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‘Probabilistic Atlas’, a new approach to assess complexity in agroforestry systems using UAV images: example of the spatial effect of Faidherbia albida on pearl millet NDVI

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'Probabilistic Atlas', a new approach to assess complexity in agroforestry systems using UAV images: example of the spatial effect of *Faidherbia albida* on pearl millet NDVI.

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Abstract

Trees in agroforestry parklands significantly contribute to improving and adapting farming systems while providing ecosystem services. However there is limited information on crop productivity and environmental performance. How do crop growth in such heterogeneous agroforestry systems vary according to distance, crown size, and azimuthal direction ? We use a novel approach based on advanced image analysis derived from medical imaging combined with multispectral imagery (known as the "probabilistic atlas") to analyze the crop, tree and soil interactions. We analyzed the influence of 72 *Faidherbia albida* trees on 13 millet fields in 2021

and 2022. Using "Voronoi" diagrams to separate individual trees. The Normalized Difference Vegetation Index (NDVI), was used as an indicator to assess the tree effect on pearl millet crop. We observed that, at the early growth stages of millet, the effect of *Faidherbia albida* on NDVI was stronger near the crown and decreased with distance, reflecting the positive growth influence on millet near canopy. We also observed an effect of azimuthal direction on NDVI. Finally, we found that the effect of *Faidherbia albida* on NDVI was more significant for trees with a large crown size. These results are a step further in the characterization of spatial tree influence on crops in highly heterogeneous systems, with improvements for e.g. the evaluation of ecosystem services or precision agriculture

Keywords: Probabilistic Atlas, Distance of influence, Remote sensing, UAV, Agroforestry, Senegal

1 Introduction

In 2100, the population of sub-Saharan Africa is projected to reach 3.1 billion people [1]. This population growth will have a significant impact on global food insecurity [2]. Achieving food security is particularly critical in the Sahelian regions, where current crop yields are far below potential yields [3] [4]. In these regions, smallholder farming serves as both a source of income and local food production, playing a vital role in ensuring livelihood and food security. Agroforestry, which combines trees, crops, and livestock, is the most common native practice in the region and recognized as a key resilience mechanism for achieving food security and mitigating climate change [5]. Several studies have highlighted the positive effects of tree-crop associations in terms of ecosystem services, such as improving soil fertility and providing nutrients to plants [6–8]. In the Sahel, agroforestry systems have become an essential pillar of agroecological intensification and agricultural yield optimization. The study site used in this research is a *Faidherbia albida* parkland located in Senegal's peanut basin. *F. albida* is a particularly interesting tree species due to its reverse phenology (i.e., it sheds its leaves during the rainy season and blooms in the dry season). This characteristic results in a quasi-absence of competition with surrounding annual crops. *F. albida*-based agroforestry systems have demonstrated significant contributions to optimizing crop productivity in the Sahel over the years [9]. For instance, field experiments in Niger showed that millet yields under the canopy of *F. albida* were approximately 36% higher than in open fields [10]. In 2016, [11] in a review study evaluated the magnitude and spatial extent of *F. albida*'s impact on soil properties and primary productivity and found significant increases in yields of maize (150%) and sorghum (73%) under the tree canopy compared to the open area. These studies underline the importance of *F. albida* parklands in enhancing climate change resilience, agricultural productivity and improving soil fertility in the Sahel. Pearl millet (*Pennisetum glaucum*, L.), the crop in the current study, is a foundation of food security in rural areas, with consumption increasing by 50% during the lean period [12]. It is the sixth cereal [13] in terms of world production and is considered a "cereal of last resort" for farmers in especially challenging arid conditions [14]. The number of trees in agricultural plots is a delicate choice for

farmers, who should find a balance between the number of millet plants and the space allocated to trees. However, the efficient and effective placement of trees, considering their influence distances, is a fundamental factor in fully optimizing the plot's potential. [15] investigated tree effects based on distance through complex experiments that used networks of subplots around trees, however, such traditional techniques require extensive fieldwork and significant human resources. Aerial imaging offers easier insights into the effect of *F. albida* on crops, enabling a spatial characterization of this effect over time and space. UAV-based remote sensing has been used for several years to map crops [16], monitor crop conditions [17] and estimate yields, particularly in agroforestry systems ([18, 19]). UAVs allow for capturing intra-field variability, which provides a better understanding of the heterogeneity associated with tree presence, thanks to their high spatial and temporal resolution. These UAVs can be equipped with multispectral and sometimes hyperspectral sensors, which allow for the calculation of vegetation indices, such as the Normalized Difference Vegetation Index (NDVI). These indices typically correlate well with leaf area index, aboveground biomass, and crop yield, making them suitable input variables for models predicting biophysical parameters. NDVI is a highly valuable index for assessing crop health and also for mapping vegetation distribution, particularly in agroforestry systems. We argue that NDVI is a key biophysical indicator for spatially assessing the effect of *F. albida* on millet crops. This influence may vary with relative position of the crops and the trees, and other factors related to the tree, the crop, or to environmental conditions. The characterisation of the influence of the tree-crop positioning has been investigated before by using geostatistical techniques via the "range" statistical parameter to measure the maximum distance of tree influence on the NDVI of the crop [18], which was 17m in the case of pearl millet. However, such a geostatistical approach does not provide a graphical interpretation of the tree's effect on productivity in every direction and at every distance. Moreover, this study was conducted in a single plot over one year and does not allow for studying the temporal stability of the tree's effect. We argue it is also crucial to develop a model that can assess the spatio-temporal variability of the tree's impact on crops, using medical techniques. There are similarities between geostatistical tools and medical techniques in terms of detecting spatial variability. Some of the tools developed in medical sciences can be utilized in agricultural research. Medical imaging allows us to monitor, diagnose and provide solutions to diseases. For example, in medical imaging, clinicians needed to map areas where tumors were more frequent [20]. They decided to implement techniques to statistically analyze stacked radiographic images from a population of patients and to explore the spatial distribution of lesions. This provides the opportunity to position a new case of the disease in relation to the spatial distribution of known cases, which is called 'atlas'. A probabilistic atlas, when based on a large population of patients, allows for the analysis of spatial variance. Furthermore, the atlas offers the advantage of visualizing the spatio-temporal distribution of the studied phenomenon in image format [21]. Similar statistical atlas approach applied in agroforestry purposes would allow to assess the mean tree effect by combining all agroforestry plots and relying on the specific contribution of each tree to the crop. We transferred this atlas technique for the first time from medical imaging to *Faidherbia* based agroforestry systems, what we called a "*F. albida* atlas": this offers a methodological framework to map and assess

the tree's influence on pearl millet in terms of distance, azimuth and size crown and its temporal stability. Specifically, study aimed to (i) complement the traditional tree assessment approaches by applying an atlas in an agroforestry context to spatially assess the tree population's effect on the crop NDVI with three main questions: to what distance does the tree influence the crop, is its influence stable over time and is it isotropic?, (ii) evaluate whether the tree crown size modulates the crop NDVI and (iii) assess the variability of soil texture in relation to the *F. albida*. The robustness of this method was tested during two years, contrasting much with rainfall. This new approach could lead to better interpretations of tree-crop associations in agroforestry systems.

2 MATERIALS AND METHODS

2.1 Study site

The study was conducted in the agro-ecological zone of the Groundnut Basin of Senegal, specifically around the village of Sob and the municipality of Niakhar located in the Fatick region at 135 km from Dakar (Fig. 1). The climate is Sudano-Sahelian, with a wet season from July to October, followed by a dry season extending from November to June. The soil is a loamy sand [22] with a very low fertility: in quasi-absence of fertilization, crop productivity varies much in space even at short distances and relies on the very local availability of soil organic matter (SOM) [23, 24]. This site hosts high-quality instruments grouped together in the form of a collaborative platform named "*Faidherbia*-Flux" (https://lped.info/wikiObsSN/?Faidherbia-Flux), registered in FLUXNET as 'SN-Nkr'. "*Faidherbia*-Flux" installed since 2018, is located at N:14°29'44.916", W:16°27'12.851" and is equipped with instruments and facilities for monitoring ecosystem services, micro-meteorology, soil moisture, NDVI, surface temperatures, crop productivity, yields, among other parameters. The cropping system involves annual rotations between pearl millet (*Pennisetum glaucum, L.*) used as staple crop and groundnut used as cash crop, under *F. albida*. This study is on pearl millet only and covers 2 years which contrast much for rainfall (2021 is dry, 2022 is exceptionnally wet), so we used independent plots for every single year, due to the rotation. Pearl millet is fundamental for food security in rural areas, with its consumption increasing by 50% during the lean season [25].

2.2 Rainfall in 2021 and 2022

The '*Faidherbia*-Flux' collaborative platform was used to extract daily rainfall data at 30-minute intervals for the years 2021 and 2022. We aggregated the data by month for a better visualization of trends (Fig. 2). In 2021, from May to October, total rainfall was 481 mm, while in 2022, for the same period, it reached 825 mm. However, the daily rainfall data reveal a dry spell from the end of May to the end of June, which led to the loss of millet plants that had germinated around the tree canopy following the May rains. (Figure 2) illustrates a progressive increase in rainfall from July to September in 2022, with a peak observed in September. In contrast, the year 2021 exhibits the opposite trend, with rainfall decreasing between August and September.

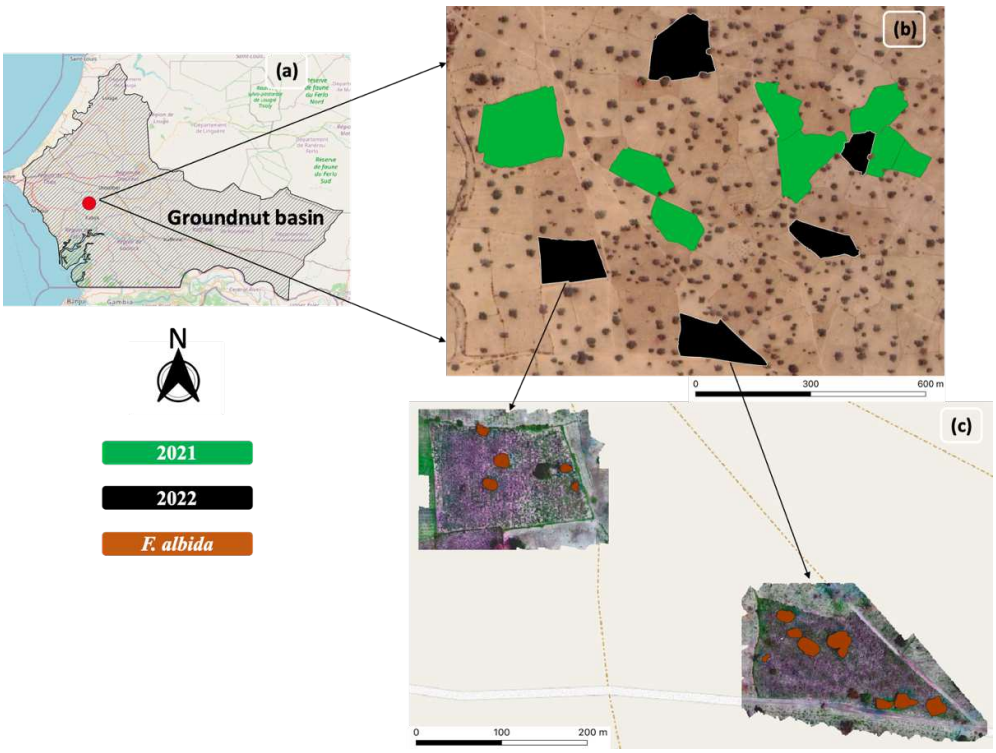


Fig. 1 (a) Location of the study area in the groundnut basin of Senegal with the position of different independent plots sown with pearl millet and monitored in 2021 and 2022 (b). Image source: Google Satellite ©* background, 2022. c) is the zoom of two plots survey in 2022 season; red polygons are *F. albida* canopy projections in these plots.

2.3 Data acquisition and processing

UAV images were acquired during the agricultural campaign in 2021 and 2022 on a network of smallholder plots composed of eight and five pearl millet fields, respectively (Table 1). A Phantom 4 RTK (P4RTK) UAV equipped with a dji multispectral camera with five (05) spectral bands centered at 450, 560, 675, 730, and 840 nm with a spectral resolution of 10 nm was used. The P4RTK has a flight autonomy of around 18 minutes depending on battery status and environmental conditions. In addition to the limited flight time, the available number of batteries did not allow to cover all plots in a single day. Therefore, UAV flights were conducted at intervals of two to three days for each campaign and within the time range of 12:00 to 16:00 local time. This time interval, characterized by clear skies, minimizes shadows cast by trees on the crops. The DJI Gs Pro [26] application was used to define flight missions. Camera parameters were adjusted according to sunlight exposure. Images were captured every two seconds with a longitudinal overlap rate of 80% and a lateral overlap rate of 70%. Flight altitudes were set at 25 m, yielding a spatial resolution of 1.3 cm, except above the flux (30 m high) tower plot for safety reasons (at 50 m high; spatial resolution 2.6 cm). This image

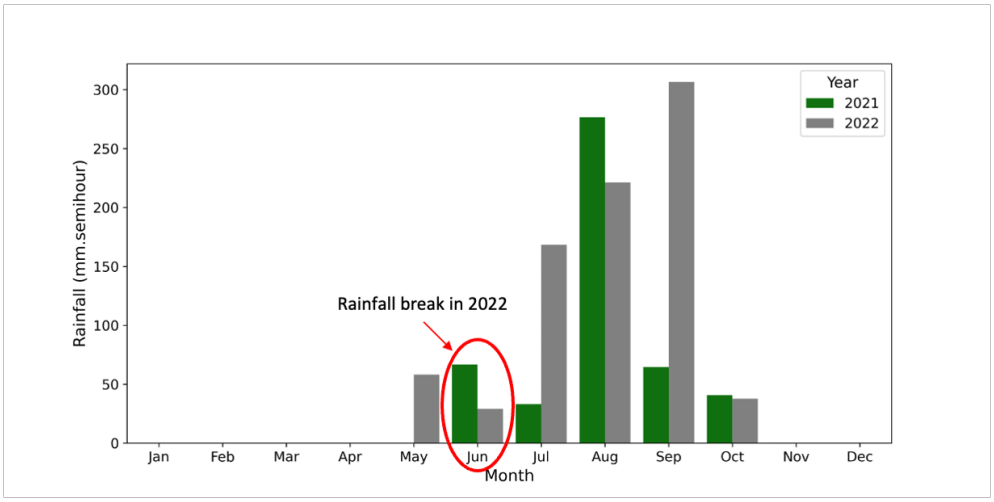


Fig. 2 Rainfall distribution around '*Faidherbia*-Flux' in 2021 and 2022.

acquisition technique, including overlaps, enables the extraction of common parts among raw images of the entire plot to reconstruct a stereoscopic vision, thereby obtaining a 3D model. This model, combined with geometrically rectified orthoimages, generates an orthophoto-mosaic of the entire agricultural plot. An automated multispectral image processing pipeline was established to build orthophotomosaics of each plot using Agisoft Metashape Python API (Metashape Professional 2.0.1). Subsequently, co-alignment was performed to align images from different dates and overlay them accurately. All 2021 and 2022 images were coregistered using the image of the harvest date of the respective year as reference (Table 2). This technique was run under version 4.2.2 of the R software [27] using the rgdal [28] and raster [29] packages.

Table 1 Acquisition of multispectral (Ms) images during two experimental years, according to pearl millet growth stages.

Sensors	Experiment	Acquisition date	Growth stage
DJI Multispectral	2021	2021-08-15	Pre-heading
	2022	2022-08-15	Pre-heading

2.4 Methodology

According to [18] and [19], we used the Normalized Difference Vegetation Index (NDVI) as an indicator to assess the effect of trees on pearl millet crop. We built an innovative workflow that allowed the assessment of the effect of *F. albida* on pearl millet NDVI under agroforestry, in terms of distance, azimuth to the tree and regarding tree crown

Table 2 Description of the crop year for 2021 and 2022.

Year	Crop	Variety	Density (plants m^{-2})	Sowing	Annual rainfall (mm)	Harvest
2021	Millet	Souna	1.23	25-07-2021	481	05-10-2021
2022	Millet	Souna	1.23	10-07-2022	825	29-09-2022

size. First, the NDVI was computed on UAV multispectral orthomosaic of pearl millet plots monitored for the years 2021 and 2022 by using the red and near infrared bands. For each of these years, the August data were selected by visual analysis to avoid noise in the crop NDVI signal. Subsequently, an original method named probabilistic atlas, known for its application in medical imaging study brain tumors [21], was employed to investigate the spatio-temporal variability of the effect of a *F. albida* population on pearl millet NDVI. Additionally, we used this technique to (i) compare the effect of *F. albida* as a function of tree crown size, (ii) analyze directional variability of the effect and (iii) to assess the variability of soil texture. This entire process is facilitated by a Python open access package named "Atlas of Faidherbia" that we developed [30].

2.5 Computing Voronoï diagram

Using a geostatistical approach, [18] demonstrated that the influence of *F. albida* is a decreasing function of distance from the tree. Thus, we can suppose an influence zone centered on the tree and decreasing far from it. In our context, the plots contain randomly distributed trees, which makes the analysis of spatial variability complex. We therefore decided to divide the plot into regions, each containing one tree. Thus, we estimate the region's Voronoï of each tree by computing the Voronoï diagram [31], to divide the crop plot into individual regions calculated using the centroid of the tree of a plot (Fig. 3). The center of each *F. albida* is obtained by calculating the centroid of the shapefile defining its crown (dots). Each voronoï region corresponds to the set of points that are closest to the centroid of a given tree compared to all other trees. The application of a probabilistic atlas to evaluate the influence of *F. albida* on pearl millet requires the establishment of a population of *F. albida* to assess its spatial impact based on distance, direction and tree crown size. Each Voronoï polygon surrounds an area that is considered under the influence of one single tree, affecting pearl millet NDVI around it (Fig. 3).

2.6 Probabilistic atlas of *F. albida* parkland

By adapting the atlas technique to our study, we aim to investigate the contribution of *F. albida* to pearl millet NDVI. To achieve this, we isolated each *F. albida* tree using the voronoï diagram and defined voronoï regions using geometric techniques. Each voronoï region constitutes a tree contribution (Fig. 4) with its influence on pearl millet NDVI. Thus, we combine image patches of voronoï regions to compute a mean individual centered on the tree. The combination of all these voronoï regions allows one to study the average effect of trees at the scale of a population of trees.

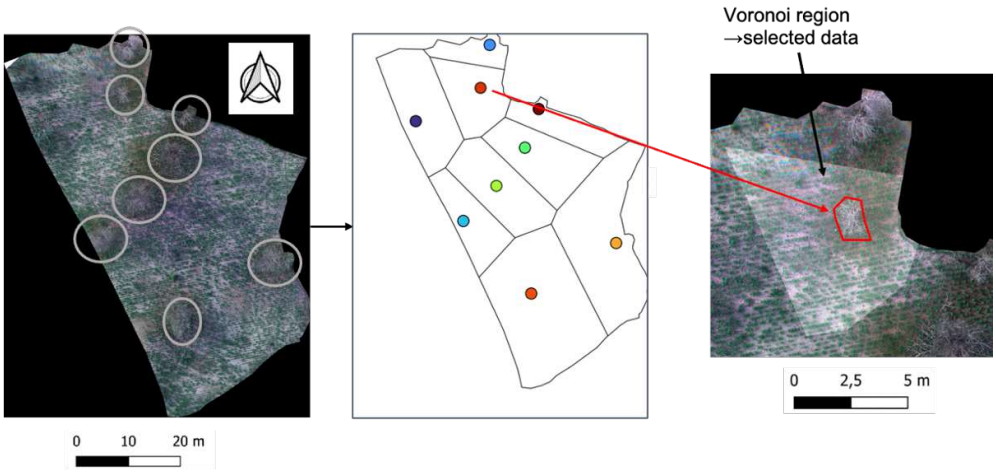


Fig. 3 Description of the influence area of each *F. albida* tree in a plot, using a Voronoï formalism in a RGB image of 15-08-2021. The greys circles correspond to the position of the trees.

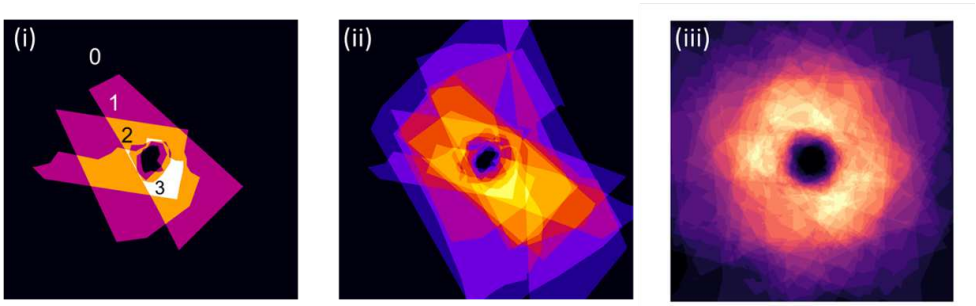


Fig. 4 Map of the contribution of each *F. albida* in a population of trees : (i) refers to 1 to 3 contributions, (ii) = 10 contributions and (iii) = 48 contributions.

2.7 Coregistration

A probabilistic atlas allows for the aggregation of information from a population of the Voronoï areas to create an average individual tree. To adapt this method to the environment of a *F. albida* parkland, we must align all trees from different images. To that end, for each *F. albida* tree, we extracted a patch of 4000 x 4000 pixels centered on the tree, enabling it to combine all the patches by computing a pixel-wise average.

2.8 Spatio-temporal probabilistic atlas of *F. albida*

For each image acquisition date on the network of monitored smallholder plots, an average *F. albida* tree, which aggregates the information from all *F. albida* trees in the plots (08 plots in the 2021 cropping season and 05 plots in the 2022 cropping season),

was constructed and represents an atlas of *F. albida*. The spatio-temporal assessment of the tree's effect on pearl millet NDVI, based on the construction of the *Faidherbia albida* atlas, involves three key steps (Fig. 5): (i) Addition of the NDVI resampled 4000 x 4000 pixels images, (ii) binarizing the images where a value of 1 corresponds to green pixels (NDVI ¿ 0.1) for a crop and 0 to all other pixels (e.g. soil), and (iii) calculating the ratio between the sum of the NDVI of the images and the sum of the binary masks at the 1.3 cm spatial resolution. In 2021, the network of monitored plots enabled the contribution of 48 influence zones centered on *Faidherbia albida*. In 2022, with the number of plots reduced by half, 22 influence zones contributed to the construction of the atlas for the acquisition date. To enhance the robustness of the study, for each atlas we have considered areas where a minimum of 5 contributions overlap for the average in order to be representative of the variability. This method was adopted to eliminate areas with low contribution and enable rigorous analysis. Note that UAV measurements could not be acquired below the crown but that crop development is potentially even higher below the crown. The probabilistic atlas of *Faidherbia albida* enables the identification of each tree's contribution and the assessment of the spatial distribution of *F. albida*'s effect on pearl millet canopy cover. [18] demonstrated, using an agroforestry plot and geostatistical techniques, that *F. albida*'s effect on millet NDVI extends up to 17 meters, assuming an isotropic environment. For safety here, we considered a 20-meter influence zone, with areas beyond this distance assumed to represent control zones (not under the influence of trees). In addition, to simplify the analysis of the tree's effect on NDVI, binning (grouping by steps) was performed to average the values and smoothen the distance decay-effect curve.

2.9 Azimuthal Variability of the effect of *F. albida* on NDVI

In 2020, Roupsard et al. [18] reported that the environment was isotropic, i.e. that the effect of *F. albida* on pearl millet varied in the same way in all directions. This observation was based on a single plot and a single crop year. In this study, the variability of the effect of *F. albida* on pearl millet NDVI was analyzed on 13 different plots and two crop years. Based on the geographical coordinates of each pixel and the center of the tree, the azimuth between the positions of the tree and each pixel was calculated for each acquisition date in the years 2021 and 2022. We used a boxplot to analyze the global distribution between the different azimuths. In addition, a descriptive statistic was computed for giving more details of the variability effect of *F. albida*. In fact, to analyze the significance of directional variability, a one-factor ANOVA was performed on the data after checking that the data followed a normal distribution using the shapiro test.

2.10 Effect of different *F. albida* crown sizes

The agroforestry system under study exhibits heterogeneity in tree size, which may be caused by tree age, pruning rate or spacing. Based on a census of 180 *F. albida* trees [32] where the diameter of each tree was measured, analysis of different classes of *F. albida*, in terms of crown radius, was conducted to distinguish small from large *F. albida* tree crowns. In this study, the radius of each *F. albida* tree crown was retrieved

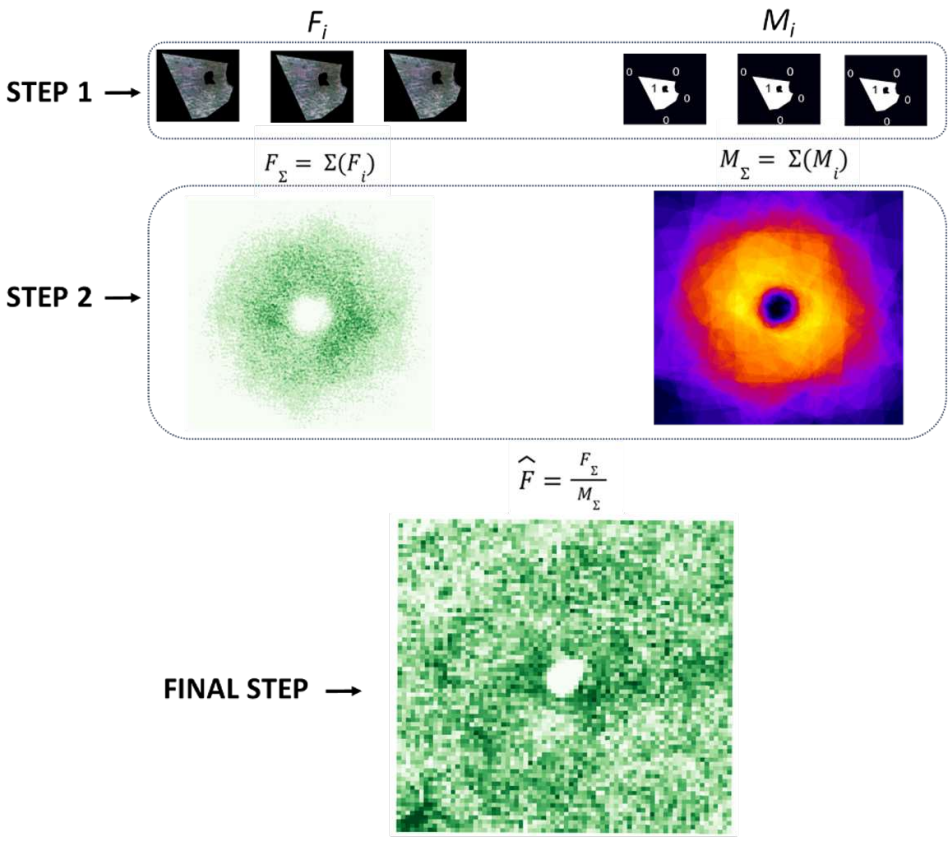


Fig. 5 The main steps in atlas design: step 1 represents the voronoï regions of images and binary masks, step 2 is the sum of images and masks and the final step corresponds to the ratio between the sum of images and the sum of masks.

from the shapefile of the tree. All trees with a radius less than 1/3 of the maximum radius (around 6 m) are considered small *F. albida* trees, while all trees with a radius greater than 2/3 of the maximum radius are considered large *F. albida* trees. The distribution of small and large *F. albida* trees was performed based on the number of *F. albida* trees during the entire 2021 and 2022 growing season. Consequently, a contribution of 23 large (15 for 2021 and 8 for 2022) and 21 small (15 for 2021 and 6 for 2022) *F. albida* trees was obtained for two classes.

2.11 Variability of soil color

In addition to studying the impact of the tree's effect on the health of the crop, based on the crop's NDVI, the construction of the probabilistic atlas enables us to look at the effect of *F. albida* on soil color and, by analogy, on soil properties. Indeed, we can assume that the tree has a positive effect on soil health under its crown with a higher

nutrient content. *F. albida* increases soil organic carbon, nitrogen, and potassium levels significantly under its canopy compared to open areas, which can lead to a darker soil color due to increased organic matter content [33]. The research of Sileshi et al. [33] indicates that soil organic carbon levels increased in 96% of the cases studied when comparing soil under the *Faidherbia* canopy to that in open areas. To study the effect of the tree on soil texture, the crop's NDVI was used as a variable for segmentation thresholding between crop or soil pixels. For each date, the threshold value is defined by the lowest NDVI value of the millet plant. As a reminder, the acquisition dates correspond to the start of crop growth, implying an absence of weeds and plant senescence. Thus, for 2021, a threshold of 0.1 was chosen to separate plant and soil pixels (NDVI ¡ 0.1). To analyze the effect of the tree on soil texture, a polar plot was applied to the probabilistic atlas obtained after thresholding by segmentation. However, it should be noted that NDVI values ¡ 0.1 are not necessarily just soil, due to the presence of other factors like animal waste in the plot.

3 Results

3.1 Spatio-temporal assessment of the effect of *F. albida*

The probabilistic atlas of *Faidherbia albida* based on pearl millet revealed spatio-temporal variability in NDVI for the years 2021 and 2022. In 2021, the rainy season totalized 481 mm of precipitation, which should be considered a normal to dry year, and the results showed a pronounced effect of *F. albida* around the tree crown during the growing season (Fig. 6). We consider below that the effect of the tree on the crop's NDVI is the difference between the local NDVI and the reference, taken as the NDVI observed at distances ¿ 20 m from the tree crown (Fig. 6). We observe that at the early growth stage (2021-08-15: pre-heading), the effect is much more pronounced near the crown, with an NDVI ¿ 0.25 at 5 m from the tree crown and up to 0.30 near the crown edge. The effect then gradually decreased up to 20 m from the tree. Overall, for 2021, the results suggest that the extent of the effect of *F. albida* is greater at the crown edge, with a decrease based on distance at a vegetative stage where the crop's health is favorable. This approach confirms the positive effect of the tree on the crop, which is not linear with distance but follows an exponential curve, with a large effect within 5 m from the crown edge and a moderate effect at greater distances. In 2022, which should be considered a very wet year (total rainfall= 825 mm), the results from the statistical atlas (Fig. 7) showed a less pronounced effect around the *F. albida* crown, with a rapid decrease and an increase in the effect farther from the tree. Indeed, the slowly decreasing NDVI profile was similar to the one of 2021 at distances ¿ 13 m from the crown, but we observed a strong depletion close to the crown in 2022.

3.2 Directional variability of the effect of *F. albida*

The azimuth between the NDVI points and the center of the tree allowed for the study of the directional variability of the effect of *F. albida* on the NDVI of the pearl millet crop for the years 2021 and 2022. The NDVI values indicated in the figures correspond to the distribution of NDVI according to direction. The results show

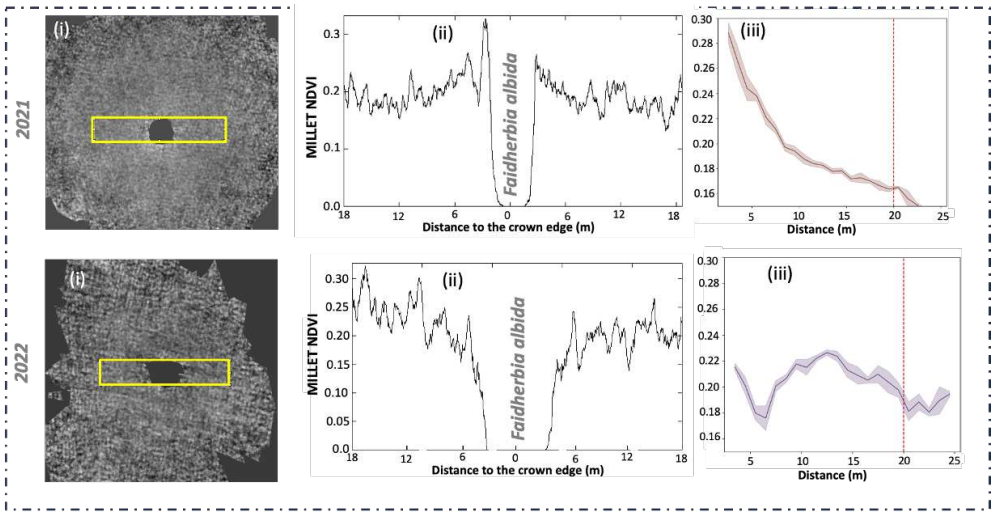


Fig. 6 Statistical analysis of the effect of *Faidherbia albida* on millet NDVI as a function of distance to the edge of the tree crown in 2021 (normal to dry year) and 2022 (exceptionally wet year). (i) NDVI's atlas of corresponding year, (ii) variation of NDVI based on a transect (yellow's polygon) and (iii) smoothing of the average effect of the tree for all the NDVI atlas. The red lines are the position of the limit of the control area.

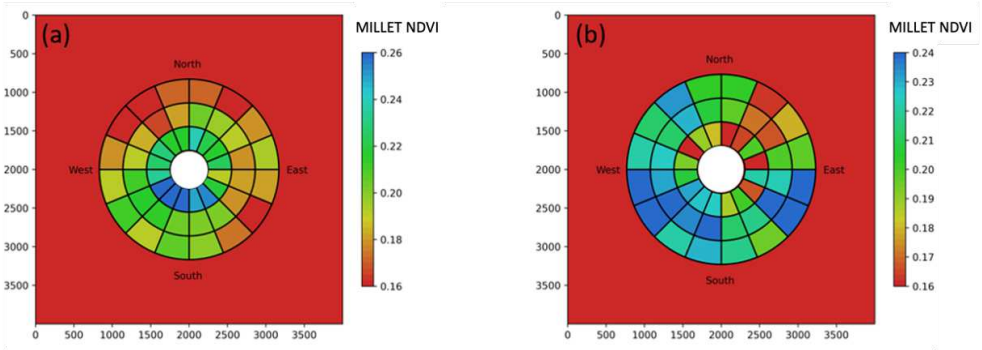


Fig. 7 Probabilistic atlas of the effect of *Faidherbia albida* on millet NDVI in 2021 (normal to dry year) : (a) and 2022 (exceptionally wet year) : (b). The white circle is the position of the area of the tree crown. Note that the lowest NDVI values (red colour) are located at high distance from the trees in 2021 and at short distance in 2022.

directional variability in the effect of the tree on the crop's NDVI (Fig. 8). Indeed, for both 2021 and 2022, the distribution of NDVI values differs across directions, with the median NDVI values varying from one direction to another. A more pronounced effect of *F. albida* is observed in the West-South direction for both 2021 and 2022. In 2021, the South-East and East-North directions exhibit similar variability according to the median. In 2022, all directions show different variabilities in the tree's effect on

NDVI. The one-factor ANOVA test showed a significant $p - value$ less than 0.05 for 2021 and 2022. Overall, the effect of *F. albida* on the NDVI of the pearl millet crop is anisotropic for both years of cultivation.

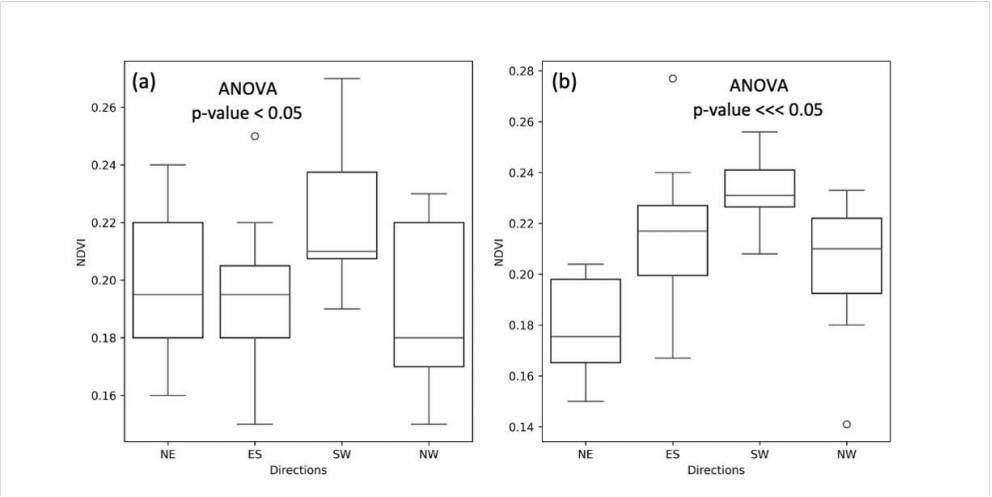


Fig. 8 Directional variability of the effect of *F. albida* on pearl millet NDVI in 2021 (a) and in 2022 (b). SW : South-West, ES : East-South, NE : North-East and NW : North-West.

3.3 Assessment of the effect of the crown size of *F. albida*

We studied the effect of tree crown size in relation to distance and azimuth. The results showed that *F. albida*, regardless of its size (small or large), affects differently the NDVI of pearl millet in the years 2021 (normal to dry) and 2022 (wet) (Fig. 9 (a and b)). For 2021, the results indicate that large *F. albida* trees have a stronger effect, even at considerable distances from the tree, leading to a larger radius (¿10 m) of influence compared to smaller trees. In 2022, due to the dry spell at the beginning of the growing season, the results generally show a greater NDVI further from the tree crown (Fig. 9 (c and d)). Indeed, this effect is more significant for trees with a larger crown size than for trees with a smaller crown size. Thus, we argue that, for both 2021 and 2022, *F. albida* with a larger crown size exerts a stronger positive effect on crop NDVI than trees with a smaller crown size, and this effect persists at higher distances.

3.4 *F. albida* can lead to a darker soil color

The impact of the *F. albida* on soil color in its surroundings was assessed using NDVI of soil pixels through the probabilistic atlas (in 2021). Figure 10 shows darker soil in the vicinity of the tree crown. We also observed soil lightening far from the tree crown.

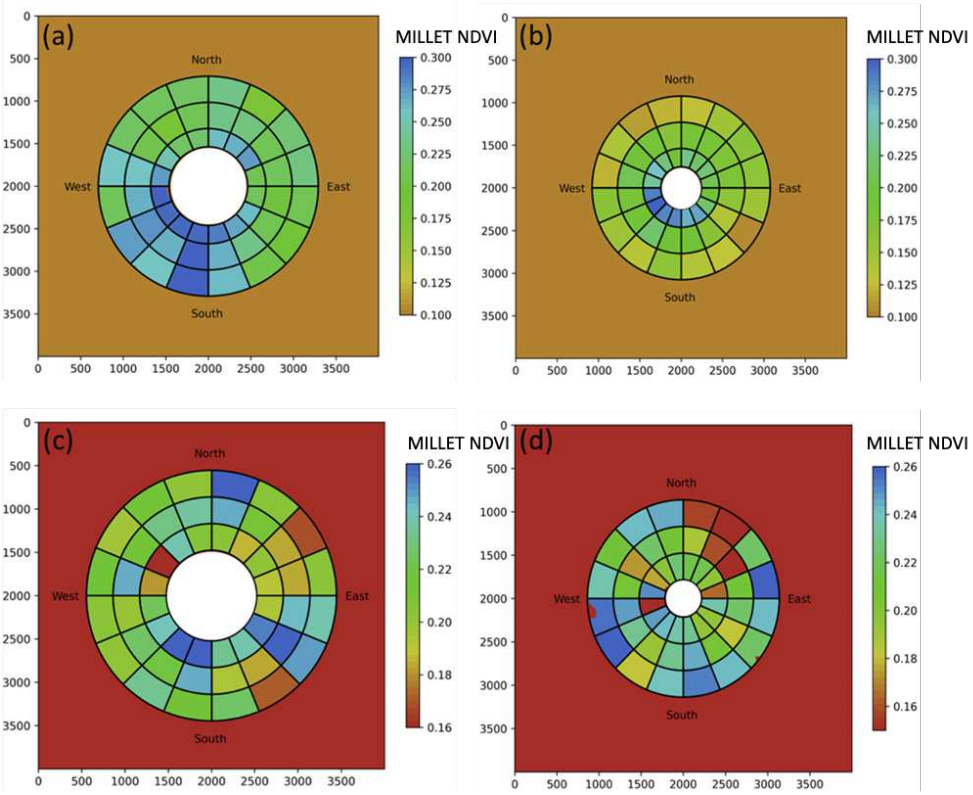


Fig. 9 Probabilistic atlas of crown size effect of *F. albida*. (a) and (b) correspond to large and small trees, respectively, for 2021, and (c) and (d) for 2022. The white circle corresponds of the area to the tree crown. The NDVI scale is the same for one given year, whatever the crown size, but differs between 2021 and 2022.

4 Discussion

Agroforestry is a pillar of ecological intensification. Given its potential in providing ecosystem services and ensuring food security, the adoption of agroforestry is a fundamental asset. The spatial approach using UAV equipped with a multispectral camera or satellite images to understand the functioning of agroforestry systems opens up new research perspectives. We have proposed an innovative approach based on UAV data and probabilistic atlas to highlight some characteristic effects of agroforestry, e.g. crop and soil NDVI per distance and azimuth around the tree. We will discuss below whether this approach significantly enhances the understanding of tree effect on crop, under the specific case-study of *F. albida* and pearl millet in a senegalese parkland.

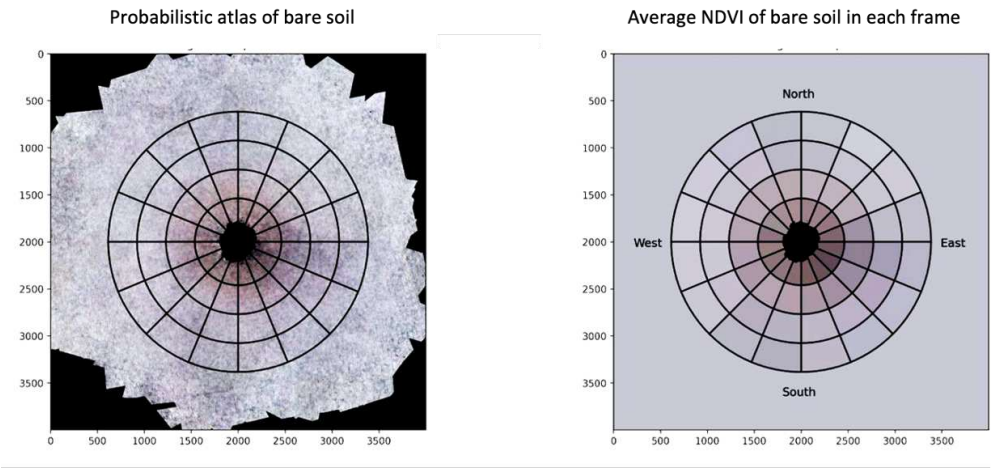


Fig. 10 Probabilistic atlas the impact of *F. albida* on the soil color.

4.1 Probabilistic atlas of agroforestry trees : a new method to graphically assess the distance and directional influence of the tree on the crop

As a reminder Roupsard et al. [18] used geostatistical techniques with aerial imagery on an agroforestry plot to estimate the influence distance of *F. albida* on the NDVI of pearl millet in Senegal. They also noted that their approach was valid primarily for the specific spectral index (NDVI) used and indirectly for all productivity variables well correlated to NDVI. Although this method was statistically sound, it hardly provided graphical evidence of the directional and azimuthal effect of the tree on the crop and on the soil. Here, we proposed a new approach, also based on crop NDVI to graphically evaluate the tree effect in terms of distance and azimuth across a network of agroforestry plots and two agricultural seasons. A probabilistic atlas was used here for the first time in an agroforestry context and confirmed a positive tree effect around *F. albida*, decreasing with distance, according to specific patterns that may vary along the cropping season or between years. The atlas provides an average influence of a population of *F. albida* for 2021 and 2022 across multiple agroforestry plots. This could be attributed to factors such as the "fertile island" effect [34], i.e.(higher overall fertility and soil water availability around the trees, among others. Compared to the results obtained by Roupsard et al. [18], our findings confirm the positive tree effect, using here a much larger amount of replicates: Here, the atlas represents an average effect across a network of farmer-managed plots over two years. The probabilistic atlas graphically captured very well the interannual variability. 2021 was a rather normal to dry year, but in 2022, the rainfall was exceptionally high (825 mm), although the early wet season was also marked by a long dry spell just after the first rains and germination: this happened in July, between the sowing date and the second actual onset of the rainy season, which began in August, i.e. much later than in 2021. From August to the harvest in October, the rainfall conditions were exceptionally wet, allowing the plants that

survived the July drought to recover and exhibit very good productivity. Consequently, the first pearl millet plants, which initially grew better under and nearby the tree crown as in 2021, withered or even died during the July dry spell, likely due to their excessive Leaf Area Index (LAI) under dry conditions. Millet plants located further from *F. albida*, which grew more slowly in June (before the drought), expressed a lower LAI and survived better during the dry spell. This study also examined the directional variability of the tree effect across multiple plots. Understanding this parameter is important for optimizing the planting pattern in agroforestry plots to maximize overall productivity. Here, for randomly spaced trees, the relationship between the NDVI of pearl millet and the azimuths of millet plants shows varying influences in all directions (N-S-E-W) regarding the tree's effect. Thus, we found that the effect was anisotropic on the atlas, which contrasts with the results obtained by Roupsard et al. [18] through geostatistics, likely due to the single plot study used versus the probabilistic atlas. In fact, the potential of the atlas would likely be best expressed in line plantations to optimize the line orientation. Ismail [35] studied the crown architecture of *F. albida* and light exposure and showed that the crown is asymmetrical and influenced by the tree's phenological rhythm and the position of the sun during different seasons. Ismail [35] demonstrated that this asymmetry provides a better ability to capture light in a northerly direction. The directional variability of the tree's effect on the NDVI of pearl millet, in our case, may be due to the fact that the light conditions provided by the tree crown (inverse phenology resulting *F. albida* is leafed out during the growing season) enhance pearl millet growth or due to a heterogeneous distribution of light and tree management effect.

4.2 Impact of tree crown's size on pearl millet NDVI

In Senegal, within the groundnut basin, the effect of *F. albida* on crop NDVI [18] and pearl millet yield [19] has been shown to be positive around the tree crown and decreasing with distance. The presence of trees in agricultural plots leads to significant landscape heterogeneity. The size of *F. albida* tree crowns varies from tree to tree and from plot to plot. However, the tree's influence has traditionally been measured by considering any trees in plots, without accounting for tree crown size. In this study, we tackle this limitation and present the first application of the effect of crown size on pearl millet NDVI based on probabilistic atlas. We categorized tree crown size into two classes: small and large. The results for both years demonstrated that a large *F. albida* has a more pronounced positive impact on crop NDVI than small trees. The reverse phenology of *F. albida* prevents tree crown competition with pearl millet for light. The crown size effect could be attributed partially to the moderate shading of branches. More likely, the benefit should be explored considering the age of trees. Large trees are assumed to have provided above and underground litter for a longer period and to have more expressed their fertility island effect [34]. Underground in particular, *F. albida* trees were reported to develop a safety net of lateral roots just below the crop roots, the extent of which is very large (¿ 30m) [24] and may vary with crown size. The fine lateral roots are thus assumed to be at higher extent and density for large trees, proportionally to their leaf area and fine root activity and mortality may contribute to soil fertility (including hydraulic redistribution). Sileshi et al. [36] evaluated the scaling

relationships between *F. albida* growth in height, stem diameter and crown size. They showed that taller trees bring more benefit to the surrounding ecosystem with better microclimate conditions. These results are consistent with our findings. A large crown size of *F. albida* indicates that the trees are older and could improve resource availability and potentially better growing conditions than smaller or younger trees. Moreover, the branch shedding of larger *F. albida* trees reaches further distances, providing necromass under decomposition to millet plants around them. Overall, several factors (agronomic, biological, and microclimatic) could explain the crown-size-dependent effect of trees. However, in this study, our approach is limited to spatially illustrating this variability. This analysis demonstrates, for the first time, an effect of *F. albida* on NDVI linked to crown size, representing a novel application in agroforestry, especially regarding optimal tree densities along ageing and tree pruning. The atlas is a well designed tool to study the effect of tree pruning on annual crops, during several years.

4.3 *F. albida* affected soil color

The probabilistic atlas also allows for the spatial study of the tree's influence on soil properties, particularly color. The results showed a relationship between *F. albida* and soil color at the edge of its crown, where the soil color is much darker compared to areas further from the tree (which are lighter). This enhanced soil coloration could be explained e.g. by higher litter deposition in the vicinity of trees, soil organic matter protection against decomposition by direct sunlight in the shade, or animal preference to stay longer in the tree shade and deposit more faeces. We assume here that darker soil coloration indicates higher organic content and nutrient availability. Sileshi [37] demonstrated that *F. albida* increases soil organic carbon by about 46% and total nitrogen by 50% under its canopy compared to open areas. Abdella et al. [38] established a link between increased nutrient levels, including phosphorus and potassium, and the darker color of the soil, noting that an increase in organic matter generally leads to darker hues. In the same study area, [22] showed that the root system of *F. albida* improves soil moisture retention, which can affect soil color by enhancing microbial activity and organic matter decomposition. All these studies converge with the results obtained in this paper, supporting the idea that *F. albida* has a positive effect on soil color, thereby causing darker soil color at the edge of the crown. The findings of the present study demonstrate that the diminishing effect of *F. albida* on agricultural productivity with distance is intrinsically linked to soil properties varying with distance. Therefore, we argue that *F. albida* not only enhances crop productivity but also serves as a lever in improving soil color.

5 Conclusion and perspectives

This paper illustrates, in general, how agroforestry parklands provide mechanisms to ensure productivity through the positive effect of trees on crops. More specifically, the results demonstrated the impact of *Faidherbia albida* on the NDVI of pearl millet, with a decrease observed at larger distances from the tree. An image analysis technique inspired by medical imaging was applied for the first time in agroforestry, in a parkland primarily dominated by *Faidherbia albida*. NDVI of the crop and of the soil was used as

a random variable varying according to the distance from the tree, azimuthal direction, and tree crown size. The results lead to the conclusion that the *Faidherbia* trees contribute to the improvement of pearl millet and soil NDVI and, by extension, to the productivity of pearl millet crops. Moreover, a tree with a large crown size has a more pronounced effect on crop productivity. This paper also explored the effect of *F. albida* on soil properties, particularly soil color. In this regard, *F. albida* leads to a darker soil color beneath the edge of its crown, which indicates higher levels of SOM. Furthermore, the results revealed an anisotropic effect of the tree on the millet crop's NDVI. This novel graphical approach proved to be particularly effective for evidencing various aspects of spatial heterogeneities around agroforestry trees that were supported by previous agronomic observations and interpretations. The tool was only exemplified here in a single agroforestry system and for a single pair of tree and crop species, but appeals for wider applications: in particular, this tool would be very helpful to monitor the effect of trees on crops on the long term, after the installation of a new agroforestry system, during the development of the trees. When many years of data are available, images for each single tree could be stacked in the atlas as well. In the case of mixed tree plantations in an agroforestry system, the impact on crops could be compared by tree species. Also, this tool is highly suitable for comparing planting designs (random, aggregated, in line, pruned etc.). Other crops, tree-crop associations, densities and other vegetation indices (drought stress indices; diseases impacts) are worth being tested further. Yet, one limitation with using UAV images is the absence of data in the crown projection area : such limitation should be circumvented, especially here where the tree has a positive effect on the crop, e.g. by using images from poles.

Declaration of Competing Interest

The authors declare they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

S.M.D did the field work and wrote the main manuscript text, I.D did the field work, R.F. advised methodologically, A.A.D and H.C. contributed with writing and advise, and O.R, A.A , L.L, M.D and I.S conceptualized the study and secured funding. All authors reviewed the manuscript.

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