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A Continental-Scale Connectivity Analysis to Predict Current and Future Colonization Trends of Biofuel Plant's Pests for Sub-Saharan African Countries

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Abstract: Biofuel production in Sub-Saharan Africa is an important part of local low-income countries. Among many plant species, *Jatropha curcas* gained popularity in this area, as it can be grown even where crops of agricultural interest cannot. A natural African pest of *J. curcas* is the *Aphthona cookei* species group, for which future climatic suitability is predicted to favor areas of co-occurrence. In this research, we identify the possible climatic corridors in which the colonization of *J. curcas* crops may occur through a circuit theory-based landscape connectivity software at a country scale. Additionally, we use the standardized connectivity change index to predict possible variations in future scenarios. Starting from ecological niche models calibrated on current and 2050 conditions (two different RCP scenarios), we found several countries currently showing high connectivity. Ghana, Zambia and Ivory Coast host both high connectivity and a high number of *J. curcas* cultivations, which is also predicted to increase in the future. On the other side, Burundi and Rwanda reported a future increase of connectivity, possibly acting as “connectivity bridges” among neighboring countries. Considering the economic relevance of the topic analyzed, our spatially explicit predictions can support stakeholders and policymakers at a country scale in informed territorial management.

Keywords: biofuels; *Jatropha curcas*; *Aphthona cookei* species complex; landscape connectivity; Sub-Saharan Africa; agricultural economics; Circuitscape; agricultural pests; standardized connectivity change index; ecological modelling



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1. Introduction

In recent years, the biodiversity crisis has become more and more pronounced [1], with effects increasingly perceived not only by the scientific community but also by the general public [2]. Because of climate and land-use change, as well as invasive alien species, many plant and animal species are declining both locally [3–5] and worldwide [6–8], with populations delivering some important ecosystemic functions reported as decreasing or on the brink of local (or global) extinction [9]. Among these, species providing the ecosystem services gain the attention of stakeholders due to their economic importance [10]. The fundamental role they carry out is multifaceted, ranging from food supply and water partitioning to climate regulation and the production of specific marketable products [11].

In Sub-Saharan Africa, one of the ecosystem services considered to be important for local economies is the production of biofuels through the processing of *Jatropha curcas* [12], a shrub native to Central America that is currently cultivated in many other territories [13]. This plant plays an important role in several African countries, as it can be cultivated under different environmental features, such as degraded and semi-arid areas, as well as in humid ones [14]. This characteristic makes *J. curcas* greatly important in the light of current land use-land cover changes since many other species used for biofuels production (such as sugarcane or maize) were reported to cause detrimental effects on food production and

the related costs. In fact, these plants represent the so-called ‘first-generation biofuels’, for which broad cultivated extents are needed, with the related biodiversity loss issues [15,16]. Thus, the possibility of cultivating a plant which does not imply high rates of land reclamation, and possibly its association with many other agricultural species, have made *J. curcas* an important species during the last years in Sub-Saharan Africa [17].

On the other hand, co-occurring insect species often damage plants of commercial relevance [18–20], with subsequent high economic losses [21]. Indeed, the presence of native flea beetles belonging to the *Aphthona cookei* species complex *sensu* Biondi et al. (2013) [22], hinders the cultivation of *J. curcas* in Sub-Saharan Africa, as they feed on its leaves, leading even to the death of the plant [23,24].

Notwithstanding the relevance of this topic, at least in terms of the possible economic damage, recent research by De Simone et al. [21] is the only work dealing with this issue in the light of climate change. The outcomes of this research showed the assets at a sub-continental scale (western, eastern, central and southern Sub-Saharan Africa), where economic losses in terms of ecosystem services (carbon storage and biofuel production, USD millions) provided by *J. curcas* could reach ~50% when it co-occurs with the *A. cookei* species complex. Another important aspect is represented by the future possibility that individuals from the *A. cookei* species complex will reach *J. curcas* cultivations in areas where these flea beetles do not currently occur. This issue still remains uninvestigated, even though it is well known that climate change is altering connectivity at a landscape scale, negatively impacting biodiversity conservation and favoring biological invasions [25].

In this research, we aim to:

- (1) Sharpen the findings of De Simone et al. [21] by investigating the current and future connections among *A. cookei* species complex populations and *J. curcas* cultivations, for both current and future climatic conditions, in the whole of Sub-Saharan Africa (excluding Madagascar);
- (2) Measure the possible increase or decrease of connections that are likely to occur through the use of the recently introduced “standardized connectivity change index” [26];
- (3) Calculate and statistically test the differences in connectivity (and its corresponding future changes) for each Sub-Saharan African country, providing useful information for informed planning of current and future *J. curcas* cultivations.

2. Materials and Methods

2.1. Target Species and Study Area

Jatropha curcas L. is a perennial broad-leaved plant belonging to the Euphorbiaceae family. It is a monoecious plant that blooms throughout the year in permanently humid equatorial regions. The fruit releases three large black seeds (nuts) and, in good humid conditions, germination occurs in 10 days. It is best suited to arid and semi-arid conditions. The current distribution confirms that its introduction has been most successful in similar arid regions of the tropics with average annual rainfall of between 300 and 1000 mm. Numerous pests and diseases have been reported [27], although in most countries, they do not severely affect the plant. *Jatropha curcas* suffers the presence of different pests, comprised in various insects groups such as Thysanoptera, Hemiptera, Lepidoptera (e.g., Phycitinae) and Coleoptera (e.g., Chrysomelidae, Curculionidae). Among these, one of the major pests of this plant in the Afrotropical region is represented by the defoliators of the genus *Aphthona* [22,24,28]. Its native range includes the Central American territories [29], but it is nowadays cultivated in Sub-Saharan Africa and some Asian countries (China, Cambodia, India, Indonesia and Thailand) [13]. This shrub is used for different purposes, such as in medicinal applications, material for living fences and feedstock for biofuels production [30].

Aphthona Chevrolat is a widespread flea beetle genus mainly found in the Palaearctic, Oriental and Afrotropical regions [31]. The three target species of *Aphthona* that are considered here, namely *A. cookei* (Gerstaecker), *A. dilutipes* Jacoby and *A. whitfieldi* Bryant (hereafter called *A. cookei* complex), are among the most damaging pests of Sub-Saharan *J. curcas* cultivations (e.g., [22,32,33]). Indeed, these flea beetle species feed on leaves, leading

to heavy defoliation as well as to the death of the plant, even with a few hundred individuals [22–24,34]. These three species were chosen as a unique modelling unit, considering their overlapping trophic niche and taking into account the morphological features and phenological cycles [21].

Although the analyses detailed below were performed on all Sub-Saharan countries, a sub-set of them was selected considering their high number of *J. curcas* cultivations, thus focusing the relevant information obtained from our results on specific territorial contexts.

2.2. Connectivity Modelling

In this research, to infer ecological corridors, we take advantage of one of the most used connectivity software in biodiversity-related topics [35], Circuitscape v. 5.0 [36–38], run in Julia language v. 1.5.3 [39]. This software takes advantage of both random walks processes and circuit theory to model the ecological connectivity, outperforming other algorithms when knowledge about the direction/route to be used by the moving species is missing [40]. Circuitscape requires two main inputs, namely the friction map (which represents the resistance or conductance that the target territory offers to the species moving) and the occurrence localities. All inputs used in this process derive from the published information of De Simone et al. [21]. Regarding the first input, the climatic suitability for current and future (2050_RCP4.5 = 2050_4 and 2050_RCP6.0 = 2050_6, see below) scenarios deriving from the ecological niche modelling processes of the aforementioned research were selected. The information deriving from the Ecological Niche Modelling depicts the suitability that a target area has with respect to the ecological requirements of a species, on which the models are calibrated [41], providing much information on biogeography, conservation and invasion biology, landscape management and many other fields [18–20,26,42]. In this case, the models were built by De Simone et al. [21] starting from climatic predictors. The RCPs (representative concentration pathways) depict the different scenarios derived by the greenhouse gases concentration trajectories used by the Intergovernmental Panel on Climate Change. De Simone et al. [21] used the 4.5 and the 6.0 scenarios, which represent greenhouse gases peaking and then starting to decrease in 2045 and 2080, respectively [43].

Circuitscape was set with the ‘habitat_map_is_resistances’ argument to ‘False’, so that these suitability maps were used as landscape conductances.

Then, the Circuitscape ‘Advanced mode’ was chosen, which allows the consideration of the occurrence localities of the *A. cookei* complex (60 localities) as sources and the *J. curcas* cultivations (671 localities) as destinations.

2.3. Connectivity Changes and Geostatistical Analyses

To assess connectivity variations between the current and future scenarios, the standardized connectivity change index (SCCI) [26] was calculated in ArcMap 10.0 [44]. Regardless of the connectivity values of the spatial data being compared, the index returns a map whose values range from -1 (connectivity loss) to $+1$ (connectivity gain), with $SCCI = 0$ depicting corridors’ stability.

The two future (2050_4 and 2050_6) connectivity scenarios were thus compared to the current one, and the resulting standardized connectivity change maps were further processed in a GIS environment. We first used spatial data representing the boundaries of Sub-Saharan African countries to extract the corresponding raster maps for both current and future scenarios and evaluated the current potential of connectivity and the future variations between *A. cookei* complex populations and *J. curcas* cultivations. Then, after having checked data for normality through the Kolmogorov–Smirnov test, we performed a Kruskal–Wallis ANOVA (considering the non-normality of the data, $p = 0.05$, see Results) to evaluate whether significant differences in connectivity existed among countries for each temporal scenario.

Considering that the selected RCP4.5 and RCP6.0 imply two different 2050 scenarios, countries could benefit of or suffer from the corresponding situation, depending on the distinct condition they represent. To highlight these possible differences, we tested each

of the selected countries to see whether future SCCIs were significantly different through a Mann–Whitney U test (considering the non-normality of the standardized connectivity change index values for the two RCPs considered).

For all tests, with the exception of post hoc correction for multiple comparisons, where the level of significance changed and was thus accordingly evaluated, the significance level was set at $p = 0.05$; all tests were performed through the ‘agricolae’ [45] package in the R environment [46].

3. Results

The corridor network estimated on suitability maps derived from the ecological niche models calibrated on the current climatic conditions [21] shows high and widespread connectivity for the *A. cookei* complex in central and eastern Africa, along with a more isolated corridor system in west and south-eastern Sub-Saharan Africa (Figure 1). Specifically, the Sub-Saharan African countries hosting *J. curcas* cultivations and reporting the highest connectivity (median value) are Ghana, Uganda, Zambia, Ivory Coast, Ethiopia and Central African Republic. Additionally, Burundi, Guinea and Rwanda have high connectivity values even though they host few *J. curcas* cultivations (Figure 1).

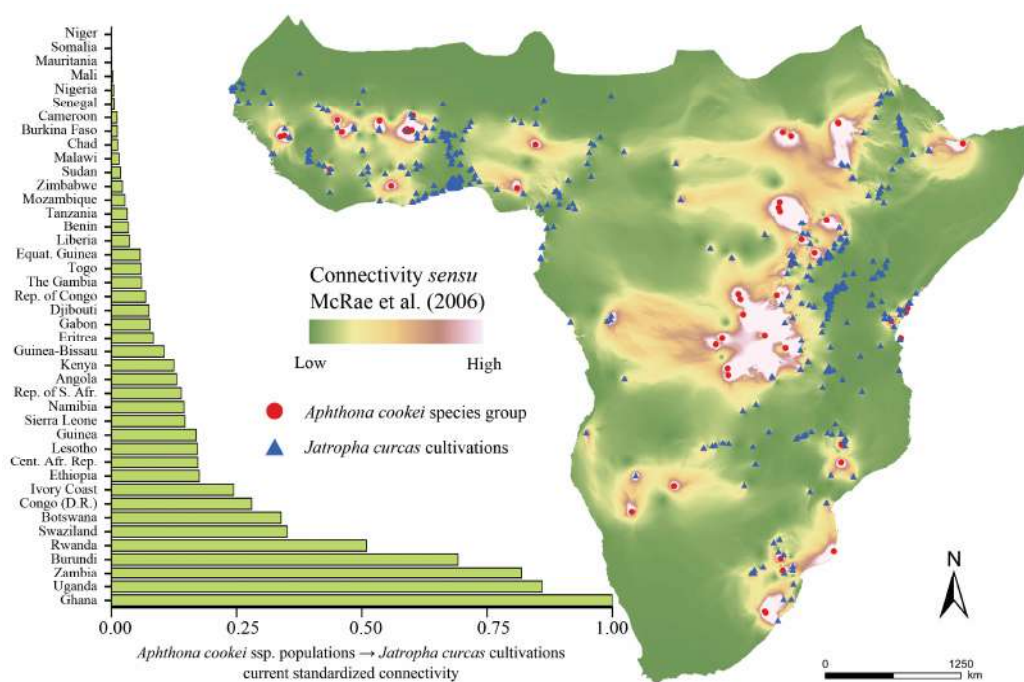


Figure 1. Connectivity among *Aphthona cookei* species complex populations and *Jatropha curcas* cultivations inferred for current climatic conditions.

According to the standardized connectivity change index, different assets emerge for the countries of major interest, namely the ones hosting the largest *J. curcas* crops. In fact, in the 2050_4 scenario (Figure 2a,c), Guinea shows the highest median connectivity loss (SCCI = -22.1%), followed by Kenya (SCCI = -7%), Uganda (SCCI = -4.5%) and Mozambique (SCCI = -4.1%). For some countries, such as Tanzania, Benin and Ethiopia, the corresponding values predicted they would remain stable (SCCI \sim 0), while an increase in connectivity ($1.5\% < \text{SCCI} < 28.8\%$) can be observed in Ivory Coast, Republic of South Africa, Zambia, Ghana, Cameroon, Mali and Malawi. Similar within-country connectivity changes are found in the 2050_6 scenario (Figure 2b,d), although with slightly different SCCI values. In fact, Guinea still reports a high loss (SCCI = -16.5%) together with Mozambique (SCCI = -7.4%), followed by South Africa (SCCI = -4.1%), Kenya (SCCI = -4.1%) and Benin (SCCI = -2%). Ivory Coast connectivity is predicted as stable (SCCI \sim 0), while connectivity increases ($1.1\% < \text{SCCI} < 32\%$) emerge for Tanzania, Ethiopia, Zambia, Ghana,

Cameroon, Malawi and Mali. On the other hand, even though Niger and Burkina Faso report the highest connectivity gains, with + 92.3% for both 2050_4 and 2050_6 for the former, and + 36.9% (2050_4) and + 39.4% (2050_6) for the latter, the starting current connectivity is low (Figure 1), thus making these gains negligible.

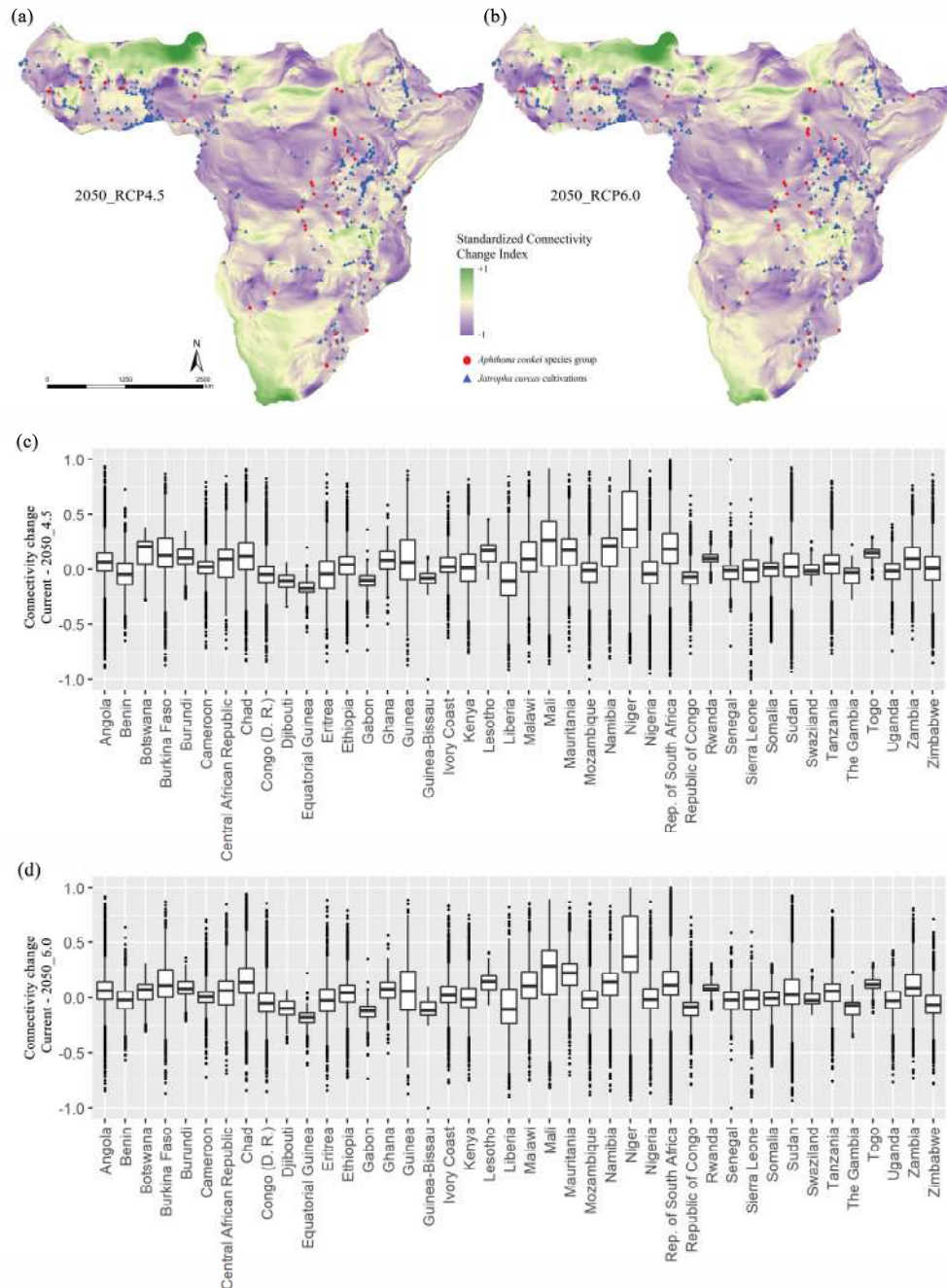


Figure 2. Changes in connectivity among *Aphthona cookei* species complex populations and *Jatropha curcas* cultivations from current to future (a) 2050 RCP4.5 and (b) 2050 RCP6.0 climatic conditions, calculated through the standardized connectivity change index [26]; the corresponding values are also reported in boxplots for (c) 2050 RCP4.5 and (d) 2050 RCP6.0.

Neither the current connectivity values nor the SCCI ones followed a normal distribution (K-S test, $p = 0.05$) for any Sub-Saharan African country (Supplementary Table S1). The subsequently performed Kruskal–Wallis ANOVA reported significant differences in connectivity (or its variation, in future scenarios) among the considered countries (current:

$\chi^2 = 9510.2$, $df = 41$, $p = 0.0$; 2050_4: $\chi^2 = 6550.7$, $df = 41$, $p = 0.0$; 2050_6: $\chi^2 = 6716.7$, $df = 41$, $p = 0.0$).

The Mann–Whitney U test (performed after a K–S test for each pair, Supplementary Table S1) was used to determine possible significant differences between the two RPC scenarios analyzed and resulted in mixed patterns (Table 1). Among countries which both host a high number of *J. curcas* cultivations and have the highest predicated current connectivity, only Ghana showed significant differences between the two RCPs ($U = 34,962$, $p = 9.65 \times 10^{-6}$), with an increasing future connectivity trend (Table 1). Furthermore, differences between the two RCPs were statistically significant for Burundi ($U = 34,001$, $p = 1.54 \times 10^{-5}$) and Rwanda ($U = 32,635$, $p = 0.004$) (high current connectivity values), while for Benin ($U = 32,592$, $p = 0.004$) (which hosts a high number of cultivations), Guinea and South Africa (high current connectivity value; $U = 38,722$, $p = 4.19 \times 10^{-12}$ and $U = 34,351$, $p = 5.88 \times 10^{-5}$, respectively) the future connectivity is predicted to decrease differently depending on the RCP considered (Table 1).

Table 1. Pairs of countries of interest tested for differences between the two 2050 scenarios considered, the RCP4.5 and the RCP6.0, with the corresponding variation between them (Δ , reported as percent difference), their features and future trend of increase, stability or decrease in predicted connectivity (double arrows represent a stronger trend).

	Mann–Whitney U Test			Δ (Percentage)	High Number of Cultivations	High Current Connectivity	SCCI 2050 Trend	
	Significance	U	<i>p</i>				2050_4.5	2050_6.0
Benin	Yes	32592	0.004	1.5%	X		↓	↓
Burundi	Yes	34001	0.000	2.1%		X	↑	↑↑
Centr. Afr. Rep.	No	27316	0.503	0.7%		X	↑↑	↑↑
Ivory Coast	No	30750	0.106	1.4%	X	X	↑	↑
Ethiopia	No	25691	0.080	1.9%	X	X	↑↑	↑
Ghana	Yes	34962	0.000	2.1%	X	X	↑	↑
Guinea	Yes	38722	0.000	5.5%		X	↓↓	↓
Rwanda	Yes	32635	0.004	2.7%		X	↑	↑
Rep. of South Africa	Yes	34351	0.000	5.8%		X	↓↓	↓
Tanzania	No	29307	0.512	1.1%	X		—	—
Uganda	No	28912	0.694	0.6%	X	X	↓	↓
Zambia	No	27117	0.422	0.1%	X	X	↑	↑

4. Discussion

One of the primary raw materials used to produce biofuels in Sub-Saharan Africa (SSA) is *J. curcas*; in 2008, 120,000 hectares were dedicated to *Jatropha* projects in SSA (about 13% of the total production in that year) [47]. From the Gexsi report [47], the primary producers are located in Zambia, Tanzania, Ghana, Ethiopia, Mozambique and Malawi, while minor projects occur in Kenya, Uganda, Zimbabwe, Namibia, Cameroon, Nigeria, Ivory Coast, Mali, Senegal and Gambia.

Jatropha curcas is affected by many types of pests, which cause various problems regarding crop productivity and yield [48–53]. In our study, we focused our attention on one of the most important *Jatropha* pests, the *A. cookei* species complex.

The work of De Simone et al. [21] highlighted how the influence of the *A. cookei* complex is predicted to mostly affect (for the current climatic conditions) Ghana, Ivory Coast, Ethiopia, Kenya, Tanzania, Uganda, Malawi and Mozambique, where currently many *J. curcas* crops occur. These results are supported by the connectivity analysis carried out in this research, where the highest values are predicted for Ghana, Uganda, Zambia, Ivory Coast and Ethiopia, making these countries the most exposed to potential attacks by the *A. cookei* species complex.

Regarding both the considered RCPs, the standardized connectivity change index shows that some countries will experience an increase in connectivity between the *A. cookei* complex and the cultivation of *J. curcas* in a variable index range. Ghana, Zambia and Ivory Coast are predicted to be the countries that will be mostly affected by the *A. cookei* complex presence, in accordance with De Simone et al. [21].

Although lacking major *J. curcas* crops, our analyses revealed that Central African Republic, Burundi and Rwanda are of great importance from the connectivity point of view. In fact, these countries play a crucial role in hosting high connectivity values under current conditions, with predicted connectivity gains in the future. Considering their geographic position, they represent “connectivity bridges” for the possible colonization of *A. cookei* complex between countries, where large *J. curcas* cultivation projects persist. Indeed, some countries hosting several *J. curcas* projects, such as Tanzania and Uganda, could run into future *A. cookei* species complex colonization from individuals passing through the abovementioned “bridge countries”, thus making a cross-boundary surveillance crucial. Additionally, a general tendency of lower connectivity increase (or higher connectivity decrease) is inferred for the 2050_4 scenario with respect to the 2050_6, highlighting the importance of the different magnitude of greenhouse gases emissions (modelled as lower for the RCP 2050_4). Consequently, countries predicted to suffer from the invasion of *A. cookei* complex may benefit from lower current and future emissions.

As a general trend, *J. curcas* is grown in climatically favourable areas; notwithstanding these suitable circumstances, major cultivation projects are in a critical condition. Indeed, this issue derives from several problems, such as limited experience in cultivation and management, poor business planning, institutional barriers, conflict with food supply, structural, infrastructural and logistics, limited local research and cultural barriers [54]. In the past, *J. curcas* was defined a “miracle crop”, which was promoted in the SSA as the solution to the demand for biofuels [55]. This “promise” was based on its high yields, low water requirements, lack of competition with food crops and growth on marginal land. Of all hectares planted to date, only some projects have shown long-term sustainability, such as those occurring in Malawi (based on small landowners) and Mozambique (large-scale plantations) [55]. The application of trans-boundary surveillance is thus crucial for Zambia and Republic of South Africa, which may play a role of “connectivity bridges” favouring the future dispersion of *A. cookei* complex in the two aforementioned countries, which in turn represent a farsighted example of sustainable plant biofuel production.

5. Conclusions

Refining ecological niche models through circuit theory-based connectivity analyses has shown to offer several advantages in studying the potential spread of pests towards crops of economic interest. Our approach allowed the evaluation of current landscape corridors and their possible future variations at a country-scale level. The resulting information is crucial for elaborating effective planning strategies aimed at reducing non-effective investments in low-income countries. Considering the broad applicability of this framework, our approach can be applied to any type of cultivation and the corresponding pests, ranging from biofuels to food crops, supporting local policymakers in a smart planning process at all spatial scales.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/land10111276/s1>, Table S1: *p*-values ($\alpha = 0.05$) obtained for Kolmogorov–Smirnov test performed over connectivity values (or future changes of it) of each Sub-Saharan African country.

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Data Availability Statement: The datasets generated during and/or analyzed during the current study are partially available in the Supplementary Materials and may be requested from the corresponding author upon reasonable request.

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