

Ecological and human impacts on stand density and distribution of tamarind (*Tamarindus indica* L.) in Senegal

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Abstract

Indigenous fruit tree species such as tamarind (*Tamarindus indica* L.) in African sub-Saharan traditionally act to build resilience into the farming system in terms of food security, income generation and ecosystem stability. Therefore, increasing our knowledge on their ecology and distribution is a priority. Tamarind is mainly grown for the fruits but is also a valuable timber species. The fruit pulp has a high content of vitamin B and is eaten fresh or made into jam, chutney, juice or sweets. Flowers, leaves and seeds are also edible and used in a variety of dishes. The main objective of this study is to evaluate actual density of tamarind in Senegal and the climate change effects on its distribution for better conservation strategies. Tamarind's distribution and density around villages were recorded and modelled in different agro-ecological zones in Senegal using transect method and under current and future climates. Distribution under two future climate scenarios were modelled using four climate models and three time slices (2020, 2050 and 2080). Results show a decreasing gradient in tree density (from 7 to 1 trees km⁻²) from the Sudano agro-ecological zone (in the south) to the Sahel (in the north). Future climate predictions show that although tamarind distribution will increase in the north-west and south of the country in 2020; by 2050, the area identified as suitable for its growth will be greatly reduced. Areas in the north-west basin appear to be an important refugia for the species under future climate conditions. However, density around villages in this area was found to be relatively low indicating that this could lead to problems of poor connectivity and inbreeding depression. This region should therefore be highlighted as important conservative

management and protection strategies of tamarind in this region.

Key words: Sahel, modelling, ecology, MAXENT Senegal, climate change

Résumé

En Afrique subsaharienne, les espèces d'arbres fruitiers indigènes tels que le tamarinier (*Tamarindus indica* L.) servent traditionnellement à constituer un effet de résilience dans le système de production agricole en termes de sécurité alimentaire, de source de revenus et de stabilité de l'écosystème. C'est pourquoi il est indispensable d'améliorer nos connaissances de leur écologie et de leur distribution. Les tamariniers sont principalement cultivés pour leurs fruits mais leur bois est aussi de grande valeur. La pulpe des fruits contient une quantité élevée de vitamine B et on la consomme fraîche ou en confiture, en chutney, en jus et en friandises. Les fleurs, les feuilles et les graines sont aussi comestibles et entrent dans la composition de nombreux plats. L'objectif principal de cette étude est d'évaluer la densité actuelle de tamariniers au Sénégal et les effets des changements climatiques sur leur distribution pour trouver de meilleures stratégies de conservation. La distribution et la densité des tamariniers autour des villages ont été rapportées et modélisées dans différentes zones agro-écologiques du Sénégal en recourant à la méthode des transects, avec des données de climat actuel et futur. On a modélisé la distribution selon deux scénarios de climat futur en utilisant quatre modèles de données climatiques et trois échéances chronologiques (2020, 2050 et 2080). Les résultats montrent un gradient décroissant de la densité des arbres (de 7 à 1 arbre/km²) de la zone agro-écologique soudanienne (au sud) au Sahel (au nord). Les prédictions climatiques pour

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l'avenir montrent que même si la distribution des tamariniers va s'augmenter dans le nord-ouest et le sud du pays en 2020, la surface identifiée comme propice à sa croissance aura fortement diminué en 2050. Des zones du bassin du nord-ouest semblent être un important refuge pour l'espèce dans les conditions climatiques qui prévaudront dans le futur. Cependant, on a trouvé que la densité autour des villages de cette région était relativement faible, ce qui indique qu'elle pourrait entraîner des problèmes de faible connectivité et une dépression due à l'effet inbreeding. Il faudrait donc souligner que cette région est importante pour des stratégies de gestion et de protection conservatoires du tamarinier.

Introduction

Intensification of agriculture and decreasing yearly rainfall figures has led to changes in ecological conditions in West Africa (Wittig *et al.*, 2007). Crop models suggest that climate change will cause production levels of groundnut, wheat and yams in the region to fall by an estimated 3–8% (median values) by 2030 (Lobell *et al.*, 2008). There is also increasing concern regarding the effect of climate and land-use changes on parkland tree (*Tamarindus indica*, *Adansonia digitata* and *Ziziphus mauritiana*) species behaviour (Maranz, 2009). Parklands are defined as landscapes in which mature trees occur scattered in cultivated or recently fallowed fields (Boffa, 1999). These Agroforestry parklands play an important role as agricultural systems in West Africa (Boffa, 1999). Tree species in these systems such as *T. indica*, *A. digitata*, *Z. mauritiana*, *Vitellaria paradoxa* are important to the livelihoods of rural communities (Dawson *et al.*, 2009) and play a significant role in maintaining ecological sustainability (Boffa, 1999). Through their ability to build resilience into the system, provide ecosystem services and their tolerance for extreme environmental conditions, they are likely to become increasingly important (Bowe, 2007; Dawson *et al.*, 2011) under increasing temperatures (Boko *et al.*, 2007; Christensen *et al.*, 2007) and changing precipitation (Christensen *et al.*, 2007; Meehl *et al.*, 2007) predicted by climate change models for the region. *T. indica* L. (tamarind) is a semi-evergreen multipurpose tree species of the *Fabaceae* family found widely distributed across the sub- and semi-arid tropics (El-Siddig *et al.*, 2006; Bowe & Haq, 2010). Detailed studies show

that *T. indica* appears to be at least preferentially out crossing. Flowers are hermaphroditic, but the spatial arrangement of anthers and stigma may tend to limit self-pollination (Diallo *et al.*, 2008). The tree is of nutritional and economic importance, the fruit pulp being high in vitamin B content and eaten fresh or processed into jam, chutney, juice or sweets. Flowers, leaves and seeds are edible and used in a variety of dishes. Studies on the species in Asia, Africa and Latin America have documented its domestication potential in terms of sociocultural and nutritional values, and aptitude for seeds and vegetative propagation (El-Siddig *et al.*, 2006; De Caluwe *et al.*, 2009).

Although thought to originate in Africa, here it is not widely cultivated in the continent (Buchmann *et al.*, 2009; De Caluwe *et al.*, 2009); rather, it is collected from the wild from incipient or semi-domesticated populations around farms protected by farmers or from natural stands. Although predominately wild harvested tamarind has been shown to have great nutritional medicinal and cultural importance for rural communities in Africa (Nakicenovic *et al.*, 2000; Havinga *et al.*, 2010) and who have identified it as one of the key species to be domesticated (Kalinganire *et al.*, 2000). It enjoys some legislative protection in some countries; tamarind belongs to the group of species which are partially protected by the forest code in Senegal (Law nr 98/03 of 08 January 1998) (MINEP, 2002; Ndiaye, Wade & Coulibaly, 2002; Sarr, Diagne & Dancette, 2005). Studies on the species' native populations in Africa have provided data on biochemical analysis of its fruits.

In spite of its importance, the ecological status and appropriate conservation management of *T. indica* in Africa still remain poorly understood. Furthermore, as highlighted by Fandohan *et al.* (2010) in efforts to enhance the species' utilization, the domestication processes may drive genetic erosion in the absence of an effective conservation strategy that ensures the perpetuation of wild relatives. A number of recent studies have begun to attempt to investigate the species' ecological status to develop an appropriate conservation strategy. Tamarind's global distribution has given strong evidence of its broad ecological niche across the tropics (Bowe, 2007; Bowe & Haq, 2010). Diallo (2001) identified high intrapopulation diversity in Africa, indicating no immediate risk of genetic erosion so long as ecological conditions continue to permit regeneration (Kalinganire *et al.*, 2000). However, recent studies have highlighted poor

recruitment (Nyadoi *et al.*, 2009; Fandohan *et al.*, 2010) and low densities (particularly in populations close to farmland). This combined with recorded high levels of local use, and demand for tamarind fruits and leaves (Nyadoi *et al.*, 2009) may mean populations are vulnerable especially under threat in the habitats of higher human pressure and drought stress.

Dawson *et al.* (2009) highlighted the effect of stand density on genetic connectivity for tropical tree species, and its effect on their ability to adapt to climate change. Unlike most agricultural crops, Parkland tree species such as tamarind have not undergone the long processes of local and/or commercial breeding to select out deleterious recessive alleles from populations, which are out-crossing 'incipient' or 'semi-' domesticates (Dawson *et al.*, 2009). Recent inventories have shown that many tree species have extremely low densities in tropical farms, to a greater extent than observed for natural stands of the same taxa (Nyadoi *et al.*, 2009). Low density can lead to poor connectivity and inbreeding depression, leading to the reduction in productivity and ability to adapt to changing environments. There are also concerns that on-farm populations of these species often suffer from the effects of isolation and genetic bottlenecks and are therefore vulnerable to inbreeding depression or genetic dilution from local stands (Dawson *et al.*, 2009).

Species distribution models (SDMs) are common tools that combine species distribution data and climate data sets to predict potential distribution. Such techniques have been successfully used to assess the potential impact of climate change, on species range conservation and reserve planning, invasive-species management and production yield estimates (Elith *et al.*, 2006; Hijmans & Graham, 2006; Phillips, Anderson & Schapire, 2006; Beaumont, Lesly & Pitman, 2008; Trabucco *et al.*, 2010).

In this study, SDM are combined with density data to investigate the links between current/future distribution and density of tamarind in the West African. We hypothesize that as temperature rise and precipitation changes owing to climate changes areas in Senegal may become less suitable for tamarind, species density will be an important factor in the species ability to adapt. Therefore, relating species density to future distributions will be an important factor in identifying areas for conservation and domestication management strategies.

Methodology

Data sources

Data sampling of presence and density data. Tamarind's occurrence and density (number of trees per kilometre square) around villages were measured across Senegal. Senegal has three major agro-ecological zones as follows: (i) the Sudan zone in the south, (ii) the Sudano-Sahel zone in the centre and (iii) the Sahel zone in the north (Sarr, Diagne & Dancette, 2005; Grouzis & Akpo, 2006) (Fig. 1). In these three zones, semi-structured investigation based on National Forestry Ministry information/data was conducted to identify tamarind occurrence sites. The survey consisted of field visits where tamarind presence was recorded. Presence data were also obtained from park managers and foresters from National Centre for Forestry Research, Wulaa Nafa project and the IFAN (African Black Fundamental Institute) database (Fig. 1). Thirty sites (villages) in which tamarind had been identified as present were selected for density analysis based on the accessibility of the area within the three agro-ecological zones (Fig. 1). The number of trees per kilometre square was recorded using a transect method (Fig. 2) (Assogbadjo, Sinsin & Van Damme, 2005). The centre of the village was used as starting point of each transect. Transects crossing the central point, 6 km length and a width of 0.5 km, were conducted north to south and east to west.

Current and future climate data sets. Nineteen Bioclim current climate data (2.5 × 2.5 min resolution) from the WorldClim database (Hijmans *et al.*, 2005) were clipped in DIVA-GIS using the Senegal (map) Adm0 data set (GDAM, 2009). These variables are considered to have ecological influence on the distribution of plant species and summarize mean annual and seasonal conditions, extreme values and intra-year variation (Busby, 1991). The future climate bioclim data sets for SRES emission scenarios A2a and B2a (Table 1), models CCCMA-CGCM2, CSIRO-MK2, NIES99 and UKMO-HADCM3 (Table 2) and for the time slices 2020, 2050 and 2080 (Ramirez & Jarvis, 2010) were also clipped to the Senegal extent. Scenario A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change (Boko *et al.*, 2007). B2 future climate scenario describes a world with intermediate population and economic growth, with an

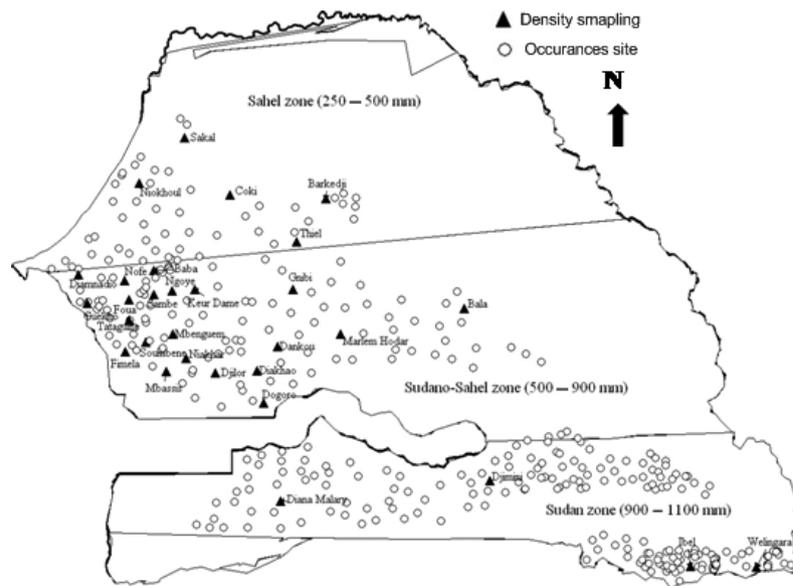


Fig 1 Distribution map of tamarind occurrence locations and locations for density analysis

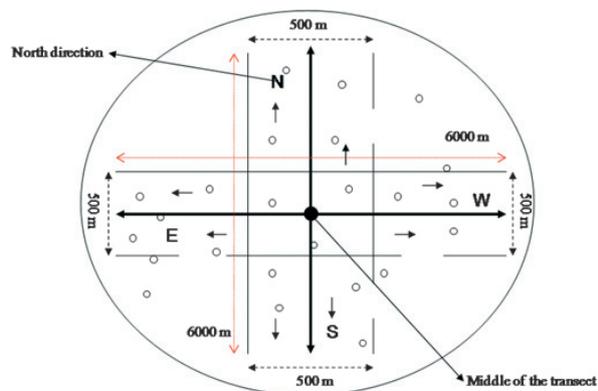


Fig 2 Schematic description of the transect method following Assogbadjo, Sinsin & Van Damme, 2005

emphasis on local solutions to economic, social and environmental sustainability. No likelihood of occurrence was attached to any of the SRES scenarios (Boko *et al.*, 2007); therefore, we assume equal likelihood of occurrence of each scenario.

Species distribution modelling. Tamarind occurrence data collected in the field and the current climate data as described above were used to model tamarind potential distribution in MAXENT 3.3.2 (Phillips, Anderson & Schapire, 2006). MAXENT (Phillips, Dudik & Schapire,

2004) is a general-purpose machine learning method which uses the principle of maximum entropy with a simple and precise mathematical formulation which has been applied successfully to species distribution modelling (Elith *et al.*, 2006; Phillips, Anderson & Schapire, 2006). MAXENT relates specimen locations and environmental geodata sets to derive the response of species probability of occurrence to environmental gradients. These environmental responses are then applied to the same geodata sets to reconstruct the geographical distribution of species probability of occurrence (Trabucco *et al.*, 2010). MAXENT has been shown to perform well when compared to other species distribution models (Elith *et al.*, 2006).

Presence points were contrasted against a randomly drawn sample of background pixels (Phillips, Anderson & Schapire, 2006; Phillips & Dudik, 2008). MAXENT relates individual specimen locations to current environmental geodata sets to derive the probability of species occurrence as guided by environmental gradients. This was then projected on to the current and future climate data sets to produce current and future maps of probability of species occurrence. Various future emission scenarios and models (described earlier) were used to account for the uncertainty in future climate predictions. Default model parameters were selected in MAXENT as suggested by the model's authors (Phillips & Dudik, 2008).

Table 1 Characteristics of the two emission scenario storylines for 2100 developed by the Special Report on Emissions Scenarios (Nakicenovic *et al.*, 2000) – derived from Beaumont, Lesly & Pitman (2008)

Scenario	Population	Economic growth	Primary energy use	Hydrocarbon resource use	Land-use change
A2	~15 billion	Medium	High	Oil: very low to medium Gas: low to high Coal: medium to very high	Medium
B2	~10 billion	Medium	Medium	Oil: low to medium Gas: low to medium Coal: low to very high	Medium

Table 2 Climate model descriptions

Model	Source	Description	References
CCCMA-CGCM2	Canadian Centre for Climate Modelling and Analysis	The second generation coupled global climate model.	Flato and Boer, (2001)
CSIRO-MK2	Australian Commonwealth Scientific and Research Organization	CSIRO Atmospheric Research Mark 2b climate model	Hirst <i>et al.</i> (1996, 1999)
NIES99	National Institute for Environmental Studies, Japan	NIES Coupled Global climate model	Emori <i>et al.</i> (1999)
UKMO-HADCM3	Hadley Centre for Climate Prediction and Research, United Kingdom and the Met Office, U.K.	Hadley Centre Coupled Global Climate model	Gordon <i>et al.</i> (2000), Pope <i>et al.</i> (2000)

Model validation. Model performance was determined by assigning a subset of presence records for training and using the remaining records to test the resulting model. Eighty per cent of the data was used to train the model and twenty per cent to test. A model with good predictive power should correctly predict the presence of the species in all test locations (Phillips, Andersonb & Schapire, 2006).

MAXENT produces a probability value of occurrence score, and a threshold must be selected to define whether an area is predicted to be present/absent and unsuitable/suitable. The area under the Receiver Operating Characteristic (ROC) score serves as threshold-independent measure of model performance in terms of sensitivity and specificity (Phillips, Andersonb & Schapire, 2006). Sensitivity (true positive fraction) for a particular threshold is the fraction of all presence records correctly classified as present (the probability a known presence being predicted as present by the model). The specificity (true negative fraction) for a particular location is the fraction of all absences that are classified as not present/absent (the probability of a known absence will be predicted as absent by the model). When a low probability of occur-

rence value threshold is selected to define presence, then both true positive fraction and sensitivity will increase; however, the true negative fraction and specificity will decrease. When a high probability of occurrence value threshold is selected, the opposite will be true.

In a Receiver Operating Characteristic/Area Under the Curve (ROC/AUC) curve true positive rates (sensitivity) are plotted as a function of false-positive rates (1-Specificity) for different cut-off points. Each point on the ROC plot represents a sensitivity/specificity pair corresponding to a particular decision threshold. As MAXENT only uses presence data and no absence data, 'the fractional predicted area' (the fraction of the total study area predicted as present) is used instead of the more standard fraction of absences predicted present (Phillips, Andersonb & Schapire, 2006). A perfect test discrimination has a ROC plot that passes through the upper left corner (100% sensitivity, 100% specificity). Therefore, the closer the ROC plot is to the upper left corner, the higher the overall accuracy of the test and the larger the area under the curve (AUC) value (Zweig & Campbell, 1993).

AUC values typically range between 0.5 (random) and 1.0. An AUC of 0.5 would show that the model is no

better than random. Values lower than 0.5 indicate that the model performs worse than a random model would. The closer the AUC value is to 1, the better the model's performance (Phillips, Anderson & Schapire, 2006). MAXENT provides an AUC score for both the test and training data.

Suitability thresholds. All probability values of the occurrence maps were reclassified into Boolean suitability maps (not suitable = 0; suitable = 1) using the 'equal training sensitivity and specificity' threshold obtained from the MAXENT model to identify areas predicted as suitable or unsuitable for tamarind (Liu *et al.*, 2005). This is the point on the ROC plot where sensitivity and specificity are equal, hence maximizing both true positives and true negatives. As neither sensitivity nor specificity was considered to be more important for this process, this was selected as the most robust threshold. To account for the variation in predictions owing to the uncertainty in climate models (Beaumont, Lesly & Pitman, 2008), the threshold maps were combined to identify areas where one model, two models or three models, etc., predicted tamarind as suitable or unsuitable for each scenario. The resulting map was overlaid with the current threshold suitability map to identify the changes between current area predicted as suitable and future areas predicted suitable.

Environment variable contribution. A number of methods were used to identify which environmental variables are most important in predicting tamarind distribution in Senegal. The per cent contribution method keeps track of which environmental variables are contributing most to fitting the model when it is being trained (Osborne & Leitao, 2009). This is measured through a MAXENT measure known as 'gain' (Osborne & Leitao, 2009). Each step in the MAXENT algorithm increases the gain of the model by modifying the coefficient for a single feature; the program assigns the increase in gain to the environmental variable(s). These are then converted to percentages and used as a measure of contribution to prediction process (Phillips, Anderson & Schapire, 2006). These per cent contribution values, however, are heuristically defined: they depend on the particular path that the MAXENT code uses to get to the optimal solution; a different algorithm could get to the same solution via a different path, resulting in different per cent contribution values. In addition, when they are highly correlated as in the case of the bioclim

environmental variables, the per cent contributions should be interpreted with caution.

Another method used is a jackknife test in which a number of models are created. With each step in the procedure, a variable is excluded and a model created with the remaining variables (Phillips, Anderson & Schapire, 2006). Alternatively, the model is also created with the variable in isolation. For each model, the gain when using the training and test data and the AUC for the training data are recorded. Variables which are important to the model show a high gain when modelled individually and a decrease in gain and AUC when removed from the model. Owing to the heuristic nature of the per cent contribution values and the high correlation between bioclim variables, only those that show significant contribution in terms of all assessment methods (per cent contribution, training gain, test gain and AUC) were considered to have made a strong contribution to the model.

Response variables. Environmental variable response curves were created by MAXENT. The response curves show how the predictions depend on the variables, which greatly facilitates the interpretation of a species ecological niche and its defining or limiting environmental factors (Buermann *et al.*, 2008; Yost *et al.*, 2008).

Analysis of density data

An ANOVA was run to identify whether there were any significant differences in density between agro-ecological zones. Spearman's rank correlation was used to assess the relationship between tree density and distance from villages for all villages in Senegal and for all sites in each agro-ecological zone.

Results

Current distribution maps

Tamarind was found to occur in the central, south (humid area) and coastal zones of Senegal. However, the species was not observed in the north and north-east of the country (Fig. 1).

Density analysis

A significant difference in density was found to occur between all agro-ecological zones (Fig. 3). Density was

found to decrease from south to north. Spearman's rank correlation ($\rho = -0.94$, $P < 0.05$) showed the number of trees sampled within each distance class to decrease with increasing distance to villages (Fig. 4). A similar relationship was found between density and distance to village when the Sudan ($\rho = -0.92$, $P < 0.05$) and the Sudano-Sahel ($\rho = -0.94$, $P < 0.05$) zones were analysed separately. The correlation between number of trees and distance from village for the Sahel zone showed a decrease with distance but was not statistically significant.

Species distribution model

Environmental factor contribution to predicted tamarind distribution. The variables identified as most important to explain tamarind distribution were temperature seasonality, annual range in temperatures – standard deviation of average monthly temperatures, maximum temperature of the warmest month, precipitation of the wettest month and precipitation of the wettest quarter.

Tamarind is shown to be restricted in terms of temperature seasonality of between 150 and 250, preferring areas with low seasonal temperature variations (Fig. 5a). Probability of tamarind occurrence is also seen to decrease in areas with high maximum temperature, suitability decreasing above 30°C and declining steeply after 40°C (Fig. 5b). High precipitation during the wettest part of the year in terms of both brief extremes and longer periods of rainfall appears to reduce suitability (Fig. 5c, d). Probability of occurrence was shown to increase with increasing precipitation up to 900 mm in the wettest quarter of the year; above this, the suitability decreases.

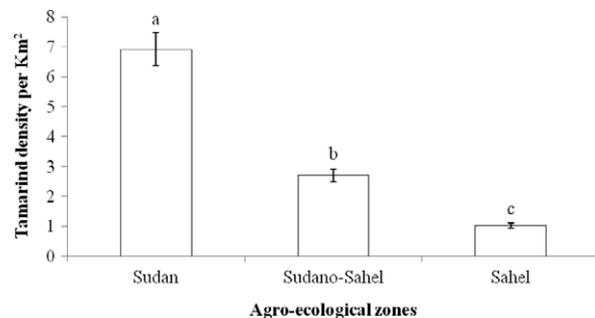


Fig 3 Variation in tree density in different agro-ecological zones (showing standard error)

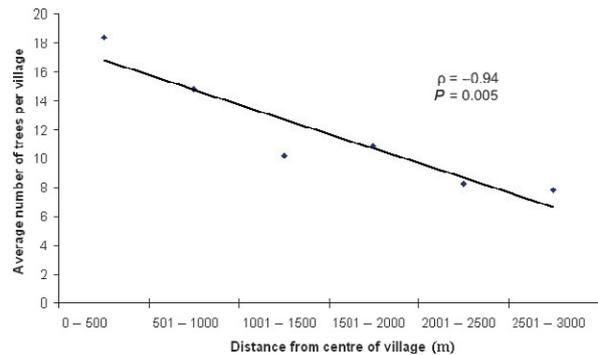


Fig 4 Relationship defined by Spearman's rank correlation between average number of trees and distance to village for all 30 villages sampled in the study

Current predicted distribution (relate to agro-ecological zones). The predicted distribution under the current climate shows that the most suitable areas for tamarind are in three regions in the groundnut basin (Thiès, Fatick and Kaolack regions) situated in the middle of the country and in the south-east (Kedougou) (Fig. 6a). When the threshold is applied (Fig. 6b), it can be seen that the most suitable areas are the groundnut basin in the middle of the country and the southern area (Kedougou and Kolda regions). No presence records were found in the Tambacounda area (east Senegal) (Fig. 2). The distribution model also predicted this area to be unsuitable for tamarind.

Future distribution. Scenarios/models prediction maps showed significant changes from the current to the future predicted distribution of tamarind (Fig. 6c). The 2020 predictions show the area in south-east Senegal, which was predicted as highly suitable in the suitability index map to become unsuitable by 2020 according to all four A2a models (Fig. 6c). However, in the middle of the country (the groundnut basin), tamarind is still predicted as suitable, the very centre of the areas (Kaolack and Fatick regions) remaining suitable in all four models. The northern parts of this region are shown to go from unsuitable to suitable in two, three or even four models. The 2020 models also showed an increase in suitability in the very southern central (Kolda region) and western parts of the country. Little difference was found between the A2a and B2a scenario predictions.

The 2050 suitability maps show a much greater area predicted to change from suitable to unsuitable by all models. Small areas are identified as being predicted to change from unsuitable to suitable in the south and the

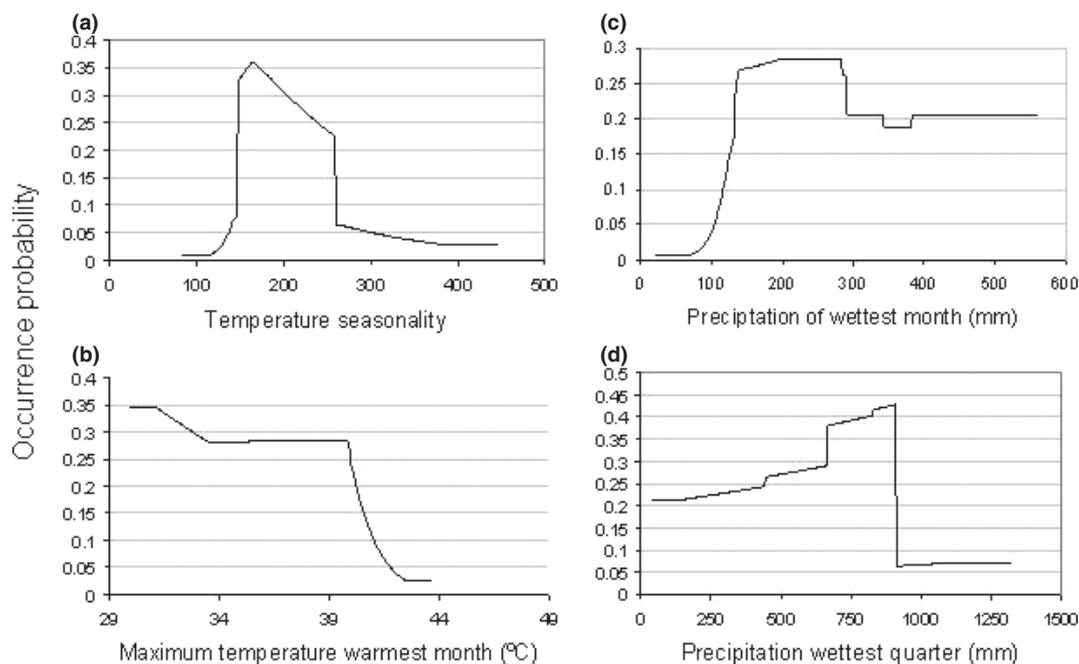


Fig 5 MAXENT response curves for most important variables in tamarind prediction models

north, but these areas are much smaller and predicted by fewer models than in the 2020 scenarios. In the A2a scenario, only a small area in the south and the groundnut region continue to show as suitable (although by only two models). For the B2a scenario, the area in the south predicted as suitable is very small, whereas a section of the groundnut basin also remains predicted as suitable by two models. The 2080 A2a and B2a models show that almost all areas are changing from suitable under current environmental conditions to unsuitable. In the A2a scenario, no areas initially predicted to be suitable remain suitable in 2080. A very small area in the north-east of the country is predicted as changing from unsuitable to suitable by one model. The B2a scenario shows a very small part of the groundnut basin (Fatick region) to remain suitable and a very small area north of this as changing from unsuitable to suitable by one model.

Model validation. The model showed a good level of performance when compared to random. Training AUC was 0.88, and the test AUC was 0.83. This indicates that most of the presence points in the test data set were predicted correctly and that the model has good predictive power.

Discussion and conclusion

Tree density

Density surveys identified a clear relationship between tamarind density and distance to villages. Assogbadjo, Sinsin & Van Damme (2005) suggest that this may indicate that the trees were introduced by man, but conceded that settlements may also have been established close to the trees to take advantages of their many services. There is evidence that tamarind is native to West Africa (Nyadoi *et al.*, 2009) although this has been found difficult to prove (Diallo *et al.*, 2008). However, the belief that tamarind is a naturalized species is integral to the farmers in Sahel and Sudan zones of West Africa. Therefore, they do not take the species into consideration for planting (Buchmann *et al.*, 2009; Havinga *et al.*, 2010). African farmers tend to cultivate exotic trees like *Mangifera indica* or *Azadirachta indica*, but not indigenous species (Diallo *et al.*, 2008), even if these species have high use values. In a recent study, only 10% of 220 informants from areas in West Africa in which the tamarind is commonly found and well utilized stated that they had planted tamarind (Buchmann *et al.* 2010). There are a few records which mention the planting of

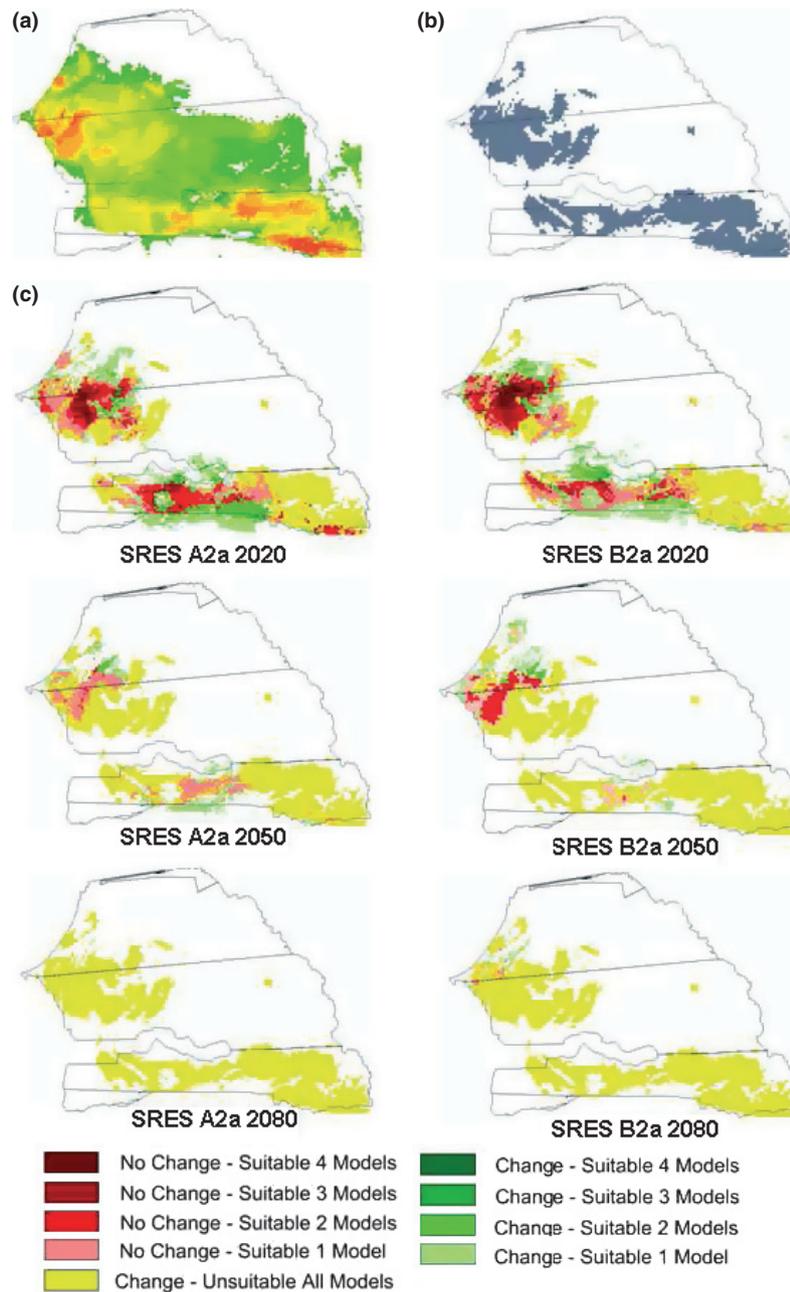


Fig 6 (a) Suitability index for predicted current distribution of tamarind in Senegal (green red index red colour represent high probability of occurrence/suitability values); (b) current distribution of suitable areas for tamarind with threshold applied; (c) suitability from current to future climate models indicating the change or no change in and number of models which effected the change

tamarind in the Sahel (Grouzis & Akpo, 2006) only the Sudano–Sahel zone (Buchmann *et al.* 2010). It therefore seems unlikely that a greater number of trees are found close to villages because they have been planted.

Quantitative evidence of differences in tree density and species composition in farmer’s fields as compared to the original savannah vegetation illustrates the impact of human selection on parkland formation (Schreckenber,

1996; Boffa, 1999). It may be the case that high density of tamarind around the homesteads is because of trees being protected owing to their high value (Boffa, 1999). Farmland is often arranged in concentric rings around settlements in rural Africa, characterized by different cropping and soil management activities (Boffa, 1999). Protection of tamarind trees may thus occur within the inner, close rings to villages. For instance, among the Bwaba-Bobo-Oulé of Burkina Faso fields around compounds, and those extending 25–50 m out, are heavily manured and enclosed with fences and contain baobab and tamarind trees (Nyandoi *et al.* 2008); further away from the settlement, the composition and other tree species dominate (Boffa, 1999). Studies in East Africa found tamarind abundance, diameter classes and growth to be higher on farms than in natural woodlands (Nyandoi *et al.* 2008), suggesting that in the region, farmers apply some protection and conservation to the trees. While our tree density results can provide some information on the conservation of tamarind in farmland and possibly the semi-farmed savannahs areas, we cannot draw any conclusions about the conservation status of any populations found further than 3 km from the villages. Fandohan *et al.* (2010) noted that tamarind density in gallery forests were more than three times higher than in woodland savannah and eight times higher than on farmland in Benin. It would appear human protection appears significant to tamarind tree density in areas of high disturbance (farmland and savannah wood). However, in areas of gallery forest, the species require little protection from farmers and regenerate well under reduced drought stress and use of vegetative propagation through root suckers along with reproduction (Fandohan *et al.*, 2010).

Tamarind distribution

The point occurrence distribution map of tamarind in Senegal showed that tamarind is widely distributed throughout the country but does not occur widely in the northern Sahel and east of the country (Fig. 1). This is likely to be due to the very high temperatures and low levels of precipitation found in these areas. The authors observed that when tamarind was found in the northern Sahel (Gnibi, Senegal), where annual rainfall is less than 250 mm, the trees are usually located where the water table is high or along seasonal water courses. Temperature seasonality and maximum temperatures were identified as important variables explaining tamarind distribution. High

rainfalls particularly over long periods of time were also found to reduce tamarind suitability. This appears to have prevented tamarind from expanding its distribution into the Guinean zone.

Future climate predictions show the area that is suitable for tamarind to decrease significantly beyond 2020. Temperatures in West Africa are estimated to rise between 2 and 6°C between now and 2100 (Boko *et al.*, 2007; Christensen *et al.*, 2007). Future precipitation models show a more mixed picture. The IPCC has noted that the Guinean coastal rain belts and the Sahel do not show as robust a response to climate models when compared to other regions in Africa (Christensen *et al.*, 2007; Meehl *et al.*, 2007). Estimates vary between decreases of approximately 20% and increases of approximately 20% by 2100 (Christensen *et al.*, 2007). Multimodel assessment average results show a modest moistening or a modest drying (Meehl *et al.*, 2007) for global and regional models, respectively. However, the increase in extremely wet seasons is usually estimated to increase (Christensen *et al.*, 2007). The future climate variable data sets used in this study reflect this with variation between increased precipitation and drying seen across different areas and within different models and scenarios.

Much of the areas that change from suitable to unsuitable in the 2020 model do so because of an increase in projected temperature. Areas on the edge of the groundnut basin close to the warm interior of the country become too warm for tamarind (maximum temperatures of 40°C). In the south of the country, a large area to the east predicted as highly suitable in the current distribution models becomes unsuitable owing to the increases in temperature. In this area, increased precipitation also makes this area too wet for tamarind during the rainy season. An increase in suitable area in the centre-west of the country (Thiès, Fatick and Kaolack regions) is most likely due to the increase in rainfall making tamarind suitable in the more eastern and northern parts of this area. In the southern part of the country, decrease in rainfall predicted by one or two models in this area means this area becomes suitable for tamarind.

The dramatic decrease in suitable area by 2050 can be explained by increases in temperature. Areas that became suitable owing to the reduction in rainfall in the south are now predominantly too warm. Only in northern coastal areas where temperatures remain below 40°C and rainfall is higher than current levels does it remain suitable for the species.

On the basis of the model in this study by 2080 Senegal is no longer suitable for tamarind owing to temperatures having risen above tamarind's range. Bowe & Haq (2010) identified a difference in tamarind's ecological requirement between East and West Africa (tamarind was experiencing, hotter and drier conditions, than in East Africa) and deduced a possible genetic difference for adaptive traits at the regional rather than the country scale. This may suggest that the regional scale may be more appropriate scale at which to model the species. However, the wide range of agro-ecological zones in which tamarind was surveyed in this study included the northern limits of tamarinds range and therefore likely to have incorporated the maximum temperature at which it can grow. Bowe & Haq (2010) identified the maximum temperature of the warmest month across its global distribution to be 41°C. Maximum temperatures predicted in Senegal by 2050 and 2080 are estimated to be above this, indicating that the species would not be able to tolerate such conditions.

It should also be noted in this regards that niche-based models have been found to overestimate detrimental effects of climate change because they do not consider phenotypic plasticity and local adaptation (Nyandoi *et al.* 2008). Species which may have origination in Africa may extend back to 30 Ma of years like those in the tribe Detariea to which tamarind allies to. This would imply that the ancestor of the species has faced and survived many climate variations which may increase the likelihood of the species being plastic in terms of its adaptation. It is important to note that variation between output species distribution models may arise owing to errors and uncertainties. The IPCC report noted that climate change models show inconsistency in rainfall projections for West Africa and is thus whether the Sahel would be more or less wet in future (Meehl *et al.*, 2007). For this reason, the results from this study must be interpreted with this in mind. In this study, we attempted to account for some of this variation by combining the result of a number of scenarios and models to predict the future suitability of tamarind in Senegal. By relating this to density measures, we have made an attempt to make some inferences on the species potential to adapt and identify areas which may be a priority for conservation under climate change.

On the basis of the future climate predictions, it would appear that the south central regions of the country and particularly the groundnut basin (Thiès, Fatick and

Kaolack regions) may become important refugia for tamarind populations in Senegal, owing to its comparatively low coastal temperatures. The groundnut basin region transects both the Sahel and the Sudano–Sahel zones; tamarind density around villages in these zones is significantly lower than in the Sudan zone. At low densities, the species may suffer from problems relating to reproductive connectivity and inbreeding depression (Dawson *et al.*, 2009) and therefore poor gene flow. This could raise concern in terms of ability of the species to adapt and survive with a changing climate. Conservative management and protection strategies of tamarind in this region could be very important to maintain the species in Senegal. Developing initiatives to encourage farmers to increase population density and gene-flow through planting of local genetic material, further protection of natural seedlings in agricultural land and protection of pollinators are likely to enhance the protection of this important species.

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