National University of Agriculture
Sciences and Technologies for Sustainable Agriculture (STSA)
ISSN: 1659-5726 (Online) 1659-634X (Print) https://www.stsa.una.bj/index.php/st

VOLUME N° (ORIGINAL ARTICLE)

Roadside invasive Hyptis suaveolens ((L.) Poit, 1806) colonies green energy potential in the soudano-guinean regions of Benin

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Abstract

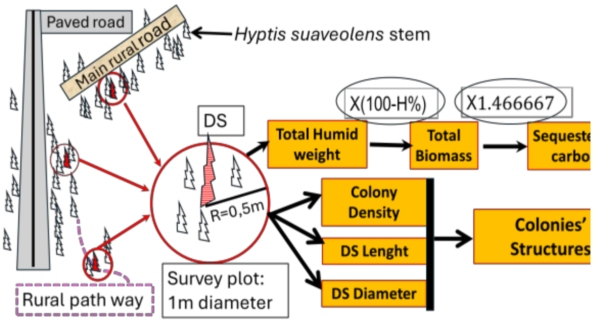
Invasive species pose significant challenges to biodiversity and the community. Mitigation strategies include eradication attempts and biomass harvesting without integrating the invader into the resource chain. In the Republic of Benin, Hyptis suaveolens is a nationwide invasive plant species that develops in pure colonies in many ecological areas, including roadsides. This research evaluated the biomass and sequestered carbon potentials of roadside colonies in the soudano-guinean regions of Benin. Main managed roads, main rural roads, and rural pathways, located in the department of Zou, were assessed using 1m diameter circular plots around the dominant stem of the colonies during the dry season (February & March) of 2024. The 5cm above-ground humid weight of the stems on the plots and their humidity were measured and converted into dry matter (biomass) per road category. The corresponding sequestered Carbon was determined by converting the biomass to sequestered Carbon based on the photosynthesis chemical reaction. These roadside Hyptis suaveolens colonies produce 7843.11 ± 320.86 kg/ha dry matter per year, corresponding to 11505.85 ± 469.44kg/ha of sequestered carbon from an average 18.49 ± 7.99 stems/m^2. The eastern parts had the lowest biomass productivity, while the south had the highest biomass potential. The roads had similar stem density. Rural pathways had robust stems and bore the highest biomass, as well as sequestered carbon. The invasive plant produces high biomass in the soudano-guinean regions of Benin. However, its valorization for green energy requires deeper investigation to prevent worsening its spread and impacts on vulnerable ecosystems.

Key words: Alien species, biodiversity, biological invasion, green energy, transport.

Highlights

- Hyptis suaveolens is an invasive plant of great concern in most tropical areas
- It thrives in pure colonies along roadsides and fallows in the Republic of Benin
- Biomass assessment of the invader was performed in Benin soudano-guinean regions
- Hyptis s. roadside colonies had high biomass productivity and sequestered carbon
- Green energy-based technologies will help mitigate its invasion in tropical areas

Graphic abstract



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1. Introduction

The worldwide biodiversity is threatened by thousands of alien invasive species. But relevant impact studies were conducted on less than 200 species, and the situation of the African countries is poorly documented even in protected ecosystems (Pysek et al., 2013). Invasive species seriously jeopardize the quality of social, economic, and environmental systems through food insecurity and social conflicts they generate (Goss et al., 2014). The specific impacts of invasive species on the social tissue are difficult to assess as their effects are amplified by the vicious cycle of climate change and other social challenges (Mainka & Howard,2010).According to Williamson (1996), invasion occurs whenecological effects on other species or ecosystems exist, or when human society is subjected to measurable direct or indirect harm from the proliferation of a species against the native ones. As such, many social structures find the contributions of nature and quality of life hindered by the direct actions of invasive species or by their different management strategies Others are impacted through the costs they incur due to their legal responsibilities, while collateral-impacted actors lose value as a result of the indirect consequences of invasive species or their management (Hulme, 2009; McGeoch et al., 2023). Besides these complex negative impacts, reinforcing the invasive added values will help improve the livelihood in cooperation with the impacted stakeholders (Díaz et al.,2015). The great challenges in implementing public policy, legislation and regulatory mechanisms to protect the confusing affected goods and services by invasive species (McGeoch et al., 2023) make it difficult to i) operationally quantify their case-by-case effects on the society and ecological entities and ii) defend the relevant required resources for their efficient control in many parts of the world. However, the issues of invasive species are still poorly addressed in terms of tangible actions at national, regional, and international levels (Pimentel et al., 2005; Diagne et al., 2021).

The common approaches in combating invasive species are eradication attempts that target removing the invasive species using chemical, mechanical, and biological controls. Although voices are raised against investing in the integration of invasive species into the resource chain of the invaded entities, social adaptation includes valorization as bioenergy and the development of a carbon sequestration economy (Harvey et al., 2010; Howard & Pecl, 2019). In the Republic of Benin and many invaded areas, numerous technologies are developed by local communities (Aboh et al. 2017), and mitigation strategies should fully integrate these approaches to control the invasion.

The concept of native versus alien deeply depends on the history of human migrations and activities (Carthey & Banks, 2012; Hardisty et al., 2019). This leads to a huge worldwide data gap on the spatial delineation of the edges of native species and invaded habitats. Despite of these knowledge gaps on invasive species distribution and their impacts, the international community is increasingly defending the establishment of synergy policies between human health, agriculture, forestry, fisheries and environment sectors at all levels to ensure that "Measures are in place to manage pathways to prevent the introduction and establishment of invasive alien species" (target 15.8 of the sustainable development goals). Through the target 6, of the decision 15/4, the Kunming-Montreal Biodiversity framework of the Convention on the Biodiversity (CBD), also sets guiding Principles for the "prevention, introduction, eradication, and mitigation of impacts of alien species" that threaten ecosystems, habitats, or species (https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf).

In the Republic of Benin, there is no relevant, exhaustive inventory on invasive species and their impacts. But 14 plant and animal species are recognized as alien invasive species, among which Hyptis suaveolens L. Poit, a Lamiaceae is of great concern (Fourth national report on Biodiversity of Benin). It is a small annual or perennial plant originating from tropical America, and the manner in which it was introduced and successfully established throughout tropical Africa has not been clearly elucidated (Hutchinson & Daziel, 1963; Raizada, 2006). According to Oumorou et al., (2010), it is a serious pasture degradation factor. In addition to its high insect repellent properties, fire and drought resistance, it is a high seed-producing plant. It also produces a large amount of nectar (Amakpe et al., 2024), which efficiently distracts pollinators from native species, leading to the limited seed production of the associated species and its rapid dominance over them (Tiedeken et al., 2016; Brett et al., 2024). These successful biological and ecological adaptations help it establish in pure colonies in old fallows, old carries and roadsides in the entire Republic of Benin (Aboh et al., 2017).

Almost no active mitigation plan is applied in the country against the plant, except some stem recuperation for building fences and the use of leaves as repellent against mosquitoes (Johnson et al., 2020; Enagnon et al., 2024). Deeper investigations are then still required to determine the expected harvestable biomass for more intensive extraction technologies. Roadside micro ecosystems determine Hyptis suaveolens colonies' characteristics, which are also impacted by the dominant effect of the most vigorous plant (Frieswyk et al., 2007; Chen et al., 2024). These investigations set out to determine if the total Hyptis suaveolens biomass in an area is determined by the road type and the most dominant stem in the soudano-soudanian areas in Benin. Using a plant survey in the entire Zou department, we i) determined the expected biomass and sequestered carbon of the Hyptis colonies along the different road categories and ii) established the on-field biomass quantification of the colonies.

2. Materials and methods

2.1. Study area and survey plots establishment

The study area was the central parts of the Republic of Benin (figure 1), which covers the Zou department. It is a transitional climatic zone between the Guinean and Soudanian climate with an average rainfall of 900 mm per year during 74 rainy days (ASECNA, 2021). The vegetation consists of degraded savannahs dominated by traditional palm groves and crop-fallow mosaics. The department hosts nine districts, which are interconnected with international, national, and local roads of different standards that bear specific roadside vegetation and Hyptis suaveolens colony patterns.

For the investigations, only colonies of at least 5 m length and 4 m width or irregular colonies of at least 8 m diameter were considered along a transect following the three main road categories of the department. The research targeted the biomass production and carbon sequestration potential of the plant. Thus, the investigations were conducted in the heart of the dry season (February and March) in 2024 when the leaves of the plant had all fallen off the stem. Only colonies that were not burnt were also considered along the following road types or sites. In order to avoid border effects, the survey plots were set beyond the runoff line bordering the traffic lanes. Colonies that are impacted by roadside residents' activities in build-up areas or in contact with crops were also avoided. The following road categories were analysed (figure 1):

- R1: Main national or departmental roads: termed main managed roads, they are made up of paved and unpaved managed roads;
- R2: Main rural roads: they are roads that are practicable all year-round, which connect R1 to the villages. They are termed main rural roads.
- R3: Rural footpaths and other open areas: they are roads connecting the village area to farms (termed rural pathways).

The survey plots were separated from each other by a minimum distance of 5 km till the end of the road or the exit point from the department. The survey plots were set around the dominant plant stem, which is the most vigorous plant of the colony.

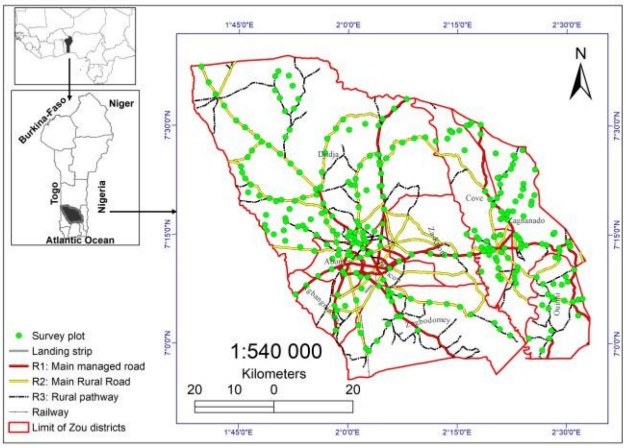


Figure 1 Survey plots location

2.2 Data collection

The survey plots were first described by the general conditions of the colony, such as its geographic coordinates and the road category. A circle of 1 m diameter was established around the dominant stem, and its relative humidity (H %) was recorded at 5 cm above the ground with an electronic humidimeter, which was first calibrated according to the manufacturer's instructions. The lowest diameter (D0) of the dominant plant was also measured with a calliper at the same section before it was cut at 5 cm above the ground. Once cut, its total weight (WT) with all the branches it bore was recorded using an electronic scale before it was carefully cleaned of all its branches using pruning shears. The total weight (W0) of the main branch was measured using the same scale, and its length (Lo) using a tape. The lengths of each of the first four branches of the main stem (L1, L2, L3, L4) were also taken using a tape graduated in centimeters. The remaining stems of the survey plot were finally carefully cut at 5 cm above the ground and weighed (Wt) using the same scale (figure 2).

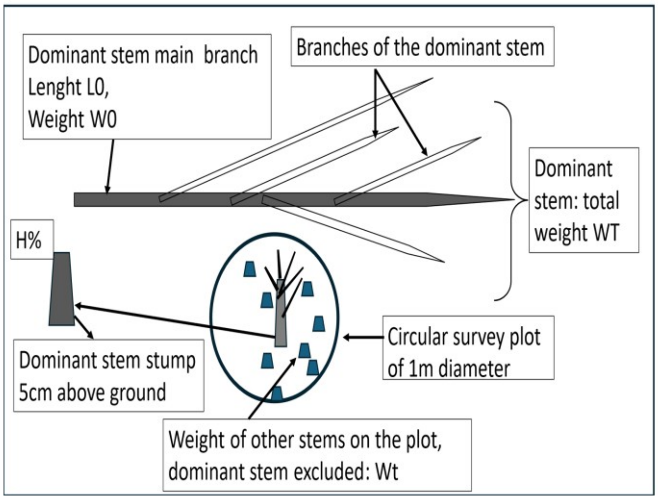


Figure 2 Measured parameters on the colonies per survey plot

L0: length of the main branch of the dominant stem of the plot

W0: humid weight of the main branch of the dominant stem of the plot

WT: total humid weight of the dominant stem

Wt: Weight of the remaining plant stem of the plot 5 cm above the ground

2.3 Data analysis

The collected information from the surveyed plots was compiled into a database, and statistical analyses were performed using StatistiXL. The accurate geographic coordinates of the surveyed plots were registered and projected in the official shapefile of the Zou department using ArcMap version 10.3.1. This helped attribute each point to its corresponding administrative district of location and discard the plots that fell outside the targeted geographic borders.

A descriptive analysis was first conducted on the lengths, weights, and relative humidity at the department, district, and road type levels. The survey plots were also submitted to the analysis of variance based on the road categories and the districts. To determine the environmental factors that best explain the differences between the survey sites and how the plots were grouped, a discriminant factorial analysis was conducted on the road type, the lengths, weights, the stem relative humidity, the number of stems on the plot, and the district of location. A correlation analysis was done to establish an allometric relation between the different factors. This helped determine the most relevant factors influencing the on-the-field productivity of Hyptis suaveolens colonies. The significance of the statistical analyses was set at 5 %.

The combination of correlations, factorial, and ANOVA analyses helped group the survey plots in homogeneous categories. These categories were characterised using the total dry matter production of the colonies.

The colony biomass per ha was calculated by converting the humid weight to dry matter per ha (equation A). The sequestered carbon of the colony was determined from the photosynthesis chemical reaction that converts the carbon dioxide into biomass (Manglili, et al., 2019; Muthmainnah et al., 2024) as indicated in equation (B)

$$DM_{5cm} = \sum_{1}^{n} \frac{(1 - Hi\%)(w_{0i} + w_{Ti})}{Sp} \quad (A)$$

$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$

(264kg) CO_2 + 108kg H_2O →180kg biomass + 192 kg O_2 and

SC = (264/180)x DM_{5cm} (B)

Combining equations (A) and (B), the total sequestered carbon (TSC_{5cm}) per geographic space or road category was calculated using the following equation (C)

$$TSC5cm = 1.466667x \sum_{1}^{n} \frac{(1 - Hi\%)(w_{0i} + w_{Ti})}{Sp} \quad (C)$$

DM_{5cm}: Total biomass 5 cm above ground (kg/ha)

$Hi\ \%$: Relative humidity of the main dominant stem, 5 cm above ground

W_{oi} = Total humid weight of the dominant stem of the plot i, all branches included (kg)

W_{Ti}: Total humid weight of the remaining stems on the plot i (kg)

S_P: survey plot area in ha (=0,0000785 ha).

TSC_{5cm}: Total annual sequestered carbon, 5 cm above ground (kg)

SC: sequestered carbon in the chemical photosynthesis reaction (kg)

The biomass and the corresponding sequestered carbon of the colony were determined from the total biomass of the dominant stem, considering the proportion it represented at each location and road category (equations D and E). The same operation helped determine the corresponding biomass and total sequestered carbon from the main branch of the dominant stem of the colony (equations F and G).

$$BT = (100 - H\%)\frac{WT}{Pt0\%}) \quad (D)$$

And

$$TSC = (1.466667)(100 - H\%)\frac{WT}{Pt0\%}) \quad (E)$$

$$BT = (100 - H\%)\frac{WL0}{PL0\%}) \quad (F)$$

And

$$TSC = (1.466667)(100 - H\%)\frac{WL0}{PL0\%}) \quad (G)$$

BT: Total Biomass in kg/ha

TSC: Total sequestered carbon in kg/ha

WT: Total humid weight of the dominant stem in kg;

H%: Relative humidity of the dominant stem at 5cm above ground

Pt0%: Proportion, the dominant stem represented per site or road type

PL0% Proportion the first branch of the dominant stem represented per site or road type

WL0: Total weight of the dominant stem in kg.

3. Results

3.1. Determinants of *Hyptis suaveolens* colonies' potential

The multifactorial analysis of variance indicated that the differences in the measured variables are significant between the location of collection (P = 0.000), while their differences were not significant when combining the bearing road type ($P > 0.05$). The overall tests of univariate models indicated that the differences in the dominant stem relative humidity, diameter, and total weight were highly significant between the location and the road categories (P = 0.000). This was the same for the length of the fourth and third branch of the most dominant stem (P = 0.000 and P = 0.035). On the other hand, the number of recorded stems per plot, the total length of the dominant stem, and the lengths of the first and second branches of the dominant stem did not statistically vary between the location and the road categories ($P > 0.05$).

The post hoc tests for the road type factor showed that the total weights of the main managed roads were similar to those of main rural roads but statistically different from rural pathways (P = 0.022).

The correlation analyses (figure 3) indicated that the total biomass was highly correlated with the total weight of the dominant stem (P = 0.000, R^2 = 0.66) and the total weight of the main branch of this dominant stem (P = 0.000, R^2 = 0.78). But it was poorly correlated with the diameter of the dominant stem at 5 cm above ground and the plant density. The total biomass and the corresponding sequestered carbon were determined by the proportion of the total dry matter of the dominant stem of its main branch. These values also depended on the location and the road type. Table 1 summarises the values of each factor per district and road type and the specific quantification conditions.

The total dominant stem dry matter represented an average of 10.14 +- 8.9 % in the entire study area and varied from 1.5 % to 100 %. The lowest values were obtained in the districts of Agbangnizoun, Bohicon, Abomey, Djidja located in the Western parts of the department. The districts of Zakpota, Ouinhi, Cove, and Zangnanado bore the highest values of the proportion of the most vigorous stem of the colonies. This factor also varied a lot upon the road type.

Regarding the dominant stem of the main branch total dry matter, the departmental average value of the conversion factor was 8.70 + -5 %. This factor, in contrast to the dominant total weight, turned out to be 5.70 % for the three main road types. Not all roads and districts had colonies around every type of road, and the conversion factor of the missing roadside colonies was attributed to the average value of the bearing district (table 1 and table 2).

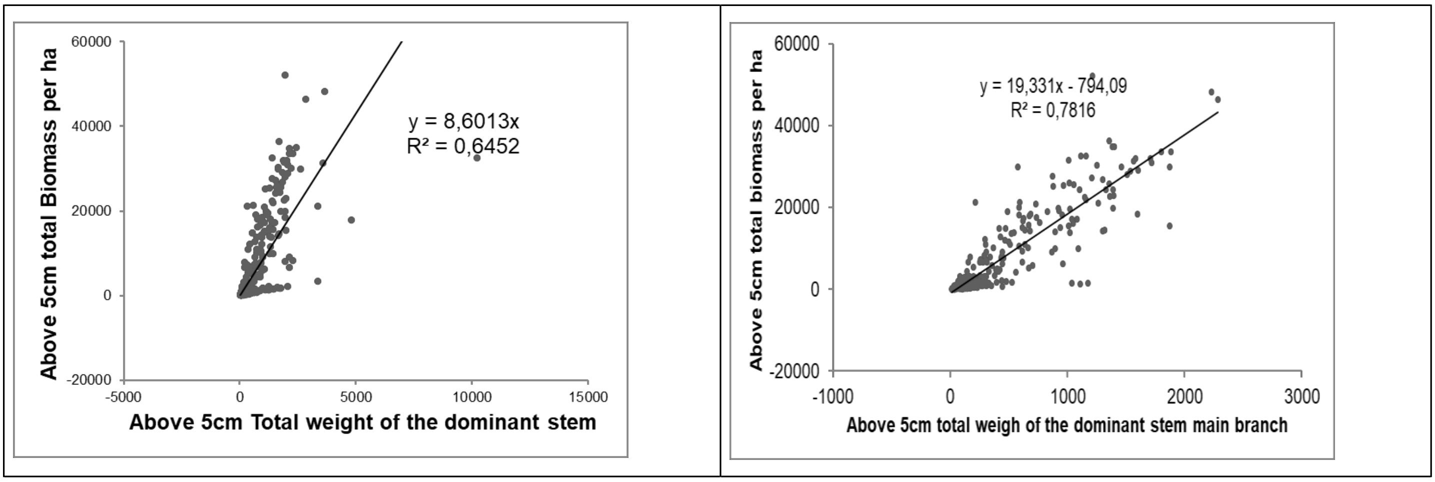


Figure 3 Correlation analysis between the dominant stem total weight, the main branch weight, and the colony total biomass

3.2 Spatialisation of Hyptis suaveolens colonies' productivity

Hyptis suaveolens colonies produced an estimated 7843.11 ± 320.86 kg/ha dry matter per year in the Soudano-guinean areas of Benin, corresponding to 11505.85 ± 469.44 kg/ha of sequestered carbon from an average18.49 ± 7.99 stems/m^2. The district of Ouinhi located in the East had the lowest biomass production (BT = 483.56 kg/ha and TC = 709.38 kg/ha) with a density of 16.61 ± 5.66 stems/m^2 while the district of Zogbodomey had the highest productivity (BT = 15686.26 kg/ha and TC = 23011.74 kg/ha) with a density of 19.16 ± 9.25 stems/m^2. The dominant stems in the department were 2.25 ± 0.48 m in length with a diameter of 1.64 ± 0.79 cm. The longest dominant stems were located in the district of Zangnanado, which also bore the stems of higher diameters. The average stem humidity was 70.32 ± 33.58 %. It varied from 40.36 ± 38.38 % in the district of Zogbodomey to 96.14 ± 4.38% in the district of Ouinhi located in the Eastern parts.

As far as the production per road categories were concerned, main managed roads had the lowest biomass production (BT = 4665.03 kg and TC = 6842.05 kg/ha). The colony density was 18.62 + -8.18 stems/m^2 along these roads, while main rural roads had the highest biomass of 10976.41 kg/ha and 16102.39 kg/ha of sequestered carbon, with 18.71 + -7.54 stems/m^2. Rural pathways had the longest stems. Main rural roads had the driest stems (59.24 ± 37.09 %) while rural pathways and main managed roads had the highest humidity values (78.22 and 80.52 % respectively). The different parameters per road and geographic areas are summarized in table 2.

The discriminant and factorial analysis grouped the plots in three main categories, which were 66.27 % discriminated by the dominant stems and the road categories (figure 4). The dominant stem characteristics represented by the factorial axis (FACT 1) explained alone 47.2 % of the difference between the three categories, while the road type and the remaining stems on the plot contributed for 19.1 %. As summarised on figure 5, the three geographic types of colonies were:

- The south region represented by the district of Zogbodomey. This region had the highest biomass production but the thinnest dominant stems, which were also shorter. It had the driest (40.36 %) and most dense colonies that supported their higher biomass and sequestered carbon potentials as described above. Regarding the road contribution, rural pathways in those areas had the lowest density but more long and large stems, while managed rural roads had the highest biomass production (23282.67 kg/ha) and sequestered carbon (34155.68 kg/ha).
- The Western areas, including the districts of Abomey, Agbangnizou, Bohicon, and Djidja. This area had intermediate biomass production of 11841.63 ± 11326.7 kg/ha, corresponding to 17371.68 ± 16616.3 kg/ha of sequestered carbon and a density of 17.7 ± 6.7 stems/m^2. The dominant stem represented 8.97 % of the total biomass of the colony, which had a relative humidity of 57.37 % ± 30.86%. The dominant stem measured 2.25 ± 0.47 m in length and

1.26 ± 0.5 cm in diameter. This area bore uniform colonies with a symmetric diametric structure around 1 to 1.5 cm in diameter. Main managed roads in this region had the highest biomass productivity (25820,74 kg/ha). The dominant stems of rural pathways and main managed roads had similar lengths and diameters. But the highest colony densities were obtained at main rural roadsides (19.9 stems/m^2).

- the group of plots located in Eastern parts, including the districts of Zangnanado, Zakpota, Ouinhi and Covè. This area had the lowest density and biomass productivity. There was a higher dominance effect of the dominant stem (more than 51.20 % of the total colony biomass), which was also more robust (2.22 ± 0.77 cm diameters and 2.30 ± 0.40 m long). The regions had an average dry matter of 1265.37 + -3060.16 kg/ha, corresponding to a sequestered carbon of 1856.30 + -4489.26 kg/ha from a higher density (19.32 + -9.1 stems/m^2). It then had the lowest carbon sequestration potential. Main rural roads in these areas had the longest and biggest stems, while the highest colony densities were found at main managed roads (19.49 stems/m^2). On the other hand, rural pathways had the highest biomass from drier stems.

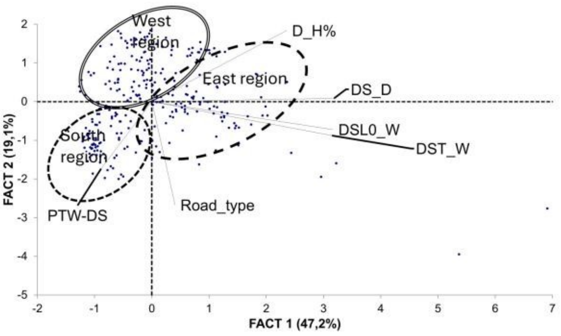


Figure 4 Factorial component analysis of the colonies

PTW-DS: Plot total weight, dominant stem excluded, DST_W: dominant stem total weight; DSL0_W: Dominant stem main branch weight; D_H: dominant stem diameter, 5cm above ground

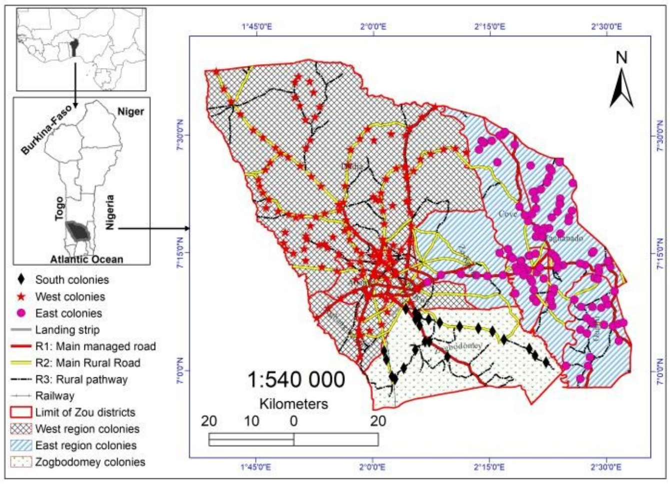


Figure 5 Geographic distribution of Hyptis suaveolens colonies in the department of Zou.

3.3. Morphologic Structures of the colonies

As indicated in figure 6a and 6b, the roads may only be distinguished when considering small-sized stems of less than 1.5 cm. Above this value, the colonies had the same diametric structure. As far as the total length of the dominant stem (TDS) was concerned (figure 6c), there was a symmetric distribution around 2 to 2.5 m for the entire roadside. Rural pathways had the highest diversity in the length of the main branch of the dominant stems in comparison to main managed roadside colonies. But, as for the diameter, most stems of the southern region were less than 1 m. They were followed by the stems of the West regions, while the East regions were dominated by longer stems of more than 2 m long (figure 6d).

The geographic diametric distribution pattern of the colonies (figure 6) indicated three colony populations with different modes. The district of Zogbodomey, located in the south, had the thinnest stems (1.1 + -0.5 cm), while the higher diameter ones were obtained in the Eastern part of the department. On the other hand, the length distribution of the stems indicated that the Eastern and Western regions had similar populations with long stems that were distinct from the colonies of the south. The different road types also had a similar distribution shape in which most colonies were 2 to 2.5 m long.

Regarding the density structure of the colonies (figure 6e and 6f), the South region colonies had a trimodal distribution while the colonies located in the West and East had a dissymmetric unimodal distribution. Rural roads had more diversified colonies that showed two modal distribution shapes.

Table 1 Conversion factor per road type and geographic areas.

Red Bold italic values are the average value of the area or type of road. DLO: Weight of the dominant stem main branch, TDS: Total weigh of the dominant stem

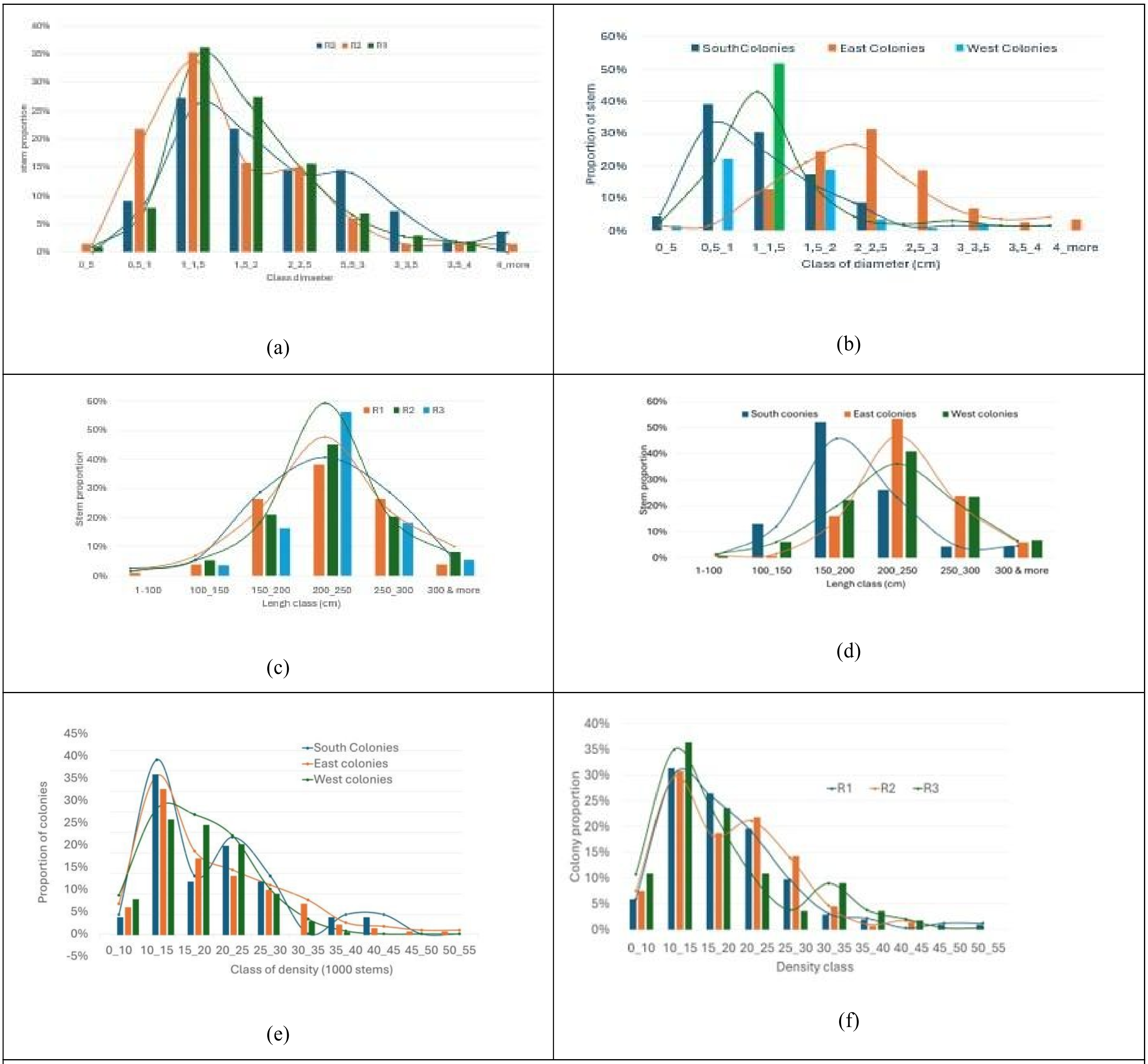
Location	General		Main paved and managed roads		Rural managed roads		Rural pathways and open areas	
	DL0 factor	TDS factor	DLO factor	TDS factor	DL0 factor	TDS factor	DL0 factor	TDS factor
Abomey	4.30%	8.16%	9.46%	18.47%	4.31%	6.28%	9.23%	100.00%
Agbangnizoun	4.09%	6.41%	9.68%	15.54%	6.35%	9.53%	**4.09%**	**6.41%**
Bohicon	7.26%	11.06%	7.33%	11.46%	7.26%	11.06%	6.58%	7.41%
Cove	26.15%	49.51%	25.02%	47.37%	28.72%	53.70%	24.14%	46.51%
Djidja	5.04%	8.86%	7.41%	12.11%	8.63%	16.14%	14.55%	35.91%
Ouinhi	24.50%	49.79%	20.14%	45.64%	25.56%	48.37%	26.25%	59.96%
Zangnanado	16.28%	42.10%	21.67%	51.23%	22.99%	67.26%	23.38%	54.85%
Zakpota	**7.75%**	**15.48%**	7.75%	15.48%	**7.75%**	**15.48%**	**7.75%**	**15.48%**
Zogbodomey	6.11%	9.01%	7.02%	14.78%	6.91%	10.39%	6.29%	10.00%

Table 2 average values of the colonies' parameter in the Soudano-guinean regions of the republic of Benin

D_DS: dominant stem diameter; TB_DS/ha: total biomass of dominant stem: L0_DS: length of the main branch of dominant stem; DSL0_W/ha: dominant stem main branch weight per ha; DS_H %: dominant stem humidity; PTW-DS/ha: total biomass of the plot, dominant stem excluded; TB/ha: total biomass per ha; % DSL0_W/TB: proportion of the dominant main stem over the total biomass of the plot; % TB_DS/TB: proportion of the dominant stem total biomass over the total biomass; SC/ha: sequestered Carbon/ha

Areas	Road_type	Density ha	D_DS	TB_DS ha	L0_DS	DSL0_W ha	DS_H %	PTW-DS ha	TB ha	% DSL0_W/TB	% TB_DS/TB	SC_ha
Zangnanado	Total	196641.6	2.4	471.1	2.4	182.1	92.40	647.9	1119.1	16.28%	42.10%	1641.7
	R_1	199575.4	2.1	458.0	2.3	181.5	94.53	449.7	907.7	21.67%	51.23%	1331.6
	R_2	200424.6	2.8	600.6	2.4	168.2	93.20	261.5	862.1	22.99%	67.26%	1264.7
	R_3	190412.3	2.5	383.5	2.4	193.8	89.41	1172.1	1555.6	23.38%	54.85%	2282.1
Zogbodomey	total	191636.7	1.1	1413.9	2.1	959.1	40.36	14272.4	15686.3	6.11%	9.01%	23011.7
	R_1	235668.8	1.4	884.4	2.4	523.0	69.27	7264.0	8148.4	7.02%	14.78%	11953.7
	R_2	174704.3	0.8	1795.1	1.8	1262.8	20.08	19096.0	20891.1	6.91%	10.39%	30647.3

	R_3	76433.1	2.2	312.1	2.3	196.2	93.00	2808.9	3121.0	6.29%	10.00%	4578.5
Zakpota	R_1	191082.8	1.8	291.6	2.3	146.1	80.38	1592.6	1884.2	7.75%	15.48%	2764.2
Ouinhi	Total	166159.0	2.0	209.9	2.1	106.4	96.14	273.6	483.6	24.50%	49.79%	709.4
	R_1	157961.8	2.1	214.9	2.1	92.5	96.50	327.8	542.7	20.14%	45.64%	796.1
	R_2	181983.6	1.9	210.6	2.1	119.1	95.68	285.1	495.7	25.56%	48.37%	727.2
	R_3	121019.1	2.1	201.3	2.0	78.9	97.33	165.8	367.1	26.25%	59.96%	538.6
Djidja	Total	179162.0	1.2	1148.6	2.3	653.1	53.01	11812.5	12961.0	5.04%	8.86%	19013.9
	R_1	177790.1	1.3	506.2	2.1	340.1	72.14	5876.4	6382.5	7.41%	12.11%	9363.2
	R_2	189209.4	1.2	1218.8	2.3	741.3	45.17	13752.8	14971.6	8.63%	16.14%	21963.3
	R_3	142958.2	1.4	1704.1	2.3	720.3	58.18	12067.6	13771.7	14.55%	35.91%	20203.0
Cove	Total	206444.4	2.1	385.1	2.3	203.3	92.39	1536.6	1921.7	26.15%	49.51%	2819.1
	R_1	198726.1	2.2	395.0	2.4	178.7	95.28	747.8	1142.7	25.02%	47.37%	1676.4
	R_2	196962.3	2.3	311.8	2.3	156.4	95.55	337.6	649.5	28.72%	53.70%	952.8
	R_3	224667.1	1.9	462.8	2.2	281.2	86.04	3670.6	4133.4	24.14%	46.51%	6063.7
Bohicon	Total	180891.7	1.4	597.1	1.9	441.5	63.66	7183.1	7780.1	7.26%	11.06%	11413.5
	R_1	179759.4	1.5	580.6	2.0	417.0	66.84	6946.1	7526.8	7.33%	11.46%	11041.8
	R_3	191082.8	0.6	745.2	1.2	662.4	35.00	9315.3	10060.5	6.58%	7.41%	14758.8
Agbangnizoun	Total	161358.8	1.4	434.4	2.3	277.3	75.14	6346.9	6781.2	4.09%	6.41%	9948.1
	R_1	195329.1	1.3	222.5	2.2	138.0	79.95	4520.5	4743.1	9.68%	15.54%	6958.1
	R_2	93418.3	1.6	858.0	2.4	556.0	65.53	9999.6	10857.6	6.35%	9.53%	15928.1
	Total	172884.4	1.3	826.6	2.2	436.1	69.43	9307.5	10134.1	4.30%	8.16%	14866.8
Abomey	R_1	151046.4	1.4	761.0	2.3	352.3	72.54	8034.8	8795.8	9.46%	18.47%	12903.4
	R_2	197452.2	1.1	910.5	2.1	685.2	58.32	13828.5	14739.0	4.31%	6.28%	21622.1
	R_3	331210.2	1.2	1242.0	2.1	114.6	92.50	0.0	1242.0	9.23%	100.00%	1822.1
Whole area	Total	184933.0	1.6	795.0	2.2	446.8	70.32	7048.2	7843.1	14.63%	30.92%	11505.84
	R_1	186212.1	1.6	513.0	2.2	279.0	80.52	4152.1	4665.0	13.12%	26.62%	6843.6
	R_2	187155.8	1.5	992.9	2.2	602.2	59.24	9983.5	10976.4	13.57%	27.77%	16102.4
	R_3	177185.9	1.9	839.2	2.3	382.4	78.22	5320.9	6160.1	6.21%	13.62%	9036.9



(a): diametric structure of the colonies per road category; (b): length structure of the colonies per road category; (c): diametric structure of the colonies per region; (d): length structure of the colonies per region. (e) Density structure of the colony per region. (f) Density structure of the colonies per road type. R1: Paved and unpaved managed road colonies; R2: Main rural road colonies; R3: rural path and open area colonies

Figure 6 Diametric, length, and density structure of the colonies along the different roads and geographic areas in the department of Zou

4. Discussion

4.1 A high biomass potential of the invasive Hyptis suaveolens

Our investigations proved that roadside Hyptis colonies were strong carbon sequestration units in the soudano Guinean regions of Benin. The colonies' productivity was higher than the total productivity and carrying capacity of the entire Sudano-Guinean areas of Benin, which ranged from 570 to 1140 kg of dry matter per ha, and the crop residues productivity that ranged from 250 to 3490 kg dry matter per ha (Sewade 2017; Djohy et al., 2022). With no care for boosting the plant yields, such high productivity and density may be the consequence of a lack of natural enemies in these ecosystems that characterize most invasive plants (Julien, 2002). In fact, Hyptis suaveolens has strong allelochemicals and essential oils that support its resistance against pathogens. It also has a great seed production and high adaptation to poor stations (Raizada, 2006; Padalia et al., 2015). Besides its strong fire resistance (Ibrahima et al., 2021), the particular soil structure and nutrient imbalance that work out from its highly dense root system and fast growth also exhaust native plants or weeds that finally starve (Hawkes et al., 2005; Afreen et al., 2018).

We found that the plant showed a global edaphic and climatic sensibility in the department as most plant species in Benin (Adomou, 2005; Sinadouwirou, 2023). In fact, the south, which benefits from higher rainfall and deeper soils, had a higher productivity. On the other hand, the Eastern region, which benefits from a higher rainfall in Benin, bore the less productive colonies, which were of small diameter and shorter. As the density of the colonies is similar between the different regions and road types, this fact indicates that the colony productivity was mainly determined by the edaphic conditions of the road categories. In these regards, two situations may explain the lower productivity of the Eastern area of the department. These areas are dominated by swamped and flooded areas, which also bear good forest cover (Adomou, 2025, IFN, 2022; Dadi et al., 2024) that limits the establishment of Hyptis colonies, which is highly heliophile. On the other hand, these areas are submitted to high agricultural land pressure (Todan et al., 2017; Souberou et al., 2018 Mashoudou et al., 2024). The regular land clearing of the roadside in these regions limits the growth of the plant considered as a weed.

The similarity of the colony's density regardless of the stational conditions also confirmed, as found by Afreen et al., (2018), the strong seedling potential of Hyptis suaveolens. This helps the plant establish in thick densities that change the structure and composition of plant communities in the dry tropical areas, where it disrupts the mineralisation procedures and Nitrogen/phosphorus balance on which native plants are built. As such, beyond the direct short-term impacts on the native plants, the invasive progressively transform the entire invaded geographic area in a "foreign" land to the local species leading to a definitive new ecological niche which becomes lethal to the native species (Aboh et al., 2017; Ngobo et al., 2004).

There was also no significant difference between the plant density at the different roadsides. This confirmed, as found by Aboh et al. (2008), the high germination capacity of the seed that didn't change upon the station. Despite the similar density per roadside categories, the colonies of rural pathways had higher productivity due to their greater size. This might be the consequence of the poorer land station of managed roadsides as a consequence of the mechanical removal of the upper rich layer. In fact, during the road management, the upper organic soils are removed, leading to a poor station that limits plant growth. Rural pathways, in addition to the fertile soil available for the invasive plant, are also less prone to erosion and constitute ideal stations in the country where Hyptis suaveolens thrive and spread to other regions through seed transportation from wind, runoffs, and human activities.

4.2. Valorization as a mitigation strategy

Hyptis suaveolens seems to be a free but very bulky vegetal resource available for different potential uses. Based on the average cost of 6 dollars/ton for sequestered carbon on the international market (https://www.hellocarbo.com/blog/compenser/prix-carbone/), the average 11.50 Tons/ha of sequestered carbon from this species in soudano-guinean regions of Benin had an average carbon potential of 75.9 dollars/ha. The thousand hectares of pure roadside hyptis colonies represent then a strong carbon capital available for the country. The high biomass production from the invasive constitutes also a strong bioenergy and other craft opportunities available in the distribution regions. In this regard, dry stems of the plants are already valued for firewood and other domestic fuel purposes, building fences, and creating crafty material (Johnson et al., 2020; Enagnon et al., 2024).

Other resource for the community is its high nectar sources that yield a great amount of "hyptis honey" in the entire country from November to December (Amakpe et al., 2024). But these great ecological footprints should be confronted to the numerous potential negative impacts of the plant in the invaded areas (McGeoch et al., 2023). In fact, roadside colonies hinder visibility, limit water circulation, making roads, invaded, swampy, and prone to road accidents. The high nectar production of the plant and its precocity also constitute great adaptation strategies that successfully lure pollinators from native plants and limit their seed production (Brett et al., 2024). As such, the plant still constitutes a great challenge to the bee populations and other pollinators in Benin (Seedley, 1985). The different valorization approaches still then require great care in order to prevent the plant spread and establish in vulnerable ecological areas which will make it more complicated to eradicate (Howard&Pecl, 2019; Johnson et al., 2018

5. Conclusions

Hyptis suaveolens is a strong dry matter productive plant in the soudano-guinean areas of Benin. It thrives in pure and uniformly dense colonies along roadsides. Such high density associated with its rapid growth. This helps the plant dominate native species, leading to a high biomass production, which may be valued as carbon sequestration and potentially as green energy. But such potentiality should be balanced with the ecological and socio-economic impacts of the species in the invaded areas. Deeper investigations are still needed in larger and more diversified ecological regions to elucidate the edaphic and ecological factors that discriminate the roadside hyptis colonies' productivity. The technical and socio-economic feasibility of the mitigation actions against this species in tropical areas should also be deepened in order not to introduce it into the production system of the country.

Acknowledgment

The authors thank the National NGO Cercle Nature et Developpement, the authorities of the different districts of the Zou department, for their kind cooperation in the data collection.

Statements & Declarations

Competing Interests

The authors have no financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Felicien AMAKPE. The first draft of the manuscript was written by Felicien AMAKPE and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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