Understanding the present distribution of the parasitic weed *Striga hermonthica* and predicting its potential future geographic distribution in the light of climate change

Die Verbreitung des parasitären Unkrauts Striga hermonthica und Voraussagen zur potentiellen zukünftigen geographischen Verbreitung unter Berücksichtigung des Klimawandels

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Summary

Parasitic weeds of the genus *Striga* (Orobanchaceae) are a major constraint to agricultural production in the semi-arid regions in Sub-Saharan Africa. Therefore, *Striga hermonthica's* current and future distribution needs to be estimated urgently in order to better and more efficiently target available *Striga* management strategies. Using innovative GIS-based modeling complemented by greenhouse and field studies, our research aims to better understand the present geographic distribution of *Striga* species and to predict potential future expansion areas of these dangerous weeds. Parameters determining the presence or absence of *Striga* were analyzed and available data complemented by new studies on *Striga* ecology and seed bank dynamics gained at the University of Hohenheim and ICRISAT, Mali.

In order to provide managers and decision maker with a useful tool to take precautionary and palliative actions against the menace of infestation by invasive or parasitic species, it is important to assess the possible future distribution of such species, especially in vulnerable areas where the parasite has not yet appeared.

Based on the present geographic distribution and the factors affecting it, different climate projections have been applied to indicate areas that will become susceptible to *Striga* invasion in the future. Datasets on the impact of climate change from IPCC workgroups have been used as basis for this assessment, combined with information gained from field trips, herbaria assessments and literature. The results of this study show trends in the potential future distribution of *Striga hermonthica*, but also indicate areas where the methodology can be improved and refined to allow more precise and reliable predictions.

Keywords: Climate change, parasitic weed, potential distribution, *Striga hermonthica*

Zusammenfassung

Mit dem Ziel der besseren und effizienteren Umsetzung von Unkrautbekämpfungsstrategien wurde die potenzielle zukünftige Verbreitung von *Striga hermonthica* analysiert. Parasitische Unkräuter aus der Gattung *Striga* (Orobanchaceae) stellen eine der wichtigsten biologischen Schadfaktoren in den Sahel und Sudan Regionen Afrikas dar, deren zukünftiges Verbreitungsspektrum und Reaktion auf einen möglichen Klimawandel dafür untersucht werden müssen. Um dies darstellen zu können, wurden für diese Arbeit GIS-basierte Modellierungskonzepte mit Daten aus Feld- und Gewächshausstudien hinsichtlich der ökologischen Rahmenbedingungen und Samenbank-dynamiken kombiniert.

Besonders in Regionen, in denen diese parasitäre Pflanze noch nicht aufgetreten ist, ist es wichtig, Werkzeuge für die Entscheidungsträger zu entwickeln, die in der Lage sind, besonders anfällige Gegenden zu erkennen um dort frühzeitig Quarantäne- und Bekämpfungsmaßnahmen umzusetzen. Ausgehend von der momentanen geographischen Verbreitung und den zugrunde liegenden Klimafaktoren haben wir verschiedene Klimaprojektionen benutzt, um solche Gegenden zu identifizieren. IPCC-Datensätze zu möglichen Klimawandelszenarien wurden in die Modellierung integriert und mit Datensätzen von Felderhebungen, Herbarien und Literaturrecherchen kombiniert.

Die Ergebnisse dieser Studie zeigen mögliche zukünftige Verbreitungsgebiete von *Striga hermonthica* und erlauben uns, die zugrunde liegende Methodik weiter auszuweiten und zu verfeinern, um genauere und verlässlichere Vorhersagen treffen zu können.

Stichwörter: Klimawandel, parasitäres Unkraut, potentielle Verbreitung, *Striga hermonthica*

1. Introduction

Parasitic weeds of the genus *Striga* (Orobanchaceae) cause considerable yield losses, especially in the savanna regions of Sub-Saharan Africa (SAUERBORN et al., 2003). The geographic distribution and the infestation level of *Striga* are steadily increasing, particularly in Sub-Saharan Africa (EMECHEBE, 2004; EJETA, 2007). There are different explanations for this trend such as trade and transport of contaminated seeds, cattle movement between fields, dispersal of *Striga* seeds through wind and surface water flows and lack of knowledge and means to control *Striga* (BERNER et al., 1994). The main driving forces for the increase of the *Striga* problem, besides convenient climate, however, are (1) reduced soil fertility (SAUERBORN et al., 2003), (2) increased land use, mostly on depleted soils and (3) expansion of the area cropped with susceptible host crops (GRESSEL et al., 2004). Future climate change may further influence the geographic distribution and invasive potential of *Striga* as habitats suitable for *Striga* growth might expand and/or shift to new areas (MOHAMED et al., 2006).

As *Striga* is a major constraint to agriculture of the semi-arid regions in Sub-Saharan Africa, *Striga´s* current and future distribution needs to be estimated urgently in order to better and more efficiently target available *Striga* management strategies. Using innovative GIS-based modeling complemented by greenhouse and field studies, this project aims to better understand the present geographic distribution of *Striga* species and to predict potential future expansion areas of these dangerous weeds. Parameters determining the presence or absence of *Striga* will be analyzed and available data complemented by new studies on *Striga* ecology and seed bank dynamics gained in green house or field studies at Hohenheim and at the International Center for Research in the Semi-Arid Tropics (ICRISAT), Bamako.

As *Striga* is mainly a problem in Africa, we decided to take two African countries as reference sites. First choice countries are Mali and Ethiopia, because of their wide range of climatic conditions (various precipitation and temperature gradations) and very diverse cropping systems. Based on the present geographic distribution and the factors affecting it, different climate scenarios have been applied to indicate areas that will become susceptible to *Striga* invasion in the future.

Among the recent challenges to ecologists the prediction of occurrence for potentially dangerous species such as pests or parasites has become vital because they represent a threat to health and the access of food for an important number of human populations over the world. This is maybe also manifested in the appearance of multiple species distribution models (SDM) in the last two decades (GUISAN AND THUILLER, 2005). Following that pathway, the aim of this document is to provide an insight into the possible future distribution of the dangerous parasitic plant *Striga hermonthica* for the African continent, under the framework of climate change for different emission scenarios. When modeling the geographical distribution of any species, their basic needs and preferences must be acknowledged *a priori*. This is typically achieved by recording georeferenced data in addition to a set of environmental variables measured *in situ* (PHILIPS et al., 2004). Species distribution models (SDM) are able to calculate the relationship between the documented occurrences of the species of interest in the landscape and the environmental/spatial characteristics at the sites they were found (ELITH et al., 2011). By doing so, we can aim to estimate or predict any species' potential distribution under particular circumstances when the right assumptions are met. In this sense it is important to highlight that this potential distribution alludes to the Hutchinson's fundamental niche in a narrow sense and comprises the suitable conditions for the species survival. Species will be effectively recorded in areas where they were able to remain after colonization; this is regarded as the realized niche of the species (ANDERSON et al., 2003; PEARSON AND DAWSON, 2003; GUISAN AND THUILLER, 2005). Realized niches (realized distributions) can be estimated by removing the areas where the species is known to be absent. This absence is often a representation of other ecological interactions such as competition or impossibility for dispersal, even anthropogenic disturbances (PHILIPS et al., 2004).

2. Materials and methods

2.1 Data availability

For this investigation, presence-only data of *Striga hermonthica* from Africa was used. The sample

consist of a total of 409 georeferenced records (Fig. 1) gathered from different sources: National Herbarium Nederland, Missouri Botanical Garden, Royal Botanic Gardens Kew, Real Jardin Botanico de Madrid, Cameroon National Herbarium, Herbarium togoense at Université de Lomé, Museum national d'histoire naturelle et Reseau des Herbiers de France and Institute of Plant Production and Agroecology in the Tropics and Subtropics at University of Hohenheim. Modeling software such as DIVA-GIS and MaxEnt have proven to be advantageous instruments in this matter (ANDERSON et al., 2003; GANESHIA, 2003; GARZON et al., 2006) and were used to predict the potential distribution of *Striga hermonthica* under different emission scenarios for the year 2020 for the whole African Continent.

Fig. 1   Distribution of *Striga hermonthica* occurrence data in Africa. A total of 408 samples have been considered. Notice the higher data density in West Africa.

Abb. 1   *Verteilung der Präsenzdatensätze von* Striga hermonthica *in Afrika.*

2.2   MaxEnt and climate datasets

When modeling, independent variables are called *covariates*, *predictors* or *inputs*. These include environmental variables like climate or soil as well as categorical variables like ecosystem types. Transformations of the available data are termed *features* and in MaxEnt, five classes are provided: Linear, product, quadratic, hinge and threshold (ELITH et al., 2011; MaxEnt 3.3.3e help). For the explanation on the functioning of MaxEnt, we mainly follow the document by ELITH et al. (2011). The maximum entropy approach for modeling is based on the premise that without the information provided by occurrence data there will be no reason to expect species to prefer any kind of environmental conditions in particular, so the best predictor will be that the species occupied the environment proportional to their availability, that is a uniform distribution (PHILIPS et al., 2004). Being aware of the uncertainties of the future that not even the most carefully thought plan can avoid, the year 2020 was proposed as the target for future distribution modeling of our target species. Datasets for current climate based on long-term observations as well as climate changes scenarios for the IPCC's A2a and B2a scenario have been used for this study (IPCC, 2007).

By predicting the distribution of *Striga* only up to the year 2020 and no further, we hope to minimize the political, social and environmental uncertainties that could otherwise be greater as we try to look further in the future, subtracting importance to the investigation presented here. Environmental covariate data was provided to MaxEnt in form of 19 bio-climatic variables. These bioclim variables are derived from the CLM files used in DIVA-GIS. The CLM files where produced following the procedure described by RAMIREZ and BUENO-CABRERA (2009) and loaded into DIVA-GIS together with a

georeferenced shapefile. Later, the study area of interest - in this case Africa - is selected and the 19 bioclim variables are extracted following SCHELDEMANN and VAN ZONNEVELD (2010). The 19 bioclimatic variables were better related to aspects of plant growth than monthly temperature and precipitation data. There was a suspicion about different subgroups of *Striga hermonthica* across the continent, so the total sample (408 points) was divided into four subgroups, namely North, South, East and West. Models were produced for each subgroup including one for the total sample. All models were run in MaxEnt using the whole African Continent as background data and the projections were also made to the full extent of the continent. It was set into the program's commands that 25 % of the samples units used for the predictions must be retained for a model random test of performance, including *receiver operating curve (ROC)* and *area under curve (AUC)* to measure the importance of each covariate in the final model. All other settings were left as default but a 10 percentile training presence was selected as the threshold rule.

3. Results

3.1 Modelling performance

The software MaxEnt also provided results for some statistical test conducted on to the data we provided in order to produce the prediction maps. The aim of these tests was to show the potential of our predictions and also by which factors they were most affected. The receiver operation curve (ROC) is a graphical representation of how well our model fitted the data (PHILLIPS, 2009); it is represented in the MaxEnt output by a light grey line (Fig. 2). Considering that we set aside 25 % of our samples to use by the model as a random test, so the dark grey line indicated the fit of the model to this test data. The black line symbolized the predicted omission which shows how a model that is no better than random would fit our data. The more the breaking point of the training and test curves approaches the upper left corner of the graphic, the better our model performs to predict the presences contained in both training and test data. In case one of the training or test lines would have been placed below the black line - which is not the case - the estimated model would have resulted worse than a random distribution model.
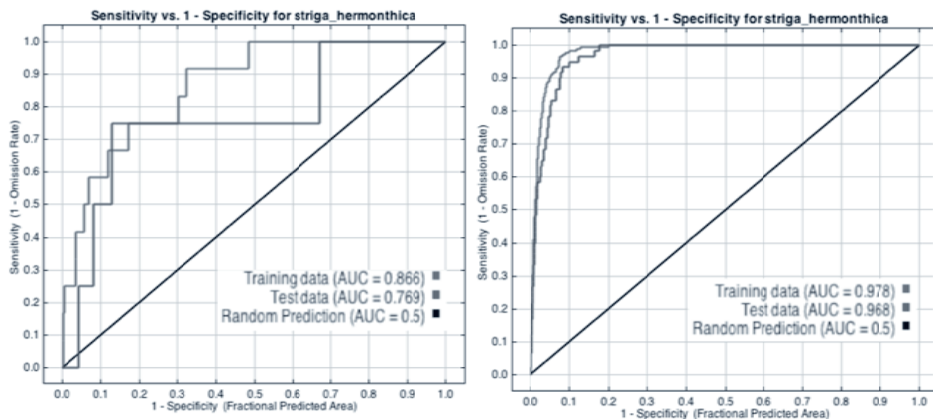

Fig. 2   Receiver operation curve (ROC) for training and test data, also showing the area under curve (AUC). The left graphic corresponds to the model estimated using the east subgroup sample. The right graphic corresponds to the west subgroup sample.

Abb. 2   *Receiver operation curve (ROC) als graphische Darstellung der Modellierungsgenauigkeit.*

The area under the curve (AUC) is a measure of the models performance independently of any threshold applied (PHILLIPS et al., 2006); for this investigation the training data AUC was 0.969 while in case of the test data, 0.954. For the training data, this implies that for 97 % of the time, a random selection from that data would have shown a better performance than the random model (FIELDING and BELL, 1997). Along with the percentage of contribution to the model a score (percentage) on

permutation importance was provided. The permutation importance depends only on the final model, regardless of the path followed to arrive at the solution. The value of each covariate was randomly permuted among training points, the score depended on the decrease of the AUC as a result of the permutation and a large decrease can be interpreted as the model strongly relied on the permuted variable (PHILLIPS, 2009). In the model produced using all the 408 samples, the most important covariates were precipitation of warmest quarter (29.3 %) and temperature seasonality (14.6 %). When analyzing the east cluster alone, the main influencing factors changed: Temperature seasonality (48.4 %), isothermality (21.8 %) and precipitation of the warmest quarter (20.4 %).

3.2   Potential Distribution of *Striga hermonthica*

For the first set of predictions for the potential distribution of *Striga hermonthica* the four subgroups (North, South, East and West) and the total sample were modeled using the 19 Bioclim covariates for the current conditions (1950 - 2000). Comparing the output of the model runs for each subgroup and the one made using the total of samples, differences in the prediction of the potential distribution of *Striga* was observed. This could lead us to interpret each subgroup of samples effectively as subgroups for the species. But a closer analysis did tell a different story. If focusing, for instance, on the potential distribution obtained from the total sample (408 points) shown in Figure 1, the output showed that the species was strongly present on Western Sub-Saharan Africa if that result was compared to our sample distribution map in Figure 1. It was possible to relate that strong western presence to a much higher sampling intensity in that region, the implication of the sampling design implemented and its consequences in the final predictions will be discussed later.
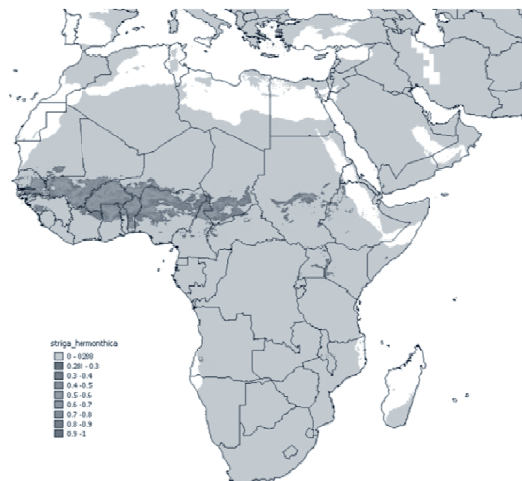

Fig. 3   Predicted potential distribution of *Striga hermonthica* in Africa under current climate conditions. Values given in the legend indicate probability of suitable climate conditions.

Abb. 3   *Prognose der potentiellen Verbreitung von Striga hermonthica unter Berücksichtigung der derzeitigen Klimaverhältnisse.*

3.3   Potential future distribution under climate change

We used the variables for most important climatic factors not only for the prediction of the current distribution of *Striga hermonthica*, but also, by exchanging the climate data layer with the layers for A2A and B2A emission scenarios, for the prediction of the potential distribution under climate change. The resulting maps can be seen in Figure 4.
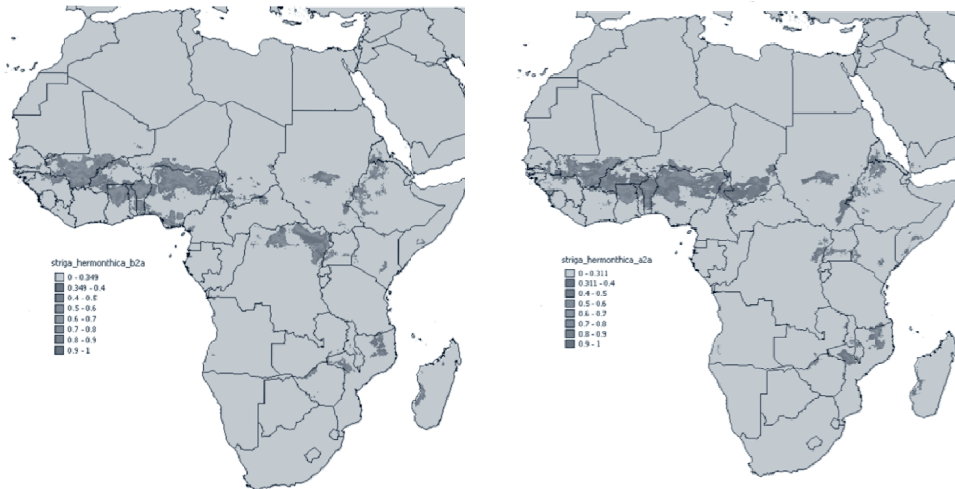
Fig. 4   Potential distribution of *Striga hermonthica* in 2020 under climate change scenarios. On the left, the potential distribution in the B2A climatic scenario and on the right for the A2A scenario. Values given in the legend indicate probability of suitable climate conditions.

Abb. 4   *Prognose der potentiellen Verbreitung von Striga hermonthica unter Klimawandelszenarien.*

4.   Discussion

4.1   Model performance

It was mentioned before during the analysis of the subgroups of *Striga hermonthica* how sampling affected the produced model. It was clear, looking at the subgroup and total models the impact of sampling effort, which in this case represented a bias. There is a strong west-cluster imprint in the potential distribution of the total sample thus both models looked and performed similarly. The background data (environmental inputs) of choice for the purpose of modeling also had an impact on the final model as demonstrated by the first study case included in the document prepared by ELITH et al. (2011). In our particular situation, the background elected was the whole African continent so the model had to extrapolate the training data to an "unknown" environmental space. A way out this problem was to restrict the prediction to areas where the species absence is known, that means to just use areas where the species is known to occur as background data, and to project the prediction to the entire continent.

Models must not only be statistically robust but also make sense ecologically. It wis recommended here to implement a suitable sampling method to improve the distribution patterns of data used as input for the modeling process. This method should not lead to classify different subgroups according to sampling effort, but to ecological implication. Also a better selection of the background data should be made. A suggestion is to select "clusters of background data" surrounding patches of samples and create a stack with them. The estimation based on the stack should be projected into the landscape of interest for current and future climate conditions.

4.2   Potential distribution and climate change

With the modeling method presented here, we can clearly see differences in the potential distribution of *Striga hermonthica* between the datasets for current climate and the two climate change scenarios. Mostly due to an increase in temperature and changing precipitation patterns within the Sudan region of Sub-Saharan Africa, the suitability of these areas for *Striga* is reduced in the climate change scenarios (e.g. Burkina Faso), with the distribution range moving further into Central Africa. Interestingly, the more extreme emission scenario A2a seems to reduce the expected range of *Striga*. The cause is most likely the more extreme impact on temperatures that are predicted

for A2a scenario. This means that not only *Striga* is less likely to be found in these places, but also its host crops will face more adverse growing conditions.

Assessments of the potential future distribution of weeds such as presented in this article can be used to improve crop and soil management systems in areas that could become susceptible to *Striga* infestation. The methods developed here can help to establish medium-term management strategies for extension work in future hotspots and raise awareness of potential threads to food security in Sub-Saharan Africa.

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