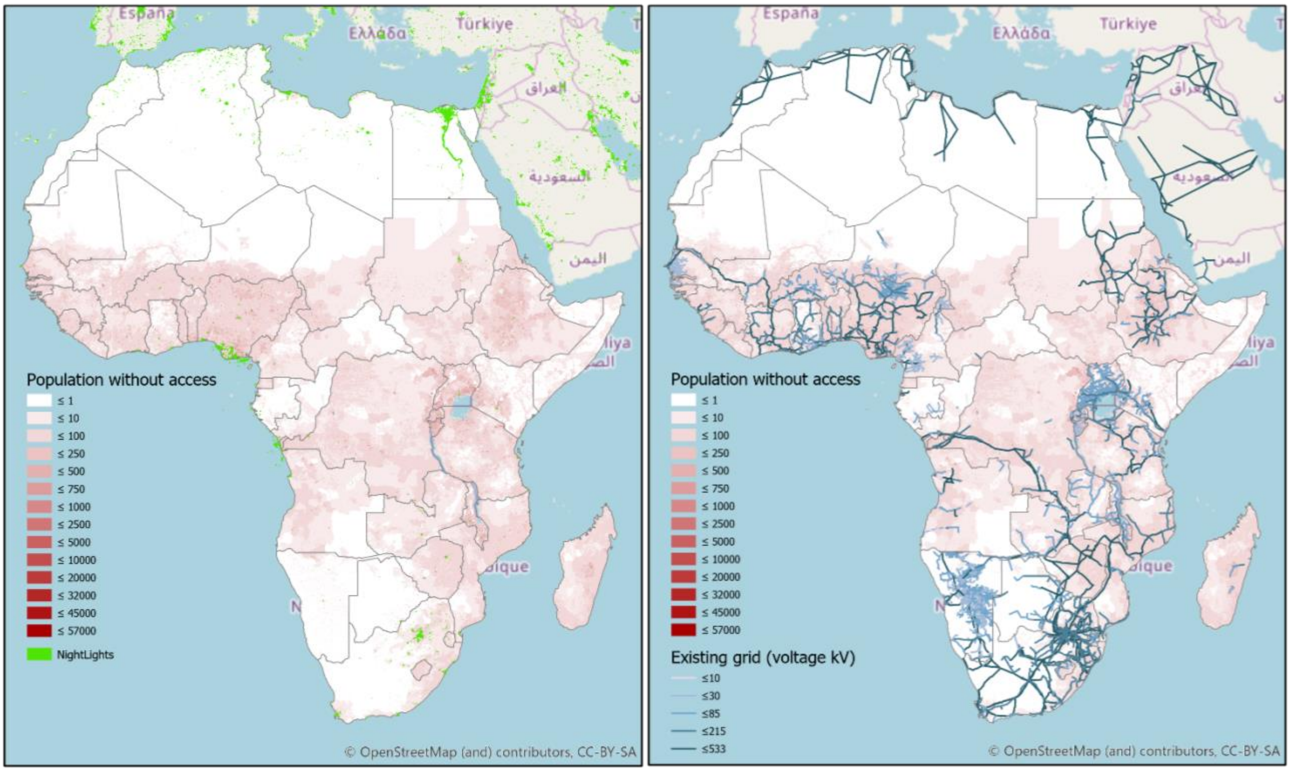

Figure 4. Coarse-scale density map of population without access to electricity based on population density and country-scale rural and urban electrification rates. Left: Distribution of visible light sources as detected at night over the period 1992-2014 (NOAA – accessed 23.07.2019 https://developers.google.com/earth-engine/datasets/catalog/NOAA_DMSP-OLS_NIGHTTIME_LIGHTS; https://code.earthengine.google.com/a097d1fad41b9664d2600af53bbb492e# - processed according to method used in Proville et al. 2017). Right: Existing grid network and corresponding voltage across Africa (The World Bank, 2017b).

In west Africa, low levels of both urban and especially rural electricity access contribute to a consistently high demand (relatively high population density without access to electricity) from Nigeria through to Senegal. Meanwhile in east Africa, Ethiopia, Uganda, Rwanda, Burundi and Tanzania all show relatively densely populated zones of electricity demand, predominantly driven by low levels of electrification in rural areas. Finally, in southern Africa zones of relatively high electricity demand are found in western Angola, northern Namibia, eastern South Africa and Lesotho, Malawi, Zimbabwe and Mozambique. Within all of these countries, a highly spatially-variable level of electricity access is predicted, with the highest levels of electricity demand found in areas of relatively densely populated rural communities.

Discussion

Two existing methods (Louhachi et al. 2015; Owen et al. 2015) of defining suitable land for *O. ficus-indica* growth were combined with environmental and land use masks to produce two potential land availability estimates. The results from this analysis show that the estimations of the suitable land available for CAM plant cultivation are lower than the values previously published (Table 2), yet provide a conservative minimum estimated range (28.09 – 54.89 million hectares) of the potential. The variability in the two estimates reflects the slightly different parameters that have been used to identify the zones of CAM plant suitability. The 54.89 million hectares following the Owen et al. (2015) method encapsulates all areas that had an EPI score greater than 0.01 and satisfied the social and environmental masks. Therefore, whilst many of these areas will be available, they may not be particularly high on the environmental suitability factor for cultivating *O. ficus-indica*. By comparison, the lower estimate of 28.09 million hectares has been restricted to only those areas with >200 mm annual precipitation and satisfy the social and environmental masks. Both land estimates were multiplied by the corresponding EPI factors in order to calculate estimated yield.

The vast majority of the land identified as suitable and available is concentrated in six countries, of which four contain large semi-arid belts accounting for c.75% of the identified available land across sub-Saharan Africa. CAM cultivation for bioenergy feedstock in these semi-arid regions has the potential to not only provide a renewable and "future-proof" energy resource to currently unelectrified regions, but also to repurpose abandoned where restoration of degraded lands can contribute to other global environmental challenges (Le Houérou, 1996; Neffar et al., 2013).

Nonetheless, it is important to consider that within the areas identified as suitable, the level of abandonment per square kilometre (resolution used in original Campbell et al. 2008 study) ranges from 5-82 % and does not cover the entire area accounted for. However, these areas represent those with a greater likelihood that either the land is already degraded and currently not being efficiently utilised or those where individuals will be more interested in seeking alternative income streams away from more precarious livelihoods such as ranching in the face of increased drought pressures. Restricting the cultivation and yield available to strictly the percentages of areas identified as abandoned within the grid cells further restricts the potential yield estimate to 92.5 MT per year (Table 3).

Establishing a bio-economy

Once harvested, CAM plants, such as *O. ficus-indica*, can be hydrolysed anaerobically to produce VFAs which subsequently can be used in a range of a products, including biogas generation. Aside from providing a possible electricity supply, CAM plants are ideal carbon capture machines which can contribute towards global targets to achieve negative emissions of CO_2 by 2060 (IPCC, 2018). The role of CAM plants in reducing global CO_2 levels and potentially curbing global environmental crises is two-fold: firstly, drawing down CO_2 directly from the atmosphere; and secondly displacing other industries that contribute to CO_2 production. For example, one of the most economically valuable opportunities for using CAM plants is through the production of protein from VFAs. Conversion of traditional ranching land to CAM plant protein production could add significant value to national agricultural production, especially in semi-arid regions already grappling with reduced livestock capacity (e.g.

Namibia) and future proof against changes in global food market dynamics (i.e. shifts to veganism). Related to the production of protein from CAM plants is the potential to avoid further deforestation for protein production from soybeans. Searchinger et al. (2018) estimate that protein production from soybeans creates up to 17 kg of CO_2 per kg of contained protein as a result of direct emissions, but largely associated land use change. Given the minimal water and nutrient needs of CAM plants, net emissions from CAM plant protein would be low. Displacing soy production would make space for reforestation, drawing down historic emissions, with substantial biodiversity benefits. Equally, recent research has demonstrated the potential for extracting biopolymers from the *Opuntia* mucilage (Gheribi et al., 2019), producing a sustainable biodegradable form of packaging (Ortiz, 2019), as well as a potential by-product from agricultural production of *O. ficus-indica* in parts of central America. These examples highlight the multi-faceted potential benefits of a cacti-based bio-economy, offering a suite of opportunities to tackle local, national and global-scale environmental issues.

Expanding beyond the base estimates: degraded lands, urban environments

Aside from the provision of renewable energy to currently unelectrified regions, the potential role of CAM cultivation for energy crops to make a material contribution to climate change mitigation and global greenhouse gas emissions reduction means that it is worth considering areas suitable for production which are perhaps not necessarily coupled with high immediate energy demand nor available under the conservative estimates of Table 3. For example, some studies (Mason et al. 2015; Kareiva et al. 2007) have suggested the need to consider an acceptable trade-off when debating the overall net benefits of using portions of land for different global goals (i.e. conserving large areas for biodiversity rather than planting CAM crops which could contribute to alternative environmental goals). Regions that are physiologically suitable, yet have been excluded from the estimates of Table 3 for alternative social and environmental criteria could be re-classified as suitable areas if a case was made that the net benefits to the environment would be greater. Table 4 demonstrates the change in available land estimate as each of the individual masks from Figure 2 were applied to the original suitability estimates.

		Increasing levels of environmental and social masks			
	Area / Yield	• >5% abandoned land	• >5% abandoned land • Excludes unsuitable land uses	• >5% abandoned land • Excludes: unsuitable land uses; WDPA zones – categories 1 & 2; CI Biodiversity Hotspots	• >5% abandoned land • Excludes: unsuitable land uses; WDPA zones – categories 1 & 2; CI Biodiversity Hotspots; areas >8% slope profile
Louhachi et al. (2015) method (>200 mm)	Area (million ha)	71.13	39.64	28.09	28.09
Louhachi et al. (2015) method (200-800 mm) [a]	Area (million ha)	30.02	20.89	15.36	15.36
Owen et al. (2015) method	Area (million ha)	163.23	74.90	55.38	54.89
	Yield (Mt yr^{-1})	3049.6	1,825.4	1,313.3	1,310.9

Table 4. Available land (million ha) and yield (Mt yr^{-1}) estimates based on applying the varying levels of environmental and social masks to the land availability analysis. With each increasing level, an additional mask (Figure 2b-f) has been applied. Refer to supplementary information. [a] Areas > 800 mm excluded as CAM succulents and cacti would likely be outcompeted by other vegetation types in these regions of greater rainfall.

Results show that removing areas that coincide with CI biodiversity hotspots and WDPA zones, excluded an additional c.25% of areas that are considered suitable and fall within the zones of > 5% abandoned land / appropriate land use. Dauber et al. (2012) provide a review on the considerations of generating bioenergy from surplus lands and the potential impacts on biodiversity and nature conservation. Converting areas to dedicated plantations for bioenergy use could put the high environmental value of particular landscapes at risk (Beringer et al., 2011), particularly in regions already identified as biodiversity hotspots and conservation priorities. However, within these biodiversity hotspots and protected areas, there are also areas of degraded land that could potentially be restored through the active cultivation of CAM species, contributing towards REDD+ goals of reducing global pressure on forested regions.

For example, Madagascar has lost over 90% of its original forest (Conservation International, 2020) and human activities since the 1950s have had devastating impacts on the natural environments of the island (Vieilledent et al., 2018), resulting in a range of international conservation efforts since the 1980s (Waeber et al., 2016). However, despite organisations such as WWF, CEPF (CI) and REDD+ all seeking to protect and conserve the remaining natural habitat with 500+ environmental based projects, deforestation remains largely unchecked (Waeber et al., 2016) and the success of small-scale livelihood projects is not unilateral (Harvey et al., 2018; Poudyal et al., 2018). Successful conservation efforts need to combine the protection of biodiversity equally with the needs of the local communities in an environment where the majority of the population depend on the natural resources. Initiatives that combine native CAM species to Madagascar with the potential production of sustainable by-products could be explored as viable complementary schemes alongside traditional conservation efforts. A more refined map of the protected areas on Madagascar show that whilst the whole island has been classified as a CI Biodiversity Hotspot, c.15% of the land across 38 Key Biodiversity Area (KBA) sites represent locations of CEPF priority and investment (Figure 5). In the proximal areas to priority KBA sites, new conservation projects could seek to reintroduce indigenous succulent species to stabilise soils, increase sequestration of carbon and provide sustainable economic opportunities to local communities. Whilst our initial analysis has focused on removing those areas defined as protected conservation areas from potential CAM plant cultivation figures, the example of Madagascar demonstrates that primary forest conservation efforts can still be pursued while areas of already degraded land could be greatly improved through initiatives that combine CAM plantation.

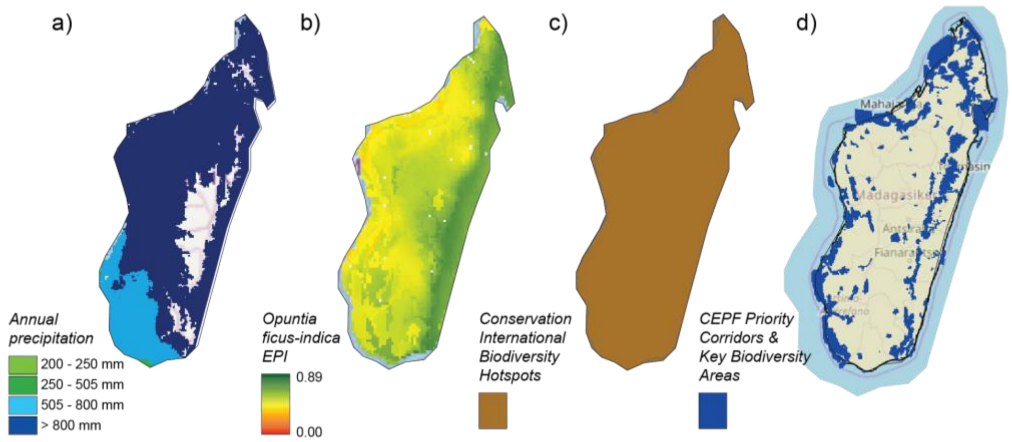

Figure 5. Land suitability estimates for *O. ficus-indica* and priority conservation areas on the island of Madagascar. a) Environmentally suitable areas according to the method used in Louhaichi et al. (2015) producing four classes of *O. ficus-indica* suitability based on annual precipitation levels; b) Environmentally suitable areas according to the method used in Owen et al. (2015) producing an *O. ficus-indica* environmental productivity index (EPI 0-1) for each individual grid cell. Land suitability and conservation priority areas of Madagascar. c) Conservation International Biodiversity Hotspot covering the entirety of mainland Madagascar (dataset from Hoffman et al. (2016)). d) CEPF Priority Key Biodiversity Areas (KBAs) and Corridors on mainland Madagascar (dataset from BirdLife International (2019)).

Additionally, the potential to include urban areas as a source of cacti material has not been included in the continent-wide estimates. Urban areas were excluded in the overlay masks since the likelihood for large-scale available land for active cultivation of CAM plants is unlikely. Nevertheless, individual existing case studies across Africa (e.g. Cactus Clean-Up initiative Windhoek, urban cacti in Kenya – Muchane et al. 2017) have commented on existing invasive cacti species spreading throughout urban areas, and efforts to clear the cacti could result in supplementary urban power generation. Whilst not on a large-scale, assessments of the potential for urban "invasives" to be included in national-scale bioenergy potential could increase the overall volume of material and thus energy generated at the country level. Equally, the close proximity of the plant material from urban centres to waste-to-energy processing sites and grid infrastructure could make these outcrops of CAM plants particularly valuable to the national bioenergy cause. The use of *O. ficus-indica* waste as a source of bioenergy in urban contexts has also been demonstrated in Milpa Alta's cactus market, Mexico (Bioenergy Insight, 2017).

On the ground validation

Results discussed in this paper are drawn from continent-scale sources and composite maps, producing a continent-wide assessment of CAM plant cultivation and bioeconomic potential. Whilst the maps present a broad continent-scale view, highlighting the larger opportunities that lie across regions and far-reaching trends associated with energy access, on the ground validation at the national-level of: 1) possible available land, 2) the demand for energy, and 3) the yields and optimisation of species, would also be beneficial.

Firstly, using Campbell et al (2008) abandoned agricultural analysis as a base, we have presented a revised estimate of available land excluding competing land uses. However, within individual countries and regions, areas that are not currently 'abandoned' could also be considered for CAM plant cultivation as a means of repurposing under-performing land or diversifying the income associated with existing land uses. National-level assessments of the appetite for private ranch owners, corporate mining companies and ecotourism resorts to dedicate areas of land to the provision of bioenergy supply could greatly increase the potential land and yield estimates presented in Table 3.

Secondly, as noted above, all current measures of electricity access are coarse-scale in one form, confounding the ability to measure the demand for energy. The use of satellite imagery provides an improved metric on sustainable and continuous access to electricity than that assumed from distance-to-grid datasets, but it is not without its flaws and assumptions. This study has looked at three metrics which could be used to infer the likelihood of access to electricity: i) population density coupled with urban and rural electrification rates at national level; ii) night time light imagery from satellite datasets; iii) existing grid connections. However, the measures referred to in this paper do not comment on the sustainability of access to electricity. For example, how many hours of access or days of the year does a household need to be connected to an electricity supply for it to be considered "electrified"? Individual country-scale assessments are needed to produce a detailed view of sustainable energy access at the national scale, capturing both on-grid and off-grid supplies as well as the barriers to future successful projects.

Thirdly, as shown in Owen et al. (2015) using a refined EPI methodology (Garcia-Moya et al., 2011; Nobel, 1988; Nobel and Meyer, 1985; Nobel and Quero, 1986; Nobel and Valenzuela, 1987) we can coarsely begin to estimate potential yields of *O. ficus-indica* and *Agave tequiliana* that could be achieved. However, localised specie-specific analysis at the country-level would provide improved estimates on the potential for indigenous CAM succulents to be cultivated in protected areas as a means of halting further land degradation and providing a sustainable method of bioenergy production. Machine learning techniques and species distribution modelling based on future climate change estimates can also improve estimates of viable future yields and suitable habitats.

Conclusions

Building on previous estimates of degraded land and *O. ficus-indica* yield estimates, we provide a revised evaluation of land available and suitable for CAM production across the African continent. Our analysis has mapped three key considerations of CAM cultivation for potential bioeconomic use: physiological requirements; land use constraints; and energy demand – to produce a coarse-scale continent-wide assessment. Using two different methods: bioclimatic envelope (Louhachi et al., 2015) and a revised environmental productivity index (Owen et al., 2015), combined with land use and abandoned land datasets, results demonstrated that 28-55 million hectares of land are suitable and available for CAM cultivation without competing with existing land and food production uses. The vast majority of the available area is located in semi-arid regions of the continent, including Namibia, Botswana and northern South Africa, providing a potential bioeconomic alternative to alleviate land degradation in regions that are already experiencing environmental stress and land abandonment in light of increased drought and climate change pressures as well as a potential source of energy through anaerobic digestion. Outside of the immediate potential to provide local bioenergy and livestock fodder, the potential scale of CAM cultivation (c. 600-1300 million DMT yr^{-1}) could contribute towards global bioprotein and bioplastic production, reducing the pressure for soya plantations and associated deforestation in other regions. Carbon sequestration, atmospheric CO_2 drawdown and land restoration are just a few of the regional and potential global environmental benefits which could be alleviated through active CAM cultivation of abandoned semi-arid environments. Future research should look to complement this continent-scale study with detailed country-level assessments, identifying the yield potential of native CAM species which could provide alternatives to invasive species and are remain relatively under-explored in the literature.

Conflicts of interest

There are no conflicts to declare.

References

Amaral S, Camara G, Monteiro A, Quintanilha J, Elvidge C. 2005. Estimating population and energy consumption in Brazilian Amazonia using DMPS night-time satellite data. Computers, Environment and Urban Systems **29** : 179–195.

Andrade-Pacheco R, Savory DJ, Midekisa A, Gething PW, Sturrock HJW, Bennett A. 2019. Household electricity access in Africa (2000–2013): Closing information gaps with model-based geostatistics. PLoS ONE **14** : 1–14. DOI: 10.1371/journal.pone.0214635

Beringer T, Lucht W, Schaphoff S. 2011. Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. GCB Bioenergy **3** : 299–312.

Bioenergy Insight. 2017. Mexican scientists convert prickly pear cactus to biogas. Bioenergy Insight [online] Available from: https://www.bioenergy-news.com/news/mexican-scientists-convert-prickly-pear-cactus-to-biogas/ (Accessed 3 January 2020)

BirdLife International. 2019. World Database of Key Biodiversity Areas. Developed by the KBA Parternship: Birdlife International, International Union for the Conservation of Nature, Amphibian Survival Alliance, Conservation International, Critical Ecosystem Partnership Fund, Global Environment Facility, Global Wildlife Conser [online] Available from: www.keybiodiversityareas.org (Accessed 15 February 2019)

Blimpo MP, Cosgrove-Davies M. 2019. Electricity Access in Sub-Saharan Africa: Uptake, Reliability, and Complementary Factors for Economic Impact . Africa Dev. World Bank: Washington, DC

Borland AM, Griffiths H, Hartwell J, Smith JAC. 2009. Exploiting the potential of plants with crassulacean acid metabolism for bioenergy production on marginal lands. Journal of Experimental Botany **60** : 2879–2896. DOI: 10.1093/jxb/erp118

Bruederle A, Hodler R. 2018. Nighttime lights as a proxy for human development at the local level. PLoS ONE **13** : 1–22. DOI: 10.1371/journal.pone.0202231

CABI. 2019. Invasive Species Compendium - Opuntia ficus-indica (prickly pear). Centre for Agriculture and Bioscience International [online] Available from: https://www.cabi.org/isc/datasheet/37714 (Accessed 15 October 2019)

Cai X, Zhang X, Wang D. 2011. Land Availability for Biofuel Production Suppoting Info. Construction **1** : 1–17.

Campbell JE, Lobell DB, Genova RC, Field CB. 2008. A global potential of bio-energy on abandoned agricultural land. Environmental Science and Technology **42** : 5791–5794.

Campbell JE, Lobell DB, Genova RC, Zumkehr A, Gikonyo CB. 2015. Seasonal energy storage using bioenergy production from abandoned croplands. Efficiency and Sustainability in Biofuel Production: Environmental and Land-Use Research : 131–148. DOI: 10.1088/1748-9326/8/3/035012

Chand T, Badarinath K, Elvidge C, Tuttle B. 2009. Spatial characterisation of electrical power consumption patterns over India using temporal DMPS-OLS night-time satellite data. International Journal of Remote Sensing **30** : 647–661.

Chaplin D et al. 2017. Grid Electricity Expansion in Tanzania: Findings from a Rigorous Impact Evaluation: Final Report. Mathematica Policy Reserach : 1–8.

Cherlet M, Hutchinson C, Reynolds J, Hill J, Sommer S, von Maltitz G (eds). 2018. World Atlas of Desertification . 3rd ed. Publication Office of the European Union: Luxembourg

Conservation International. 2020. Sub-Saharan Africa [online] Available from: https://www.conservation.org/places/Sub-Saharan-Africa (Accessed 20 January 2020)

Cushman JC, Davis SC, Yang X, Borland AM. 2015. Development and use of bioenergy feedstocks for semi-arid and arid lands. Journal of Experimental Botany **66** : 4177–4193. DOI: 10.1093/jxb/erv087

Dauber J et al. 2012. Bioenergy from “surplus” land: Environmental and socio-economic implications. BioRisk **50** : 5–50. DOI: 10.3897/biorisk.7.3036

Doll CNH, Mueller J-P, Morley JG. 2006. Mapping regional economic activity from night-time light satellite imagery. Ecological Economics **57** : 75–92.

Dregne HE, Chou NT. 1992. Global desertification dimensions and costs. Degradation and Restoration of Arid Lands : 73–92.

Fischer G, Nachtergaele F, Prieler S, van Velthuuizan H., Verelst L, Wiberg D. 2008. Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008)

Gabisa EW, Gheewala SH. 2018. Potential of bio-energy production in Ethiopia based on available biomass residues. Biomass and Bioenergy **111** : 77–87.

Garcia-Moya E, Romero-Manzanares A, Nobel PS. 2011. Highlights for Agave productivity. GCB Bioenergy **3** : 4–14.

Gheribi R, Habibi Y, Khwaldia K. 2019. Prickly pear peels as a valuable resource of added-value polysaccharide: Study of structural, functional and film forming properties. International Journal of Biological Macromolecules **126** : 238–245. DOI: 10.1016/j.ijbiomac.2018.12.228 [online] Available from: https://doi.org/10.1016/j.ijbiomac.2018.12.228

Gibbs HK, Salmon JM. 2015. Mapping the world’s degraded lands. Applied Geography **57** : 12–21. DOI: 10.1016/j.apgeog.2014.11.024

Greenstone M, Jack K. 2015. Envirodevonomics : A Research Agenda for an Emerging Field. Journal of Economic Literature **53** : 5–42.

Harvey CA et al. 2018. Local Perceptions of the Livelihood and Conservation Benefits of Small-Scale Livelihood Projects in Rural Madagascar. Society and Natural Resources **31** : 1045–1063. DOI: 10.1080/08941920.2018.1484974 [online] Available from: https://doi.org/10.1080/08941920.2018.1484974

Hill J, Nelson E, Tilman D, Polasky S, Tiffany D. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proceedings of the National Academy of Sciences of the United States of America **103** : 11206–11210.

Hoffman M, Koenig K, Bunting G, Costanza J, Williams KJ. 2016. Biodiversity Hotspots (version 2016.1) [online] Available from: http://doi.org/10.5281/zenodo.3261807

Le Houérou HN. 1996. The role of cacti (Opuntia spp.) in erosion control, land reclamation, rehabilitation and agricultural development in the Mediterranean Basin. Journal of Arid Environments **33** : 135–159. DOI: 10.1006/jare.1996.0053

IEA. 2019a. Access to clean cooking. Sustainable Development Goal 7 [online] Available from: https://www.iea.org/sdg/cooking/ (Accessed 5 August 2019)

IEA. 2019b. Africa Energy Outlook [online] Available from: https://webstore.iea.org/africa-energy-outlook-2019 (Accessed 8 January 2020)

IPCC. 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the conetxt of strengthening the global response to the threat of climate change, . Masson-Delmotte V et al. (eds)

IPCC. 2019. IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems [online] Available from: https://www.ipcc.ch/site/assets/uploads/2019/08/4.-SPM_Approved_Microsite_FINAL.pdf

Lee K, Brewer E, Christiano C, Meyo F, Miguel E, Podolsky M, Rosa J, Wolfram C. 2016a. Electrification for “under Grid” households in Rural Kenya. Development Engineering **1** : 26–35. DOI: 10.1016/j.deveng.2015.12.001 [online] Available from: http://dx.doi.org/10.1016/j.deveng.2015.12.001

Lee K, Miguel E, Wolfram C. 2016b. Experimental evidence on the demand for and costs of rural electrification. NBER Working Paper Series **22292** DOI: 10.5151/cidi2017-060

López-García F, Jiménez-Martínez C, Delgado-Macuil R, Guzmán-Lucero D, Maciel-Cerda A, Terrés-Rojas E, Arzate-Vázquez I, Cabrero-Palomino D. 2017. Physical and chemical characterization of a biopolymer film made with corn starch and nopal xoconostle (opuntia joconsotle) mucilage. Revista Mexicana de Ingeniera Quimica **16** : 147–158.

Louhaichi M, Park AG, Mata-Gonzalez R, Johnson DE, Mohawesh YM. 2015. A Preliminary Model of Opuntia ficus-indica (L .) Mill . Suitability for Jordan A Preliminary Model of Opuntia ficus-indica (L .)

Mill . Suitability for. Acta horticulturae : 267–274. DOI: 10.17660/ActaHortic.2015.1067.37

Marthews TR, Jones RG, Dadson SJ, Otto FEL, Mitchell D, Guillod BP, Allen MR. 2019. The Impact of Human-Induced Climate Change on Regional Drought in the Horn of Africa. Journal of Geophysical Research: Atmospheres **124** : 4549–4566. DOI: 10.1029/2018JD030085

Mason PM, Glover K, Smith JAC, Willis KJ, Woods J, Thompson IP. 2015. The potential of CAM crops as a globally significant bioenergy resource: Moving from “fuel or food” to “fuel and more food.” Energy and Environmental Science **8** : 2320–2329. DOI: 10.1039/c5ee00242g [online] Available from: http://dx.doi.org/10.1039/C5EE00242G

Mellander C, Lobo J, Stolarik K, Matheson Z. 2015. Night-Time Light Data: A Good Proxy Measure for Economic Activity? PLoS ONE **10** : e0139779.

Middleton NJ, Thomas DSG. 1997. World Atlas of Desertification . 2nd Editio. Edward Arnold: London

Min B, Gaba KM, Sarr OF, Agalassou A. 2013. Detection of rural electrification in africa using DMSP-OLS night lights imagery. International Journal of Remote Sensing **34** : 8118–8141. DOI: 10.1080/01431161.2013.833358 [online] Available from: http://dx.doi.org/10.1080/01431161.2013.833358

Morrissey J. 2017. The energy challenge in sub-Saharan Africa: A guide for advocates and policy markers: Part 2: Addressing energy poverty [online] Available from: http://www.oxfamamerica.org/static/media/files/oxfam-RAEL-energySSA-pt2.pdf

Neffar S, Chenchouni H, Beddiar A, Redjel N. 2013. Rehabilitation of degraded rangeland in drylands by Prickly pear (Opuntia ficus-indica L.) plantations: Effect on soil and spontaneous vegetation. Ecologia Balkanika **5** : 63–76. [online] Available from: http://web.uni-plovdiv.bg/mollov/EB/2013_vol5_iss2/063-076_eb.13118.pdf

Nobel P., Garcia-Moya E, Quero E. 1992. High annual productivity of Agaves and Cacti under cultivation. Plant, Cell and Environment **15** : 329–335.

Nobel PS. 1988. Environmental Biology of Agaves and Cacti . Cambridge University Press: Cambridge, UK

Nobel PS, Meyer SE. 1985. Field productivity of a CAM plant, Agave salmiana, estimated using daily acidity changes under various environmental onditions. Physiologia Plantarum **65** : 397–404.

Nobel PS, Quero E. 1986. Environmental productivity indices for a chihuahuan Desert CAM plant: Agave Lechuguilla. Ecology **67** : 1–11.

Nobel PS, Valenzuela AG. 1987. Environmental responses and productivity of the CAM plant, Agave tequiliana. Agricultural and Forest Meteorology **39** : 319–334.

Ortiz SP. 2019. Bioplastic bags made from cactus juice. Bioplastic News [online] Available from: https://bioplasticsnews.com/2019/12/31/bioplastics-bags-cactus-juice/ (Accessed 10 January 2020)

Otto FEL et al. 2018. Anthropogenic influence on the drivers of the Western Cape drought 2015-2017. Environmental Research Letters **13** DOI: 10.1088/1748-9326/aae9f9

Owen NA, Fahy KF, Griffiths H. 2015. Crassulacean acid metabolism (CAM) offers sustainable bioenergy production and resilience to climate change. GCB Bioenergy DOI: 10.1111/gcbb.12272

Pandey B, Joshi R, Seto K. 2013. Monitoring urbanisation dynamics in India using DMSP/OLS night time lights and SPOT-VGT data. International Journal of Applied Earth Observation and Geoinformation **23** : 49–61.

Poudyal M, Jones JPG, Rakotonarivo OS, Hockley N, Gibbons JM, Mandimbiniaina R, Rasoamanana A, Andrianantenaina NS, Ramamonjisoa BS. 2018. Who bears the cost of forest conservation? PeerJ **2018** : 1–30. DOI: 10.7717/peerj.5106

Proville J, Zavala-Araiza D, Wagner G. 2017. Night-time lights: A global, long term look at links to socio-economic trends. PLoS ONE **12** : 1–12. DOI: 10.1371/journal.pone.0174610

Searchinger TD, Wirsenius S, Beringer T, Dumas P. 2018. Assessing the efficiency of changes in land use for mitigating climate change. Nature **564** : 249–253. DOI: 10.1038/s41586-018-0757-z [online] Available from: http://dx.doi.org/10.1038/s41586-018-0757-z

Shane A, Gheewala SH, Fungtammasan B, Silalertruksa T, Bonnet S, Phiri S. 2016. Bioenergy resource assessment for Zambia. Renewable and Sustainable Energy Reviews **53** : 93–104. DOI: 10.1016/j.rser.2015.08.045 [online] Available from: http://dx.doi.org/10.1016/j.rser.2015.08.045

Szabó S, Bódis K, Huld T, Moner-Girona M. 2011. Energy solutions in rural Africa: Mapping electrification costs of distributed solar and diesel generation versus grid extension. Environmental Research Letters **6** DOI: 10.1088/1748-9326/6/3/034002

The World Bank. 2017a. Access to electricity (% of population). The World Bank Group [online] Available from: https://data.worldbank.org/indicator/eg.elc.accs.zs (Accessed 27 August 2019)

The World Bank. 2017b. Africa - Electricity Transmission and Distribution Grid Map. The World Bank Group [online] Available from: https://datacatalog.worldbank.org/dataset/africa-electricity-transmission-and-distribution-grid-map-2017 (Accessed 23 July 2019)

The World Bank. 2018. Rural population (% of total population). The World Bank Group [online] Available from: https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?locations=ZG (Accessed 5 August 2019)

Tilman D, Hill J, Lehman C. 2006. Carbon-negative biofuels from low-input high-diversity grassland biomass. Science **314** : 1598–1600.

Townsend A, Bruce D. 2010. The use of night-time lights satellite imagery as a measure of Australia's reigonal electricity consumption and population distribution. International Journal of Remote Sensing **31** : 4459–4480.

United Nations. 2011. Global Drylands: A UN system-wide response

Vieilledent G, Grinand C, Rakotomalala FA, Ranaivosoa R, Rakotoarijaona JR, Allnutt TF, Achard F. 2018. Combining global tree cover loss data with historical national forest cover maps to look at six decades of deforestation and forest fragmentation in Madagascar. Biological Conservation **222** : 189–197. DOI: 10.1016/j.biocon.2018.04.008

Waeber PO, Wilmé L, Mercier JR, Camara C, Lowry PP. 2016. How effective have thirty years of internationally driven conservation and development efforts been in Madagascar? PLoS ONE **11** : 1–13. DOI: 10.1371/journal.pone.0161115

Watson HK, Diaz-Chavez RA. 2011. An assessment of the potential of drylands in eight sub-Saharan African countries to produce bioenergy feedstocks. Interface Focus **1** : 263–270.

WDPA. 2019. WDPA Dataset. World Database on Protected Areas [online] Available from: https://www.protectedplanet.net/ (Accessed 15 October 2019)

Wicke B, Smeets E, Watson H. 2011. The current bioenergy production potential of semi-arid and arid regions in sub-Saharan Africa. **5** DOI: 10.1016/j.biombioe.2011.03.010

Wu GC, Deshmukh R, Ndhlukula K, Radojicic T, Reilly-Moman J, Phadke A, Kammen DM, Callaway DS.

2017. Strategic siting and regional grid interconnections key to low-carbon futures in African countries

Yang X et al. 2015. A roadmap for research on crassulacean acid metabolism (CAM) to enhance sustainable food and bioenergy production in a hotter, drier world. New Phytologist **207** : 491–504. DOI: 10.1111/nph.13393