Biomass and Bioenergy 91 (2016) 186–195

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Research paper

A novel bioenergy feedstock in Latin America? Cultivation potential of *Acrocomia aculeata* under current and future climate conditions

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A R T I C L E I N F O

Article history:
Received 1 August 2015
Received in revised form
14 April 2016
Accepted 19 April 2016
Available online 25 May 2016

Keywords:
Biofuel
Ecological niche modeling
Macaúba
Macaw palm
Sustainability

A B S T R A C T

Plant oil is a key commodity in the global economy, particularly for food and bioenergy markets. However, current production practices often impair smallholder livelihoods, cause land use changes, and compete for food production. The neotropical palm *Acrocomia aculeata* is currently being promoted as a novel sustainable biomass feedstock, particularly for bioenergy, but only little is known about the palm's ecological requirements. Based on a comprehensive literature and database search for recorded occurrences of *A. aculeata* in Latin America, we computed an ecological niche modeling to determine the palm's potential distribution area based on climatic and soil variables. We subsequently considered current land cover and predicted future climate change scenarios to discuss the cultivation potential of *A. aculeata* within its possible distribution area. The results revealed a large potential to cultivate *A. aculeata* in Latin America under current abiotic environmental conditions. The two core distribution regions identified were (1) Central America including the Caribbean, northern Colombia and Venezuela, and (2) southern Brazil and eastern Paraguay. A considerable proportion of the medium to highly suitable growing areas were found to be currently used for agricultural production or covered by land types with high conservation and carbon sequestration value. Applying the model under the IPCC's A2A 'business as usual' emission scenario suggested that by 2080 the vast majority of suitable growing areas severely decline in extent or disappear entirely. Our ecological niche modeling thus shows that despite the palm's high cultivation potential, a sustainable deployment of *A. aculeata* requires a precautious, evidence-based approach.

1. Introduction

The increasing demand for biomass-based energy and industrial products [1] has translated into a globally expanding agricultural production and a commodification of crop use [2]. At the same time, biomass pathways are increasingly being criticized for their negative environmental impacts such as increased greenhouse gas emissions and the loss of biodiversity caused by direct and indirect land use change of natural or semi-natural ecosystems into cultivable land [3–7]. Likewise, competition for resources, especially for land, may create negative social impacts on local communities, for example in terms of threats to food sovereignty as well as to land tenure [2,8,9]. Such downsides are often associated with the

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http://dx.doi.org/10.1016/j.biombioe.2016.04.009

production of established global commodities such as soy, palm oil and sugar cane. In the case of Latin America, for instance, soybean is typically produced in large and mechanized monocultures [3] that are not amenable to smallholder inclusion and that are known to decrease biodiversity, reduce soil quality and to promote soil erosion [[10] and references therein]. Similarly, soy in Argentina has taken a toll on that country's scant forest areas [11]. Moreover, the large-scale cultivation of the African oil palm (*Elaeis guineensis* Jacq.), which has already displaced large areas of forest in Southeast Asia, also raises concerns about a further loss of Amazonian rainforest [[12,13], but see Ref. [14]]. Oil palm cultivation has also been linked to land grabs in Colombia [15], while sugar cane has been increasingly associated with conflicts related to water access and pollution [16].

The deployment of novel biomass production pathways (particularly for biofuel industries), which were initially promoted as "more sustainable" alternatives have, as of yet, not been successful, as is evident in the case of *Jatropha curcas* L. [17]. Despite *Jatropha*'s promotion as a sustainable feedstock suitable for smallholder production in biodiesel chains, business models have often been built on a limited understanding of the species ecological requirements and productivity under various conditions [18,19] causing significant losses, in particular to vulnerable communities and smallholder farmers [20–22]. Such fallacies of established and novel biomass production pathways highlight the importance of a cautious, comprehensive and locality-specific assessment of species' fundamental ecological and agronomic requirements [7], and, based on this, of socially co-beneficial production models [23]. Efforts to introduce and prompt other alternative crops deemed more environmentally or socially sustainable are comparatively scarce.

The oleaginous macaw palm *Acrocomia aculeata* (Jacq.) Lodd. Ex Mart. (Arecaceae) is currently receiving attention as a novel oil-feedstock crop for its potential role as an environmentally and socially co-beneficial biofuel feedstock in South America [23–25]. It is native to tropical regions of the Americas and has been recorded as far north as Florida and as far south as Paraguay and northern Argentina [26,27]. The largest natural populations are found in Brazil [28]. As a hemerophilous species, *A. aculeata* mostly occurs in pastures, disturbed areas, tilled land and along roads [29]. Much discussed advantages of the palm include a broad product range, which allows for a multipurpose use of high value-added farm products, and the already existing pronounced traditional use by local communities [26,30–32]. The main commodities are the pulp oil produced in the mesocarp and the kernel oil produced in the endosperm. The oil of *A. aculeata* exhibit properties similar to the palm oil from the African oil palm *Elaeis guinennsis*, and may therefore allow similar utilizations for biofuel synthesis, for inputs in cosmetic and food industries as well as for technical applications [33–35]. Furthermore, the press cake (i.e. pulp press cake and kernel press cake) provides high-quality feed additives in animal husbandry [36], whereas the pit (endocarp) has high calorific value and is suitable as fuel or for producing activated charcoal [37–39].

Despite these many uses and its increasing promotion, particularly in Brazil [40,41], there is only scarce information about the ecological requirements of this palm species, its performance under cultivated conditions, and differing cultivation practices as well as the socio-economic benefits *A. aculeata* may provide.

To this extent, the overall objective of this study was to assess the potential distribution area and related cultivation potential of *A. aculeata* in Central and South America in consideration of climate conditions and soil related characteristics within the species' ecological amplitude as well as information on current land cover types. In a second step, we assessed how the suitability of these regions might be influenced by ongoing climate change and whether a novel production system based on *A. aculeata* can be resilient to altering climate conditions. Such long-term predictions are crucial when novel crop production systems focus on perennial species, which require an initial growth phase prior to achieving commercial yields, but subsequently produce plant oil feedstock for several decades.

2. Material and methods

2.1. Species records

Information about the occurrences of *Acrocomia aculeata* was aggregated by locality data from the Global Biodiversity Information Facility [27] and by conducting a systematic literature search. For the GBIF search we applied the key words "*Acrocomia aculeata*" and selected all georeferenced records for further analysis. For the systematic literature search, we used *Google Scholar* as search engine [42,43]. The search was performed in July 2013, using the keywords "*Acrocomia aculeata*" and "*Cocos aculeata*" which represent the accepted scientific name and the basionym of the macaw palm, respectively [44]. All literature published between 1950 and 2013 was manually checked for detected occurrences of *A. aculeata*. After rejecting duplicate records, we finally revealed 271 georeferenced occurrence points (GBIF: 59; herbarium: 35; literature review: 177; see also Appendix, Fig. A.3), which were used for the niche modeling procedure (see description below). Potential autocorrelation of included species localities was assessed based on model residuals (observed occurrences − predicted model suitabilities) [45] using distance class based spatial correlograms (R 'ncf' package v. 1.14).

2.2. Environmental datasets

We applied two predictor sets reflecting bioclimatic and soil properties to model the potential distribution of *A. aculeata.* We concentrated on the potential distribution as indication for where the species is able to occur since the abiotic habitat conditions are modeled as suitable based on included predictors [46]. For climate data we used 19 climate predictors from the Worldclim database (v. 1.3) [47]. The bioclimatic variables result from an interpolation of climate station records from 1950 to 2000 and were originally downscaled to match a spatial resolution of 5 arc-minutes representing approximately a 10 × 10 km grid cell resolution [47]. For soil properties we applied 17 predictors (for details see Appendix) from the Harmonized World Soil Database (HWSD v. 1.2) [48]. The HWSD layers were available at 30 arc-seconds. As these layers were originally obtained from maps with a much broader resolution [48], we rescaled them with ArcGIS (v 10.1) [49] to match the resolution of the applied Worldclim data. The model area extent was restricted to South America as well as Mexico and the contiguous US to capture the majority of environmental conditions prevailing in the native range of *A. aculeata.*

To assess potential distribution changes of *A. aculeata* for near, mid- and long-term perspectives under predicted future climatic conditions, we used available Worldclim data for 2020s, 2050s and 2080s based on the HadCM3 general circulation model [50] in a 10 km grid cell resolution. We focused on the IPCC emission scenario A2A [51] as it represents the 'business as usual' scenario reflecting a continuation of current economic and political assumptions.

2.3. Potential distribution modeling

We applied Maxent (v. 3.3.3k) [52,53] to model the potential distribution of *A. aculeata*. Maxent is an established and effective method to infer a species' potential distribution from presenceonly data [53,54], by calculating the probability distribution of habitat suitability across the study region. These probability values indicate the relative suitability of a given grid cell for the modeled species based on the environmental constrains, which are set by included predictors [55,56]. The model was replicated 100 times using the bootstrap replicate run type. The final average ASCII outputs were used for further analyses. Seventy percent of the data were used for model training and 30% as test data set, both randomly chosen for each model run.

We performed a correlation analysis and consulted jackknife statistics from initial model runs to reduce the overall set of bioclimatic and soil variables towards a parsimonious and non-collinear (Spearman's $r < 0.7$) set of environmental predictors that show high importance in capturing the pattern of included species localities (see Appendix, Table A.1). We set the "fade by clamping" option in Maxent to reduce clamping issues resulting from projection values beyond the range of training data [57] and opted for the logistic output format. The automatic feature selection was applied since it has been validated with respect to a broad range of species, environmental conditions, numbers of occurrences, and degrees of sample selection bias [52]. We applied 'area under the receiver operating curve' (AUC) statistics to evaluate model discrimination capabilities [57].

2.4. Analysis and interpretation

Subsequent data processing and visualization was performed with the software ArcGIS. The continuous ASCII outputs of the Maxent model for current and future climate conditions were cut based on a threshold representing the mean of the two threshold rules that involve sensitivity and specificity such as 'Equal training sensitivity and specificity logistic threshold' and 'Maximum training sensitivity plus specificity logistic threshold' according to Liu et al. [58]. Resulting grid outputs indicate the area that is potentially suitable for *A. aculeata.* The range of included suitability values was further split into three classes with equal class sizes representing low mid and high habitat suitability.

We compared the potential distribution of *A. aculeata* under current climatic conditions as well under climate change assumptions with actual land cover information for the year 2012 to define which land cover types are represented within the corresponding suitability areas. MODIS land cover type data were obtained from NASA's Reverb platform for the year 2012, at a grid cell resolution of 2.5 arc-minutes, and rescaled to match the Maxent model output resolution of 5 arc-minutes. All forest cover types occurring within the determined potential distribution range (i.e. evergreen needle leaf forests, evergreen broad leaf forests, deciduous broad leaf forest, mixed forest) were combined as one single forest cover group (henceforth referred to as 'forests'). We acknowledge that the post-hoc analysis of changes in environmental suitability on top of static land cover types does not take into account potential climate induced land cover changes. We decided to keep the parameter of land cover stable since the uncertainty in model projections of land cover shifts is high due to intermingled human and climatic effects that shape land cover.

3. Results

3.1. Model evaluation

The discrimination performance of the Maxent model revealed an averaged $AUC_{[test\ data]}$ value of 0.914 ($SD = \pm 0.013$). The three predictors that showed the highest relative contribution in capturing the pattern of included training localities were the Bioclim variables 'mean temperature of coldest quarter' (39.3%), 'precipitation of wettest month' (16.5%) and 'annual precipitation' (16.1%) with observed values ranging from 13.3 °C–21.4 °C (mean: 21.4 ± 0.2 °C), 137 mm–736 mm (mean: 269.3 ± 5.51 mm), and 658.0 mm–4261.0 mm (mean: 1586.2 ± 31.7 mm), respectively. For a complete list of predictors used in the final model and their relative contribution see Appendix, Table A.1. An autocorrelation analysis using distance class based correlograms did not reveal any significant local Moran's I values ($p > 0.05$).

3.2. Present suitability

Under present climate conditions, the niche model revealed a total potential distribution area of ~3 680 000 km^2 for *Acrocomia aculeata* in Latin America and the US state of Florida (hereafter included in the term 'Latin America') (Table 1). Two principal distribution areas were distinguished, namely (1) Central America including northern Colombia and Venezuela, and (2) southern Brazil and eastern Paraguay (Fig. 1a). On a country-scale, the largest potential distribution area occurred in Brazil, where 22.6% (~1 920 000 km^2), of the total land area was predicted to provide suitable environmental conditions to *A. aculeata*. Further large and continuous potential distribution areas were found in Mexico (17.7% of the total area, ~350 000 km^2), Venezuela (29.9%, ~270 000 km^2), Bolivia (17.8%. ~ 190 000 km^2) and Colombia (14.4%, ~160 000 km^2). In contrast, several countries such as Argentina and Peru showed only very small potential distribution area per total land size (1.6%, ~40 000 km^2 and 1.7%, 20 000 km^2, respectively). The potential distribution areas for all countries are listed in Table 1. Irrespective of country, the majority of the total potential distribution area belonged to the minor suitability class (60.1%) followed by the medium suitability class (37.1%). The high suitability class accounted for merely 2.8% of the potential distribution area. Considering the individual land cover types, the largest proportion of the total potential distribution area was located within savannas (42.6%, ~1 570 000 km^2) (Table 2), which also exhibited the highest habitat suitability value of all land cover types (Fig. 2).

The second largest potential distribution area was found for the combined forest zone (21.2%, ~780 000 km^2), in which the vegetation was dominated by broadleaf evergreen forest (93% grid cell occurrence, i.e. 1920 out of 2064 cells) followed by deciduous broadleaf forest (3.7%), mixed forest (3.1%), and evergreen needleleaf forest (0.1%). The lowest distribution potential was found in open and closed shrubland zones (in total 0.01%, ~400 km^2). However, differences in the predicted habitat suitability between individual land cover types were generally small with a median value of 0.478 found in grasslands and permanent wetlands compared to a median value of 0.562 in savannas (see also Fig. 2). Note, that divergences in total areas (Tables 1 and 2) result from differences of geometries between the independent MODIS land-cover and Worldclim raster data used to calculate areas.

3.3. Suitability shifts under climate change

The climatic changes under the IPCC's A2A 'business as usual' emission scenarios result in considerable shifts in size and suitability of the potential distribution areas of *A. aculeata* (Fig. 1b, c, d). The majority of suitable regions in Central America, North Colombia, Venezuela, and northeastern Brazil, continuously disappear over time up to the 2080s (Table 1). Similarly, a large area of the potential distribution area in southern Brazil and eastern Paraguay become unsuitable under future A2A projections, although a comparatively small gain in areas for potential future distribution was observed in northeastern Argentina (Table 1, Fig. 1d). In total, 59% (~2 130 000 km^2) of all potential distribution areas were forecasted to be lost as a result of the predicted climate

Table 1
Country-specific potential distribution areas (km^2) for *Acrocomia aculeata* in Latin America and the USA according to suitability classes (low = 0.3–0.5, mid = >0.5–0.7, high = >0.7–0.9) for four predicted time periods (baseline, 2020s, 2050s, 2080s). Countries are presented in descending order according to the size of the total potential distribution area.

County	Country size	Baseline				2020s				2050s				2080s			
		Total	Low	Mid	High	Total	Low	Mid	High	Total	Low	Mid	High	Total	Low	Mid	High
Brazil	8465676	1916616	1059800	794456	62360	1718444	1081980	591055	45409	1202722	883810	295266	23646	671411	540728	125033	5650
Mexico	1956560	350720	231546	109862	9312	53047	29401	21972	1674	218781	149307	56710	12765	144076	103270	35993	4813
Venezuela	909608	271934	185823	75857	10254	120952	103688	17264	0	129532	106618	22496	419	27832	27413	419	0
Bolivia	1086194	192833	148261	44572	0	269527	180696	76380	12451	30029	27832	2197	0	19147	17369	1779	0
Colombia	1135806	163537	115093	43317	5127	10254	9626	523	105	78473	61523	15067	1883	42794	31389	10672	732
Paraguay	398993	141983	83181	58802	0	123777	96469	24588	2720	149307	122103	27204	0	101073	91761	9312	0
Cuba	107956	88622	41329	46979	314	72613	65289	7324	0	40387	36202	4185	0	16532	15695	837	0
Nicaragua	128575	88308	65080	22182	1046	215538	108920	104525	2093	47188	41747	4813	628	25530	25111	419	0
Honduras	111790	88203	48234	38922	1046	0	0	0	0	39445	25111	14020	314	11300	9731	1465	105
Guatemala	109039	79100	35365	39132	4604	155376	92179	62046	1151	53361	37562	12451	3348	31494	21554	8266	1674
Panama	73552	49804	33691	14020	2093	37876	28878	8475	523	45200	29401	15485	314	28983	24379	4604	0
USA	7933526	49595	25739	22496	1360	20717	14125	5964	628	57651	33377	23019	1256	71672	46665	24379	628
Argentina	2781913	44991	36621	8266	105	0	0	0	0	178498	158828	19670	0	235313	194716	40597	0
Ecuador	247284	37039	23751	12660	628	22600	22391	209	0	26262	20403	4918	942	31494	25216	5022	1256
Costa Rica	51473	29924	9521	14125	6278	63720	53466	9207	1046	26576	11719	12346	2511	23437	12556	9417	1465
Dom. Rep.[a]	48320	27099	22705	4394	0	61313	38399	22077	837	5545	4499	1046	0	628	628	0	0
Peru	1292290	22286	22182	105	0	69370	46142	19670	3557	12346	10882	837	628	22286	18310	3348	628
Haiti	26923	19461	10672	8580	209	72718	52838	19880	0	9626	6801	2825	0	2616	2093	523	0
Belize	21662	19357	6696	12033	628	4918	4918	0	0	13497	11928	1569	0	8370	7324	1046	0
El Salvador	20584	16218	8998	7115	105	43840	30238	12346	1256	8580	5964	2511	105	5441	4604	628	209
Guyana	209960	13602	7638	5650	314	27099	9940	13497	3662	21972	18833	3139	0	6278	6278	0	0
Suriname	144592	8894	8894	0	0	19670	16532	3139	0	25007	25007	0	0	28145	27622	523	0
Jamaica	10865	7847	3976	3871	0	16532	10986	5336	209	7324	5232	2093	0	5336	4081	1256	0
Puerto Rico	8803	5859	4918	942	0	18624	14544	4081	0	2720	2720	0	0	628	628	0	0
Bahamas	9506	4394	3034	1360	0	13602	10254	3244	105	3767	3034	732	0	628	628	0	0
Fr. Guiana	83326	2720	2720	0	0	8057	5545	2511	0	10882	10882	0	0	17159	17159	0	0
Trin./Tob.[a]	4755	1360	1256	105	0	3871	2616	1256	0	0	0	0	0	0	0	0	0
Guadeloupe	1522	628	314	314	0	3871	3662	209	0	419	419	0	0	523	523	0	0
St. Lucia	563	419	314	105	0	314	314	0	0	209	209	0	0	0	0	0	0
Martinique	1058	314	314	0	0	0	0	0	0	314	314	0	0	209	209	0	0
Chr.-Nevis[a]	274	209	0	209	0	314	314	0	0	105	0	105	0	0	0	0	0
Barbados	440	105	0	105	0	209	209	0	0	0	0	0	0	0	0	0	0
Vin./Gren.[a]	403	105	105	0	0	105	105	0	0	105	105	0	0	0	0	0	0
Ant./Barb.	461	0	0	0	0	314	209	105	0	0	0	0	0	0	0	0	0
Chile	724407	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dominica	702	0	0	0	0	0	0	0	0	209	209	0	0	209	209	0	0
Grenada	319	0	0	0	0	209	105	105	0	0	0	0	0	0	0	0	0
Tur./Caicos	1686	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Uruguay	178190	0	0	0	0	105	105	0	0	3453	3453	0	0	14648	13916	732	0
Sum		3744084	2247770	1390534	105781	3249495	2135081	1036988	77426	2449493	1856032	544704	48758	1595189	1291762	286268	17159

[a] Dom. Rep. = Dominican Republic, Fr. Guiana = French Guiana, Trin./Tob. = Trinidad and Tobago, Chr.-Nevis = Christopher-Nevis, Vin./Gren. = St. Vincent and the Grenadines, Ant.Barb. = Antigua and Barbuda, Tur./Caicos = Turks and Caico.

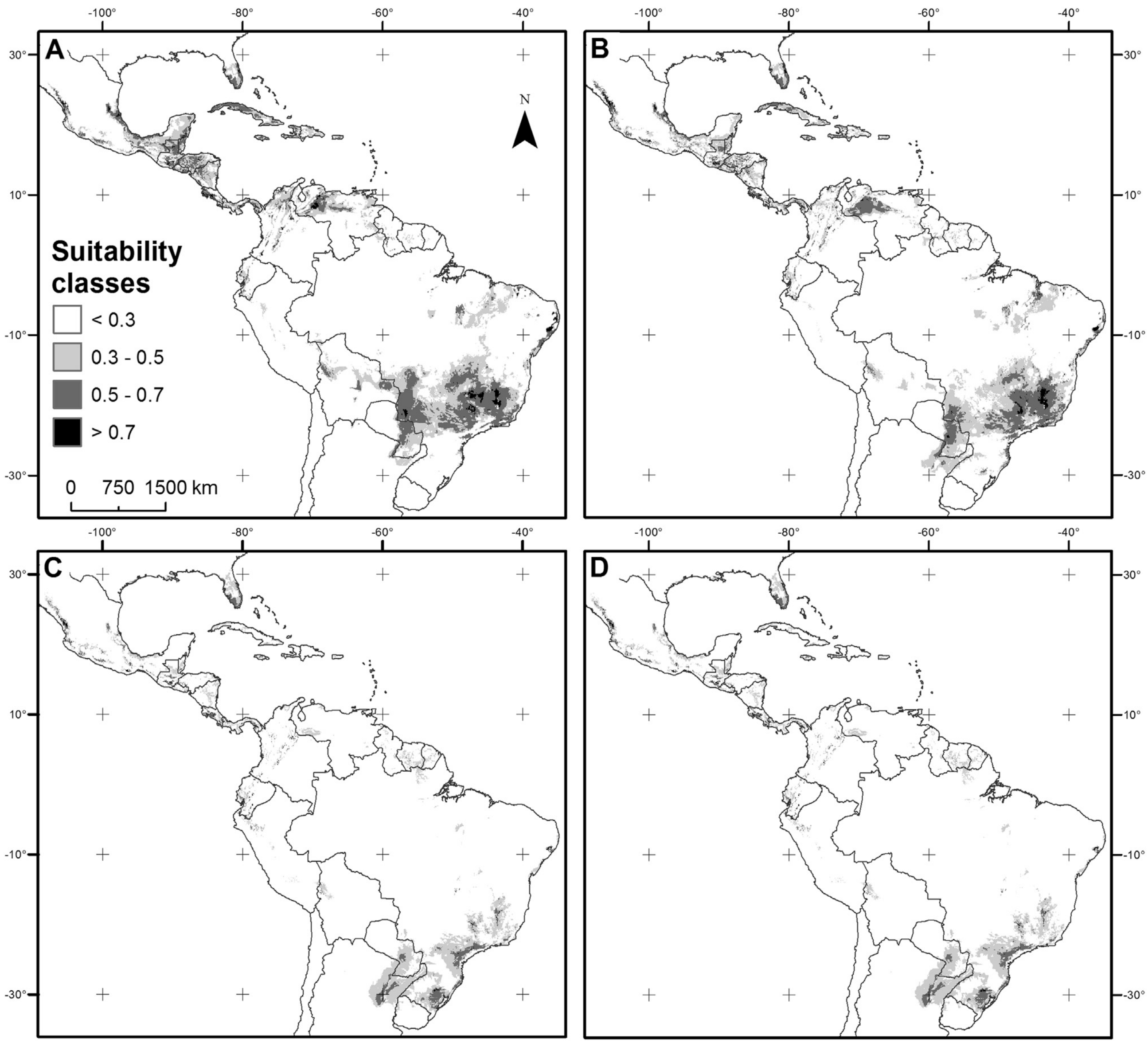

Fig. 1. Potential distribution range of *Acrocomia aculeata* in Latin America. Distribution patterns are visualized for (A) current climate conditions, as well as predicted conditions in (B) 2020s, (C) 2050s, and (D) 2080s. The niche modeling approach for future climatic conditions was based on the assumption of the IPCC A2A emission scenario.

change (Table 1). Within the remaining potential distribution areas, the proportion of minor suitable habitats was predicted to increase compared to present conditions (81.3% compared to 60.1%), whilst medium and highly suitable areas were predicted to decrease from 37.1% to 17.7% and from 2.8% to 1% of the remaining distribution areas by the 2080s, respectively (Table 1). With regards to the countries with the highest current distribution potential, the 2080s scenario predicts a future overall loss of about 65% in Brazil, 58.9% in Mexico, and 89.8% in Venezuela. As a result, the area associated with the high suitability class under present conditions decreased for about 90.9% in Brazil, 48.3% in Mexico, and 100% in Venezuela for the scenario in the 2080s. According to the overall decrease in suitable habitats, the Maxent model predicts declining potential distribution areas over time for each relevant land cover type (Fig. 2, Table 2) with the exception of grasslands (+80 147 km^2) and closed and open shrublands (+313 km^2 and +209 km^2, respectively). Moreover, the potential distribution area in woody savannas and croplands remains stable or shows a trend of increasing area sizes for low and high suitability regions primarily during the 2020s and 2050s before diminishing through to the 2080s (Table 2). In contrast to present conditions, where the largest proportion of the potential distribution area was located within the savanna zone, the predominant areas harboring suitable regions for *A. aculeata* in the 2080s shift toward forests (forests: 27.2%, 421 000 km^2, savanna: 18.7%, 289 198 km^2), at least if not considering open and woody savanna types together (36.5%, 556 110 km^2). The average habitat suitability of all individual land cover types decreases considerably up until the 2080s although the suitability of forests, open and woody savannas as well as permanent wetlands remained stable or showed a slight increase until the 2020s.

4. Discussion

The ecological niche modeling based on 19 climate and 17 soil-related predictors for 271 recorded occurrences of *Acrocomia aculeata*, to the best of our knowledge, represents the first scientifically

Table 2
Area sizes (km^2) for different land cover types split into three suitability classes (low = 0.3–0.5, mid = >0.5–0.7, high = >0.7–0.9) based on four time periods (Baseline, 2020s, 2050s, 2080s). Forests are pooled and consist of evergreen needleleaf, evergreen broadleaf, deciduous broadleaf and mixed forest types. Land cover types without any relevance were neglected (i.e. water, snow, barren land, and deciduous needleleaf forest). C/NV-mosaic = Croplands/Natural vegetation mosaic.

Land cover type	Baseline				2020s				2050s				2080s			
	Low	Mid	High	Sum	Low	Mid	High	Sum	Low	Mid	High	Sum	Low	Mid	High	Sum
Forest	542821	222653	12870	778344	466022	154747	12032	632801	409417	136542	12032	557991	326864	87261	7010	421135
Closed shrubland	105	105	105	315	–	105	105	210	105	105	105	315	523	105	–	628
Open shrubland	–	105	–	105	209	–	–	209	105	–	–	105	209	105	–	314
Woody savanna	217317	154852	16845	389014	207481	139472	22391	369344	234581	98771	19357	352709	197228	63720	5964	266912
Savanna	907875	610098	48339	1566312	815068	464557	28773	1308398	596287	167827	9417	773531	259169	29820	209	289198
Grassland	89249	41120	209	130578	136751	32331	837	169919	162177	13707	314	176198	180173	30552	–	210725
Permanent wetland	50850	31284	313	82447	49281	18415	209	67905	39550	14858	–	54408	29610	16008	–	45618
C/NV mosaic	297149	217526	23437	538112	304578	149621	11090	465289	267853	75438	6696	349987	181010	31494	2616	215120
Cropland	103165	86006	2302	191473	120429	55454	732	176615	111640	21449	–	133089	84855	15171	–	100026
Sum	208531	1363749	104420	3676700	2099819	1014702	76169	3190690	1821715	528697	47921	2398333	1259641	274236	15799	1549676

robust estimation of the potential distribution area of *A. aculeata* within Latin America. The ecological niche model revealed a large potential distribution area for *A. aculeata* in Latin America, indicating a high cultivation potential under current environmental conditions. Further ecological factors such as species interactions (e.g. competition) and human activities (e.g. disturbance) are important determinants of species distribution at a regional scale that may curtail the model-predicted allocation of suitable areas for *A. aculeata*. However, through the identification of 'mean temperature of coldest quarter', 'precipitation of wettest month' and 'annual precipitation' as the three main determinants of the potential distribution of *A. aculeata*, accounting for almost three quarters (72%) of the predictive power, our results provide policy makers and commercial growers alike a clear climatic suitability range for this oil-bearing palm. A crucial proportion of the land that is predicted to be arable for the cultivation of *A. aculeata*, however, has substantial overlap with areas of high conservation value. Moreover, predictions for a 'business as usual' climate change scenario (IPCC A2A) resulted in a substantial reduction of potential cultivation areas, suggesting a probable risk for long-term investments and sustainable deployment of the novel crop.

The largest continuous distribution areas within the examined geographical boundaries of Latin America were found in two regions: in Central America and the Caribbean including northern Colombia and Venezuela; and in eastern Paraguay and southern Brazil. At the same time, our literature review showed that the recognition of *A. aculeata*'s importance as a traditional plant species and, particularly its economic potential as a biomass feedstock for local and international markets strongly diverges between these two regions. For the first region, *A. aculeata* is mentioned only anecdotally in the scientific literature (Costa Rica: [59–61]; Cuba: [62]; Honduras: [63]; Mexico: [64,65]; Nicaragua and Panama: [66]; Venezuela: [67]; see also [68] for Central America in general). Similarly, we are unaware of any significant initiatives by scientists, governments and entrepreneurs for the promotion of *A. aculeata* cultivation and use for this region. In contrast, Paraguay and Brazil are at the forefront of implementing and fostering the development of *A. aculeata* cultivation, value chain deployment, and marketing. In Paraguay, technical processing of *A. aculeata* fruits has already been carried out for several decades [68,69]. In 2011, about 5 Mt of kernel oil were produced and merchandized by ten currently existing local factories based on exctractivism activities [31]. However, during the first Brazilian Macaúba (i.e. *A. aculeata*) congress in November 2013, Paraguayan stakeholders stated that the development potential of this industrial sector is limited mainly by a lack of the adequate knowledge of domestication and cultivation in large-scale plantations. According to our ecological niche modeling Paraguay holds almost 60 000 km^2 of medium to highly suitable land areas for *A. aculeata* cultivation under current climatic conditions, suggesting adequate land resources to provide feedstock for the local plant oil industry.

In contrast to Paraguay, Brazilian federal and state agencies as well as entrepreneurs and large business actors have, in recent years, supported scientific research [32], developed technical innovations and knowledge for domestication [70,71], and are including stakeholders such as farmers and investors (e.g. Embrapa, Acrotech, Petrobras) in the promotion of *A. aculeata* as alternative plant oil crop. These deployment efforts are explicitly linked to, if not driven by Brazil's biofuel policy, more specifically by the National Program for Production and Use of Biodiesel (Programa Nacional de Produção e Uso do Biodiesel, PNPB), which stipulated a seven percent biodiesel blending mandate in the domestic energy matrix as of November 2014 [72] and to likewise foster rural development by including family farmers in the biodiesel chain [73–75].

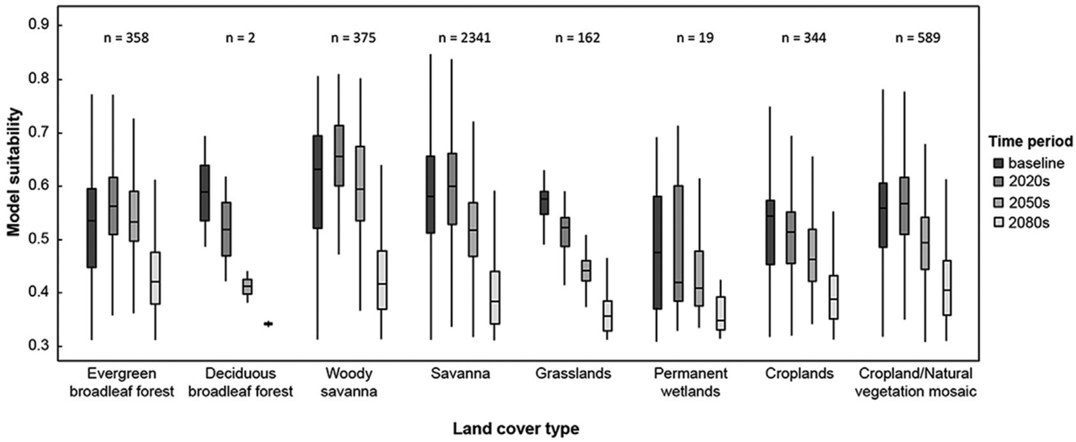

Fig. 2. Predicted habitat suitability of different land cover types for *Acrocomia aculeata* across the study region in Latin America based on current climate conditions and the IPCC A2A emission scenario for the corresponding time periods (2020s, 2050s, and 2080s). Land cover types which had no relevance (i.e. 'water', 'snow', 'barren land', and 'deciduous needleleaf forest') or which showed sample sizes of n ≤ 2 (i.e. 'closed shrublands' and 'open shrublands') were neglected. Box-whisker plots show minimum, first quartile, median, third quartile and maximum. Outliers and extreme values are not shown for clarity.

Different studies estimate that under proper agronomic management a commercial plantation based on 400 palms per hectare may produce between 3.88 and 9.2 t ha^{-1} of oil [e.g. Refs. [32,68,76,77]]. For Brazil, the niche-model based predictions of more than 1.9×10^6 km^2 of ecologically suitable distribution areas would thus project possible regional oil production of about 740–1750 Mt oil per year. In comparison, annual production of Brazil's two most important edible oils soybean and palm in 2015 were 7.7 Mt and 0.34 Mt, respectively [78], which indicates the potential commercial importance of *A. aculeata*.

However, both soybean and palm in Latin America are also associated with direct and indirect land-use change [79–81], in particular deforestation of natural forests such as the Brazilian Amazon [[12,13], but see Refs. [14,82]] or Argentina's scant forest areas [[11], see also [74]]. Deploying a more sustainable pathway of *A. aculeata* feedstock production would need to take a precautious approach in this regard. Interestingly, the potential distribution area of *A. aculeata* identified in this study indicates that almost all suitable regions are located outside of the tropical rainforest regions along the Amazon Basin in Brazil, Bolivia, Colombia and Peru. Thus, *A. aculeata* is a species that has a large cultivation potential in regions where the cultivation of the African oil palm is unsuitable due to the less favorable climatic conditions [83]. This finding is supported by the minimum values of the three main predictors contributing to our ecological niche model for *A. aculeata*, which were found to be considerably lower than the reported suitable values within the native range of *Elaeis guineensis* [84,85], in particular temperature (*A. aculeata*: 13.3 °C, *E. guineensis*: 21–24 °C) and annual precipitation (*A. aculeata*: 658 mm, *E. guineensis*: 1780–2280 mm). Hence, an increased plant oil production through the commercial cultivation of *A. aculeata* might reduce deforestation pressure on remnant natural Amazonian forests. Moreover, recent research on plantation forestry in Latin America emphasized that, compared to exotic species such as *E. guineensis*, planting native trees and palms like *A. aculeata* may show fewer negative effects on local biodiversity and ecosystem processes, fulfill traditional services to local landholders, and require less financial investment by eliminating dependency on external seed sources and foreign technologies [e.g. Refs. [86–88]].

At present, commercially managed *A. aculeata* plantations and the processes to build up structured supply chains are in their early stages [89]. The vast majority of existent *A. aculeata* stands represent natural populations on cultivated land, in particular extensively managed pastures, where the palm grows as hemerophilous species in scattered stands [89]. In the Brazilian savanna region (Cerrado), for instance, more than 500 000 km^2 out of total 2 000 000 km^2 are used for pastures. Hence, there is a promising potential for its cultivation in silvopastoral systems allowing local producers to maintain cattle farming as dominant economic activity in this region [24,90–92] while contributing to livelihoods of rural farmers through a diversification of goods they can provide leading to lower dependence on a single product market [93]. Broad-based evidence, however, whether and how environmental benefits and socio-economic development through *A. aculeata* plantings can be achieved is still lacking, and the cultivation of this undomesticated oil-bearing palm species entails essential environmental, social as well as economic risks. Hence, for commercialization to be successful, more detailed knowledge about the ecophysiological requirements of *A. aculeata*, necessary cultivation practices, and its productivity potential under differing ecological conditions is required. Recent studies in Brazil, for instance, emphasized extensive occurrences of *A. aculeata* on eutrophic soils, characterized by high base saturation [24,31]. These findings are supported by the results found in our ecological niche modeling, where the base saturation as a percentage of cation exchange capacity represented the most important variable of soil related predictors to the model (5.7% out of a total of 10.7% influence from all soil related predictors; see also Appendix, Table A.1). If the extensive occurrence on eutrophic soils thus is simultaneously linked to higher productivity, large-scale cultivation efforts run the risk of competing with food production as viable cultivation might concentrate on fertile arable land suitable for food crop production. Under present conditions, our results indeed imply a possible prospective development regarding the conversion of croplands (including those in natural vegetation mosaics) into *A. aculeata* cultivation as these land cover types currently provide for 22.4% of medium to high suitability areas in Latin America. Beyond, about 60% of the potential distribution area was considered to be of "low suitability", suggesting less favorable growing conditions, lower yields, and lower economic viability. To assure commercially viable production in these regions, developers might be forced to invest more in inputs and/or labor. Therefore, the 'business as usual' climate change scenario applied in this study suggests that large-scale distribution areas, primarily in Central America, will become increasingly unsuitable during the course of the century. Long-term yields of *A. aculeata* are reported to endure for 50–100 years

[94–96]. However, with a changing climate, high yields might not persist in the medium-to long-term.

Moreover, the results of our ecological niche modeling indicate that the development of any *A. aculeata* exploitation requires highly sensitive precaution to avoid possible environmental burdens. A crucial proportion of the land that is predicted to be arable for *A. aculeata* cultivation is situated in areas of high conservation value (Fig. 2), such as wetlands, subtropical forest systems and savannas including the Cerrado [97], a biome already classified as threatened [25,98]. Suitable distribution areas for *A. aculeata* under altered climatic conditions highlight a high risk for dry forest systems. Expansion of large-scale plantations outside currently existing boundaries of agricultural landscapes (i.e. pasture and cropland) may jeopardize ecosystem functioning and related biodiversity in remaining natural and semi-natural ecosystems.

5. Conclusion

In conclusion, our results provide a robust quantification of the potential distribution area of *A. aculeata* in Latin America and revealed a large and spatially explicit potential for the cultivation of *A. aculeata* in this region. Brazil, in accordance with the intensity of current deployment activities, holds the largest potential area. However, caution is required when transferring our findings to a potential commercial application. Local factors, ecological and social considerations need to be adequately assessed if the aim is to produce plant oil in a sustainable manner. Commercially successful cultivation will require further knowledge on the productivity and management practices of *A. aculeata* as well as the incorporation of economic risks of a changing climate into long-term business models. Pilot projects may help to test integrated management strategies that aim to benefit biomass production, conserve ecosystems and improve rural livelihoods. Finally, policy programs that aim at scaling up theoretically “sustainable” *A. aculeata* production should be developed using a precautious, evidence-based approach, and in accordance with sustainable development goals.

Acknowledgements

The development of this article was initiated in discussion with Professor Stefan Schaltegger, whom we thank for his great support. The study was conducted within the EU project Innovation Incubator ‘Platform for sustainable aviation fuels’. We would like to thank the European Regional Development Fund, the Federal State of Lower Saxony and the Leuphana University Innovation-Incubator (CCI No 2007DE161PR001) for funding this research. We thank the editor Ralph Overend and an anonymous referee for useful comments on a previous manuscript version.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2016.04.009.

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