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► **To cite this version:**

Victor Fredy Mita Quisbert, Dominique Herve. Estimating wood charcoal supply to Toliara town in southwestern Madagascar, a comparison of methods. *Scientific African*, 2021, 14 (3), pp.e01011. 10.1016/j.sciaf.2021.e01011 . hal-03849778

HAL Id: hal-03849778

<https://univ-montpellier3-paul-valery.hal.science/hal-03849778>

Submitted on 5 Jan 2024

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1 Title: Estimating wood charcoal supply to Toliara town in southwestern Madagascar, a
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20

21 Abstract

22 Wood charcoal is the main energy source used by households in developing countries.
23 However, due to the impact of wood charcoal production on forests, it is difficult to maintain a
24 sustainable supply of wood charcoal for towns located in semi-arid environments. The supply
25 of wood charcoal to the city of Toliara is a major challenge in southwestern Madagascar, the
26 most arid part of the island. To design and assess the feasibility of initiatives to address
27 these socio-environmental issues, an accurate estimation of the town's wood charcoal
28 consumption is required. This paper aims to estimate the annual quantity of wood charcoal
29 consumed in Toliara and to compare the errors associated with two estimation methods: (i)
30 observation of wood charcoal flows on the main roads entering the town, and (ii) survey
31 among Toliara wood charcoal traders (wholesalers and retailers). The first approach
32 provided an annual rate of wood charcoal entering Toliara of $43\,460 \pm 2\,017$ t (mean \pm standard
33 error). The second approach estimated annual wood charcoal consumption at $31\,247 \pm 3\,337$
34 t. The difference may essentially be explained by the fact that the first approach is more
35 comprehensive and includes all possible wood charcoal flows whereas the second approach
36 only includes those foreseen in the value chain model. The first approach gave more
37 accurate results, but is more difficult to replicate as it is more time-consuming and requires
38 more human and financial resources. Tree plantation was suggested to increase wood
39 charcoal supply in Toliara town. About 56 000 ha of eucalyptus plantations would be needed
40 to meet the current wood charcoal demand. Less than 500 ha of tree plantations have been
41 done until now essentially due to willpower and organisational problems.

42 Key words: charcoal, consumption, dry forest, flow, urban, xerophytic thicket

43 1. Introduction

44 Fuelwood (firewood and/or charcoal) is the main source of domestic energy in many
45 developing countries (Chidumayo and Gumbo 2013). Firewood is used in rural areas while
46 wood charcoal is mainly used in urban areas. The use of fuelwood as domestic energy in
47 developing countries is essentially due to the inaccessibility of alternative energy sources
48 such as electricity, gas and solar energy, which are not affordable (Cerutti et al., 2015). The
49 fuelwood market generally ensures the subsistence of poor households (Gardner et al.,
50 2015). Wood charcoal is the primary household energy source for the majority of urban
51 Africa, and its consumption is increasing with expanding urbanization (Cerutti et al., 2015;
52 FAO, 2017). Wood charcoal is an accessible, affordable and reliable energy source for
53 millions of households and its production supports millions of rural and urban livelihoods
54 through income generation (FAO, 2017). However, fuelwood harvesting causes forest
55 degradation by reducing forest biomass and tree abundance (Chidumayo and Gumbo,
56 2013). WC production is more detrimental to tropical forests than firewood harvesting
57 because it involves cutting down green trunks while the latter is generally associated with dry
58 wood collection (Minten et al., 2013; Win et al., 2018). Consequently, satisfying the growing
59 urban demand for wood charcoal remains a challenge for many poor tropical countries.
60 This challenge is all the more difficult to resolve in tropical semi-arid areas where the
61 sustainability of fuelwood production remains a socio-environmental issue (Ghilardi et al.,
62 2009). Dry forest annual wood increment is overall low (Mbow et al., 2013; Randriamalala et
63 al., 2017b) and wood harvesting for fuelwood production in semi-arid areas is largely
64 unsustainable (Ghilardi et al., 2009; Randriamalala et al., 2017b). Consequently, this activity
65 generally leads to dry forest degradation (Mbold et al., 2011; Chidumayo and Gumbo, 2013).
66 Dry forests, accounting for 40% of tropical forests worldwide, represent a crucial
67 conservation issue and are associated with high biodiversity (Miles et al., 2006). These dry
68 forests also are associated with low regeneration capability and resilience to disturbances
69 (Quesada et al., 2009).

70 In Madagascar, dry forests account for almost half of the forested surface area and are
71 associated with conservation issues, high biodiversity and low resilience to disturbances
72 (Waeber et al., 2015; Randriamalala et al., 2017b). Wood charcoal is the main energy source
73 for cooking in Madagascar (Minten et al., 2013). In the Central Highlands, wood charcoal
74 comes essentially from exotic tree plantations, while in western Madagascar, it comes mainly
75 from natural dry forests (Bertrand et al., 2010; Charpin et al., 2019). The main causes of
76 deforestation and forest degradation in western Malagasy semi-arid areas are slash-and-
77 burn agriculture and wood charcoal production (Casse et al., 2004; Brinkmann et al., 2014;
78 Randriamalala et al., 2017a and b). Bertrand et al. (2010) and Rafransoa et al. (2010) have
79 observed for decades that the fuelwood supply to towns in dry western Madagascar
80 (Mahajanga in the north and Toliara in the south) was not sustainable. Applied research to
81 define city fuelwood supply strategies was carried out in Mahajanga (1999-2000) and in
82 Toliara (2007-2008). Available wood resources, fuelwood consumption of rural and urban
83 households and fuelwood value chains were assessed (Rafransoa et al., 2010). One
84 condition for sustainable wood charcoal production is that the weight of wood removed
85 annually for wood charcoal production is lower than the annual wood biomass increment
86 associated with production sites (Brinkmann et al., 2014; Ranaivoson et al., 2015 and 2017;
87 Randriamalala et al., 2017b). The case of the city of Toliara is of greater concern because it
88 is in the most arid area of Madagascar (mean annual rainfall less than 400 mm and more
89 than nine dry months per year) where annual biomass increment of natural forest is weak
90 (Randriamalala et al., 2017b; Gaspard et al., 2018).

91 In southwestern Madagascar, wood charcoal production has contributed to the decline of the
92 dry forest biomass and may lead to the local extinction of wood charcoal tree and shrub
93 species within a couple of decades (Randriamalala et al., 2017b). Toliara is the main town
94 and the main wood charcoal consumer in southwestern Madagascar (Andrianarivony et al.,
95 2012; Masezamana et al., 2013; Randriamalala et al., 2017b). Wood charcoal production is a
96 safety net activity for households essentially during the dry season (Masezamana et al.,

97 2013; Gardner et al., 2015). The sustainability of Toliara's supply of wood charcoal remains
98 problematic (Andrianarivony et al., 2012; Randriamalala et al., 2017b), because it is
99 dependent on the conservation of the southwestern dry forest and local population growth.
100 The dry forests also are an important source of livelihoods as they provide firewood,
101 construction wood, non-timber forest products and pasture for goats (Waeber et al., 2015;
102 Randriamalala et al., 2016).

103 The implementation of a fuelwood supply strategy in Toliara resulted in (i) the promulgation
104 in 2012 of a regional decree governing the fuelwood sector (*Arrêté Régional 022 MATD/RSO*
105 *du 30 mars 2010*), and (ii) the development in 2018 of a Regional Biomass Energy Plan
106 (PREB) for the period 2019-2033 (*Région Atsimo Andrefana, 2018*). These two provisions
107 serve to promote the following activities:

- 108 (i) identification of the main actors of the fuelwood value chain (producers, transporters,
109 traders),
- 110 (ii) promotion of sustainable management of forestry resources through the transfer of forest
111 management to local communities for wood charcoal production,
- 112 (iii) implementation of decentralised control systems and a decentralised tax system,
- 113 (iv) promotion of improved wood charcoal kilns.

114 These initiatives are implemented jointly by the regional branch of the Ministry of Forestry
115 and international NGOs (WWF and GIZ). The availability of accurate and up-to-date data on
116 wood charcoal consumption in Toliara is a key factor for the assessment of the feasibility and
117 potential success of these initiatives. However, such data are scarce (ABETOL, 2007;
118 Andrianarivony et al., 2012).

119 Furthermore, such an estimate of wood charcoal supply/consumption presents
120 methodological challenges even at the international level. The approach that has been
121 currently used to tackle this problem involves surveys of part or all the actors of the fuelwood
122 (firewood and/or charcoal) value chain: producers, collectors, transporters, traders,
123 consumers (Mwampamba, 2007; Baumert et al., 2016; Puentes-Rodriguez et al, 2017; Win
124 et al., 2018). The objectives of such approach are the assessment of fuelwood consumption

125 (Mwampamba, 2007 for charcoal; Serrano-Medrano et al., 2017 and Win et al., 2018 for
126 charcoal and firewood), the analysis of fuelwood value chains (Baumert et al., 2016 for
127 charcoal; Puentes-Rodriguez et al., 2017 for firewood) and/or fuelwood value chain
128 sustainability analysis by comparing fuelwood consumption to biomass production at the
129 harvest sites (Masera et al., 2006; Ghilardi et al., 2009 and 2016, for firewood; Bär et al.,
130 2017; Chiteculo et al., 2018 for firewood and charcoal). An inference of data from actors of
131 the fuelwood value chains (consumptions and/or supply quantities) is generally the method
132 used by these previous studies to assess the amount of fuelwood supply/consumption.

133 Another approach is less widely applied, the observation of WC flows on the transportation
134 axes connecting forest sites to urban consumers (Rafransoa et al., 2010 and Charpin et al.,
135 2019 in Madagascar, Alem et al., 2010 in Ethiopia). To date, there has been no critical
136 analysis of this wood charcoal flow approach. Furthermore, hardly any study has examined
137 the statistical errors associated with estimates of urban charcoal consumption, although the
138 reliability of the estimations is contingent on these.

139 This paper tackles the socio-environmental problem of wood charcoal supply in semi-arid
140 southwestern Madagascar and the methodological aspects involved in estimating urban
141 wood charcoal consumption. The aims are to (i) assess the wood charcoal consumption of
142 the town of Toliara, the main wood charcoal consumer in southwestern Madagascar, and (ii)
143 compare the reliability of two approaches (corresponding to minimal error), wood charcoal
144 flow observation on the main roads entering the town of Toliara and surveys of wood
145 charcoal traders in the town.

146

147 2. Methods

148 2.1. Study site

149 The study site covers the Districts of Toliara I and II in southwestern Madagascar (Fig. 1).
150 The climate is semi-arid with a high rainfall gradient. The climate is drier in the southern part
151 of the study site ($P < 400$ mm/year; ≥ 9 dry months; Gaspard et al., 2018) and wetter in its
152 northern part ($P = 600-1000$ mm/year; 7-8 dry months; Leprun et al., 2009).

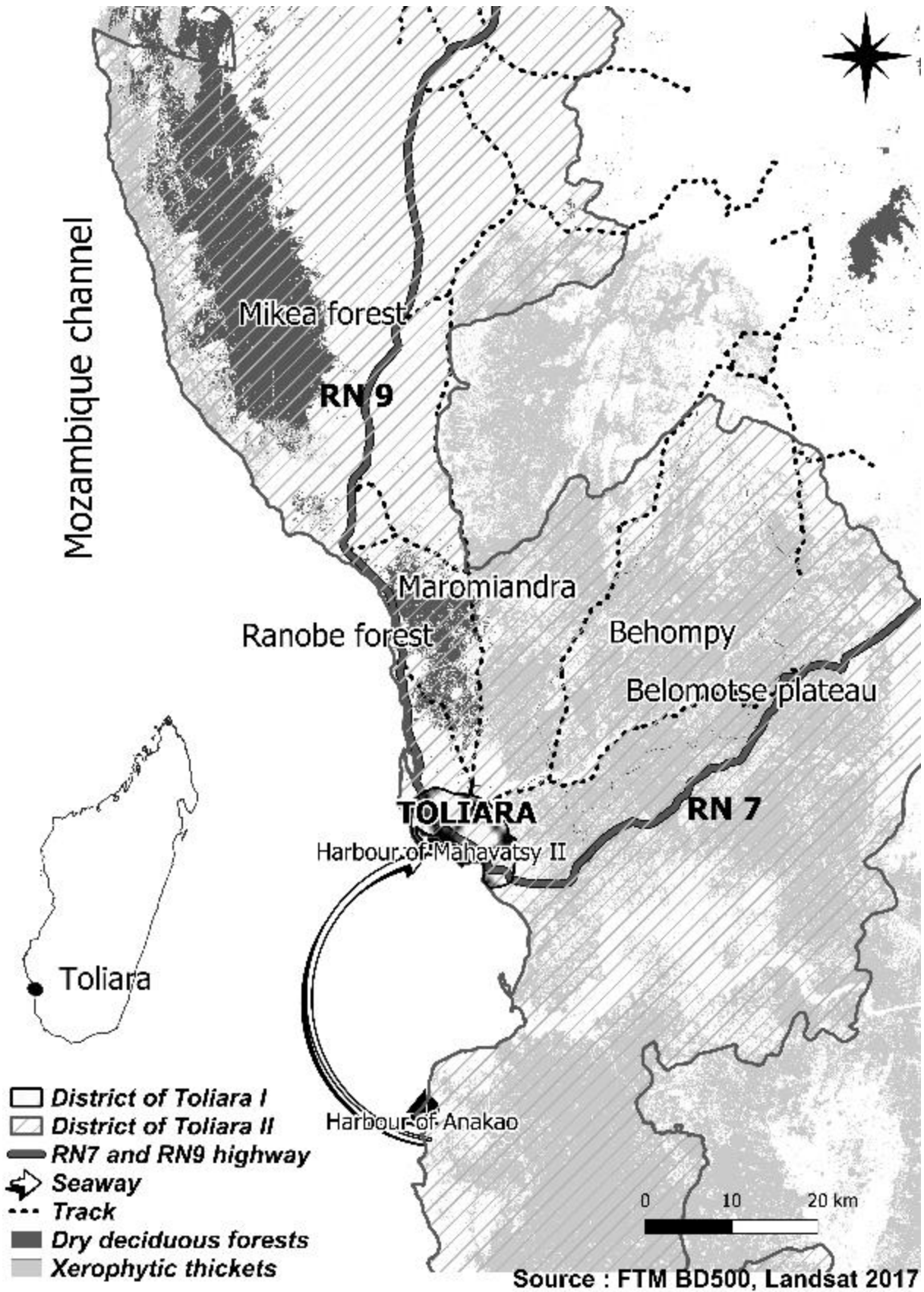
153 The natural vegetation of the study site (Fig. 1) is shrubby xerophytic thickets in the southern
154 part, characterised by *Didiereae* and *Euphorbia* spp., <5 m height (Randriamalala et al.,
155 2016), and woody dry deciduous forest in the northern part, characterised by *Commiphora*
156 spp. and *Euphorbia* spp., with emergent individuals >10 m height (Raherison and Grouzis,
157 2005) and savanna dominated by *Heteropogon contortus* (Rakotoarimanana et al., 2008).
158 The population of Toliara I District, which includes Toliara town and its surrounding villages,
159 was 169 760 inhabitants in 2019 (INSTAT, 2019) and the population of Toliara II District was
160 369 485 (INSTAT, 2019). Local populations belong mainly to the *Tanalana*, *BaraMasikoro*
161 and *Vezo* ethnic groups.

162

163 2.2. Wood charcoal production at the study site

164 Wood charcoal is mainly used to cook daily meals. Demand for charcoal in southwestern
165 Madagascar comes essentially from Toliara, the main town in the area, and is increasing as
166 the town grows (Andrianarivony et al., 2012; Masezamana et al., 2013; Gardner et al., 2015).
167 Wood charcoal production is an important source of income for poor people who possess
168 small herds of small ruminants and bovines and who do not possess extensive crop fields
169 (Raoliarivelo et al., 2010; Masezamana et al., 2013; Neudert et al., 2015). Wood charcoal is
170 produced from between 9 and 12 months out of the year (Masezamana et al., 2013). The
171 current main wood charcoal production sites in Toliara II District are located within a circle of
172 less than 40 km radius around Toliara town (Fig.1), that is to say in the Ranobe dry
173 deciduous forest and in the xerophytic thicket of the Belomotse Plateau (Andrianarivony et
174 al., 2012; Randriamalala et al., 2017a). The wood charcoal production process had been
175 described precisely by Randriamalala et al. (2016).

176



177

178 Fig. 1. Study site and location of the main transport axis of wood charcoal in Toliara town

179

180

181 There are five main wood charcoal transport axes entering Toliara town, as identified in Fig.
182 1: (i) the RN9 highway, (ii) Maromiandra track, (iii) Miary tracks from Behompy and
183 Belomotse Plateau, (iv) the RN7 highway and (v) Mahavatsy II harbour. The three first
184 transport axes come from the Ranobe and Behompy forests in the north (Fig. 1). RN7
185 crosses the xerophytic thickets of the Belomotse Plateau in the southeastern part of the
186 study site (Fig.1). WC produced in the xerophytic thickets of the southern part of the study
187 site (Soalara-Sud and Beheloka municipalities) is unloaded at Mahavatsy II harbour
188 (Randriamalala et al., 2017b).

189

190 2.3. Direct observation of wood charcoal supply flow to Toliara town

191 A census of the daily number of wood charcoal transports entering Toliara town was carried
192 out during the dry (October 2017) and rainy (January 2018) seasons. The census was
193 carried out from 5 am to 6 pm on the five main wood charcoal transport axes entering the
194 town for one week (seven days) per axis (five axes) and per season (dry and rainy seasons).
195 The main types of transport observed are listed according to their maximum height capacity
196 (Hervé et al., 2021b): (i) trucks, (ii) pirogues, (iii) private cars (essentially off-road vehicles),
197 (iv) public transport vehicles (*minibus*), (v) taxicabs, (vi) ox-carts, (vii) man-hauled carts, (viii)
198 motorcycles, (ix) bicycles, (x) tricycles (*cyclopousse*), and (xi) human carrying. The size and
199 number of wood charcoal sacks are observable in all of these means of transportation except
200 in trucks. To estimate the mean number of sacks transported by trucks, six wood charcoal
201 unloads were observed to count the number of unloaded sacks and check their size. For
202 each type of transport and for each type of sack, sampled sacks ($N \geq 6$) were weighed in order
203 to estimate their mean weight.

204 Wood charcoal production is expected to be more intensive during the dry season, when
205 transportation is easier and food shortages occur (Raoliarivelo et al., 2010). This is the
206 reason why two seasons are distinguished, the dry and rainy seasons. The duration of the

207 dry season is $d_s=274$ days (365 days x 9 months / 12 months) and the duration of the rainy
 208 season is $d_h=91$ days (365 days x 3 months / 12 months).

209 The weight of the wood charcoal, which is carried via roads and tracks to Toliara city, is
 210 estimated by multiplying the mean weight of charcoal sacks by the daily number of sacks,
 211 which enter the city, and the duration of the season. The calculation is completed by season,
 212 by road, by type of sacks, and by means of transportation, accordingly to equation (1):

$$213 \quad AW = \sum_{s(s=1-2)} \sum_{i(i=1-5)} \sum_{j(j=1-2)} \sum_{k(k=1-11)} E(W_j) \times E(SN_{ijks}) \times d_s = [E(W_1) \times E(SN_{1111}) \times d_1] + \dots + [E(W_j) \times$$

$$214 \quad E(SN_{ijks}) \times d_1] + \dots + [E(W_2) \times E(SN_{25211}) \times d_2]$$

215 Where AW is the annual weight of wood charcoal entering Toliara town (kg), $E(W_j)$ the mean
 216 weight of j^{th} type of sack (kg), $E(SN_{ijks})$ the mean daily number of j^{th} type of sack transported
 217 by k^{th} means of transport on the i^{th} transport axis during the s^{th} season, and d_s is the duration
 218 of the s^{th} season (day).

219 Errors associated with WC weights entering Toliara town could be estimated by applying the
 220 errors propagation principle (Ku, 1966; Farrance and Frenkel, 2012). If Y is a function of $X_1,$
 221 X_2, \dots, X_n variables with uncertainties $\delta X_1, \delta X_2, \dots, \delta X_n,$ the error associated to Y can be
 222 calculated by the following equation (2):

$$223 \quad \delta Y^2 = ([dY/dX_1] \times \delta X_1)^2 + ([dY/dX_2] \times \delta X_2)^2 + \dots + ([dY/dX_n] \times \delta X_n)^2$$

224 Where dY/dX_i is partial derivative of Y with respect to $X_i,$ X_i variables represent mean sack
 225 weight $E(W_i)$ and mean daily sack number $E(SN_{ijk})$ in equation 1 and δX_i are their standard
 226 errors.

227 The main error sources are the mean sack weight and the mean daily number of sacks. The
 228 error associated to wood charcoal weight unpacked in a particular sack type entering Toliara
 229 town through a particular transport axis, by a particular means of transport during a particular
 230 season can be calculated by the equation (3):

$$231 \quad e = ([d_s \times E(SN) \times \delta_w]^2 + [d_s \times E(W) \times \delta_{SN}]^2)^{1/2}$$

232 Where e is the error associated to wood charcoal weight during a particular season (kg), d_s
 233 the length of the season (day), $E(SN)$ the daily mean number of counted wood charcoal
 234 sacks during the season, δ_w the error associated to the sack weight (standard error; kg),

235 E(W) the mean sack weight (kg) and δ_{NS} the error associated to the daily mean number of
 236 counted wood charcoal sacks during the season (standard error; kg).

237 Total error associated to wood charcoal weight entering Toliara town can be calculated by
 238 the equation (4):

$$239 \quad e = \left(\sum_{s=(1-2)} \sum_{i=(1-5)} \sum_{j=(1-2)} \sum_{k=(1-11)} e_{ijks}^2 \right)^{1/2} = (e_{1111}^2 + \dots + e_{ijks}^2 + \dots + e_{2521}^2)^{1/2}$$

240 Where e is the total error associated to wood charcoal weight entering Toliara town, e_{ijks} the
 241 particular error taking into account season (s; two), transport axis (i; five), sack type (j; two)
 242 and means of transport (k; 11) (Tab. 1).

243

244 2.4 Wood charcoal trade surveys in Toliara town

245 Wood charcoal traders were surveyed in Toliara town to corroborate the data from the five
 246 transport axis observations. All of the wood charcoal wholesalers and retailers in the 40
 247 *arrondissements* of Toliara town were inventoried by questioning the *arrondissement* chiefs
 248 or representatives, amounting to 185 wholesalers and 755 retailers. Monthly wood charcoal
 249 (i) supply frequencies and (ii) sales of random samples from 53 wood charcoal wholesalers
 250 and 52 wood charcoal retailers were surveyed. The sale units of wholesalers are the sacks
 251 that they make themselves. Retailers do not source from wholesalers because this would
 252 increase the cost of the wood charcoal. Retailers receive wood charcoal directly from
 253 producers and pay the transport costs (Masezamana et al., 2013), they then unpack sacks
 254 from producers to make retail sales.

255 The monthly quantity of wood charcoal supplied to a wood charcoal trader is the product of
 256 three factors: (i) the monthly frequency of supply, (ii) the number of sacks per supply and (iii)
 257 the average weight of the sack, which are shown in the equation 5:

$$258 \quad w_i = f_i \times N_i \times E(SW)$$

259 Where w_i is the monthly wood charcoal supply of the i^{th} WC trader (kg); f_i is the monthly
 260 frequency of wood charcoal supply of the i^{th} WC trader, N_i is the number of sacks at each
 261 wood charcoal supply of the i^{th} WC trader; and $E(SW)$ is the mean sack weight (kg).

262

263 To obtain the total monthly quantity that is supplied to a wood charcoal trader, repeat the
 264 above operation for each type of sack and add these up.

265 The annual quantity of wood charcoal supplied to all of the wood charcoal traders in the city
 266 of Toliara is the sum of the quantities of wood charcoal per season (equation 6) :

$$267 \quad W=(E[w_{1ds}] \times NR \times d_{ds}) + (E[w_{1rs}] \times NR \times d_{rs}) + (E[w_{2ds}] \times NW \times d_{ds}) + (E[w_{2rs}] \times NW \times d_{rs})$$

268 Where $E[w_{1ds}]$ is the mean monthly wood charcoal weight supplied to retailers during the dry
 269 season (kg), NR is the total number of retailers in Toliara town (=755), d_{ds} is the duration of
 270 the dry season (months), $E[w_{1rs}]$ is the mean monthly WC weight supplied to retailers during
 271 the rainy season (kg), d_{rs} is the duration of the rainy season (month), $E[w_{2ds}]$ is the mean
 272 monthly wood charcoal weight supplied to wholesalers during the dry season (kg), NW is the
 273 total number of wholesalers in Toliara town (=185), $E[w_{2rs}]$ is the mean wood charcoal
 274 monthly weight supplied to wholesalers during the rainy season (kg).

275 The sources of error in the calculations are (i) the average frequency of monthly supplies, (ii)
 276 the average number of sacks per average monthly wood charcoal supply, and (iii) the
 277 average sack weights (Tab. 1). The same propagation error rules (equations 2 to 4) were
 278 applied to estimate errors associated to the results.

279

280 Tab. 1. Main error sources of wood charcoal trade surveys

Type of wood charcoal trader	Season	Monthly frequency of wood charcoal supply	Number of sacks at each wood charcoal supply	
			1st type of sack (25.11±0.51 kg; n=10)	2nd type of sack (51±1.76 kg; n=10)
Retailer	Dry season	9.46±1.50	7.79±1.37	
	Rainy season	10.38±1.60	7.35±1.30	
Wholesaler	Dry season	6.91±0.30	27.92±1.62	29.78±2.77
	Rainy season	2.96±0.17	25.28±1.92	29.64±2.59

281

282

283

284 3. Results

285 Two main types of wood charcoal sacks were reported: small sacks with a mean weight of
286 25 ± 0.51 kg (N=10) and large sacks with a mean weight of 51 ± 1.76 kg (N=10). These large
287 sacks are only used by wholesalers (Tab. 1).

288

289 3.1. Wood charcoal supply flow to Toliara town

290 The annual weight of wood charcoal entering Toliara town is $43\,460\pm 2\,017$ t (Tab. 2;
291 equations. 1 to 4). Trucks are the main means used to transport wood charcoal (>60% of the
292 annual wood charcoal weight; Fig. 2). Most of the wood charcoal supplies for Toliara town
293 (Fig. 3) arrive via RN9 (>50% of total weight) and RN7 (>20%).

294

295 3.2. Wood charcoal trade surveys in Toliara town

296 The annual weight of wood charcoal supplied to Toliara traders is about $31\,247\pm 3\,337$ t. The
297 share supplied to retailers ($16\,910\pm 3\,158$ t) is roughly equal to that supplied to wholesalers
298 ($14\,337\pm 1078$ t). Trucks are the main means used to transport wood charcoal supplies to
299 wholesalers. The number of wood charcoal retailers is greater but their total wood charcoal
300 weight does not differ significantly from those of wholesalers because they are supplied by
301 ox-carts, pirogues, bicycles and to a lesser extent by trucks. Urban households are the main
302 wood charcoal customers of wholesalers and retailers. Other customers of wholesalers are
303 restaurants, small restaurants (*gargotte*), and school canteens.

304 Tab. 2. Annual weight of wood charcoal by transport axis (Value±Error calculated by error propagation principle). First type of sack
 305 weight=25±0.51 kg (n=10); Second type of sack weight=51±1.76 kg (n=10)

Axis of transport	Means of transport	Dry season			Rainy season		
		Mean daily number of 1st type of sack	Mean daily number of 2nd type of sack	Wood charcoal weight entering Toliara town (t)	Mean daily number of 1st type of sack	Mean daily number of 2nd type of sack	Wood charcoal weight entering Toliara town (t)
Mahavatsy harbour	Pirogues	40.86±13.5 2	107.14±28.33	1 782.56±411.05	61±58.53	57.86±40.48	1 230.23±232.08
Maromiandra track	Ox-carts	436.86±73. 27		3 002.90±506.42	726.86±56. 43		1 594.30±129.45
Miary track	Ox-carts	187.14±30. 78		1 296.41±212.60	327.57±35. 44		658.80±73.26
	Tricycles (<i>cyclopousse</i>)	0.71±0.71		4.91±4.91			.
	Bicycles	0.71±0.36		4.91±2.47			.
RN7 highway	Trucks		380.29±54.38	5 330.08±502.11		411.98±69.6 7	1 924.75±332.12
	Bicycles	302.14±6.3 1		2 076.89±60.67	368.29±21. 44		843.85±160.55
	Public transport cars (<i>minibus</i>)			.	26.57±3.20		60.88±7.43
	Private cars (essentially off-road vehicles)			.	7.00±1.38		16.04±3.18
	Ox-carts	1.71±1.71		11.78±11.79			.
	Man-hauled carts			.	3.00±3.00		6.87±6.88
	Tricycles (<i>cyclopousse</i>)			.	0.38±0.38		0.00±0.86
RN9 highway	Truckss		1 045.19±106.67.0 0	14 657.73±1 577.40		950.71±146. 33	4 441.74±700.41

Axis of transport	Means of transport	Dry season			Rainy season		
		Mean daily number of 1st type of sack	Mean daily number of 2nd type of sack	Wood charcoal weight entering Toliara town (t)	Mean daily number of 1st type of sack	Mean daily number of 2nd type of sack	Wood charcoal weight entering Toliara town (t)
	Public transport cars (<i>minibus</i>)	411.29±52.30		2 827.12±364.12	538±53.64	216.29±37.93	1 232.71±125.45
	Ox-carts	26.71±5.93		183.63±40.91	51±6.02		116.86±13.99
	Private cars (essentially off-road vehicles)	11.14±0.91		76.59±6.45	7.14±1.37		16.37±3.16
	Tricycles (<i>cyclopousse</i>)	1.00±0.72		6.87±4.98	7.43±3.18		17.02±7.30
	Bicycles	0.86±0.55		5.89±3.81	7.00±1.23		16.04±2.85
	Human carrying	0.57±0.37		3.93±2.54	2.43±0.87		5.56±0.48
	Taxicabs	0.86±0.40		5.89±2.78			.
	Motorcycles			.	0.14±0.14		0.33±0.33
	Total			31 278.10±1 830.06			12 182.35±847.80

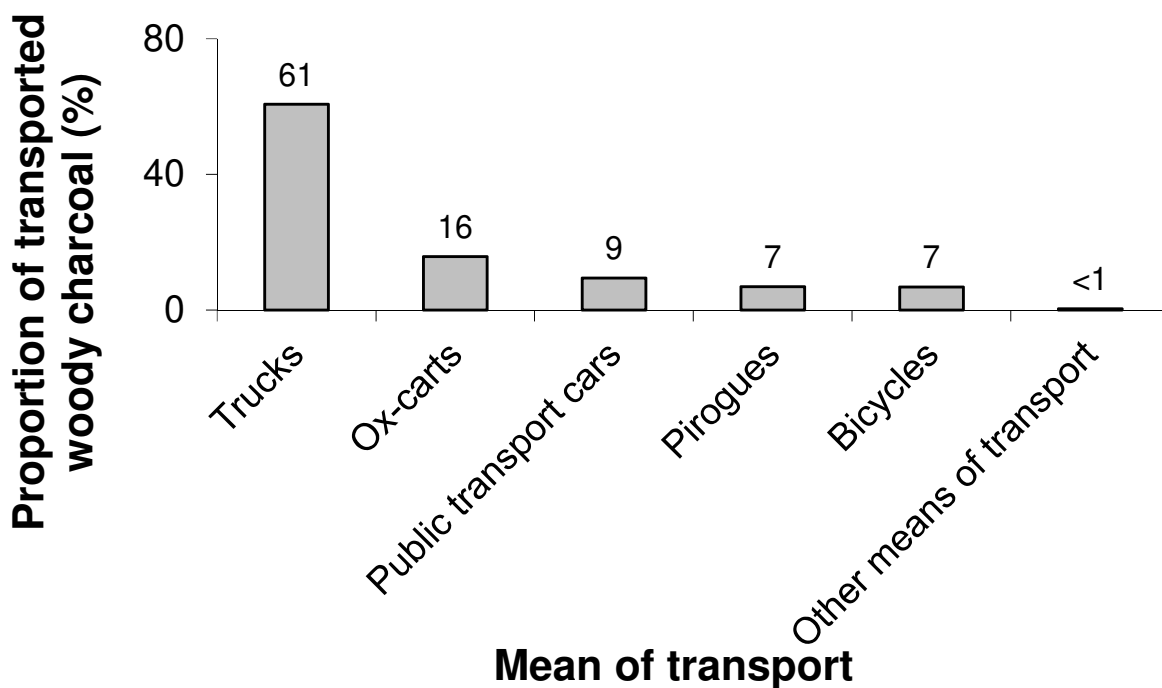
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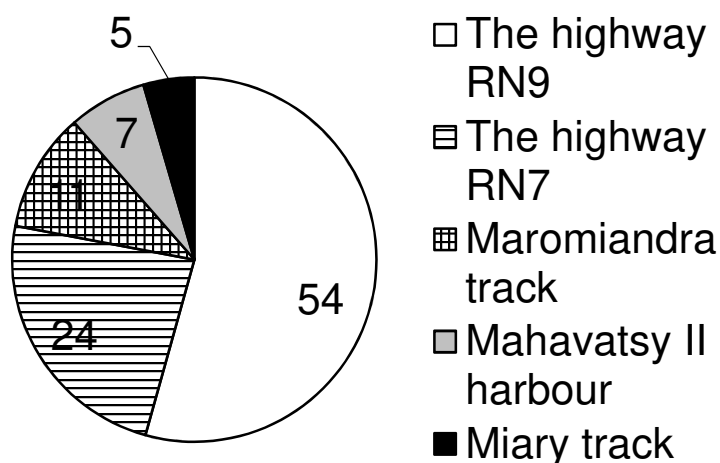
310



311

312 Fig. 2. Share of the different means used to transport WC supplies to Toliara town (% of
 313 43 460 t wood charcoal)

314 [Other means of transport: private cars and taxicabs, tricycles and motorcycles, man-hauled carts and
 315 human carrying]



316

317 Fig. 3. Provenance of wood charcoal supplies to Toliara town (% of 43 460 t wood charcoal)

318

319

320 4. Discussion

321 4.1. Which approach is the best to estimate wood charcoal supply?

322 There is a considerable difference between the wood charcoal supply estimated from the
323 observation of transportation axes (43 460 t) and that estimated from the survey of wood
324 charcoal traders (31 247 t) (~12 000 t; ~28% of value obtained by transport axis
325 observation). This may be explained by the fact that some wood charcoal goes directly to
326 consumers, for example that transported by public transport vehicles (minibus) and private
327 cars (essentially off-road vehicles). Moreover, some of the wood charcoal transported by
328 bicycles, ox-carts and pirogues is delivered directly to urban households and does not transit
329 through wholesalers or retailers. The higher value (43 460 t) estimated by the axis transport
330 observation method thus may be nearer the real annual wood charcoal consumption of
331 Toliara town. Moreover, the relative error (SE/mean) associated with the axis transport
332 observation method (5%) was lower than that associated with the wood charcoal traders
333 survey (11%). To our knowledge, an assessment of uncertainties related to annual urban
334 wood charcoal consumption has never been carried out. The uncertainties associated with
335 existing data, even at the international level, are generally not available.

336 The axis transport observation method seems to be more reliable because it includes all
337 possible wood charcoal flows whereas the trader survey approach only includes those
338 predicted in the value chain model (producer→transporter→trader→consumer) and may omit
339 other unknown market circuits. Moreover, the observation method is more objective as it
340 consists of direct observations of flows and does not depend on subjective information from
341 wood charcoal traders. The structured interviews were conducted within a sample of wood
342 charcoal traders with several limits. Human memory is not infallible (Wright et al., 1997;
343 Carrasco et al., 2014) and responses from face to face interview can be biased as these can
344 be influenced by question formulation (Minson et al., 2018) or by the interviewers themselves
345 (Alshenqeti, 2014). In addition, it has been shown that structured face-to-face interviews
346 result in less honest responses than mail surveys (Preisendörfer and Wolter, 2014).

347 Moreover, wood charcoal traders generally have an interest in minimising the reported
348 values of their wood charcoal supply to protect themselves against possible increases in
349 taxes payable to the forestry and fiscal authorities. All these factors may also explain the
350 underestimation of the WC supply values obtained by trader surveys approach.

351 The interests of the axis transport observation approach are the possibility to repeat the
352 observations at another date with the same protocol and to detect outliers results, but it
353 requires more logistical and financial means (staff and their wages, duration and planning of
354 observations). This approach is adapted to wood charcoal urban supply estimation and is
355 difficult to generalise to a larger scale (district, province or country) as it would have to be
356 implemented for at least all major urban areas.

357

358 4.2. Mean rate of wood charcoal consumption

359 The annual wood charcoal consumption of Toliara town is far lower than that of Antananarivo
360 town, the capital of Madagascar, which amounts to 230 292 t (Charpin et al., 2019). The
361 difference in the population sizes of these two towns may be one reason behind this. In fact,
362 the population of Toliara is seven times smaller than that of Antananarivo (169 760 vs
363 1 275 207; INSTAT, 2019). However, the wood charcoal consumption per capita of Toliara
364 town (ratio between annual wood charcoal consumption and population size) is higher than
365 the wood charcoal consumption per capita of Antananarivo town, 256 and 104 kg/year per
366 capita, respectively (Charpin et al., 2019). The availability of alternative energy sources for
367 cooking, such as gas and electricity, in Antananarivo may explain the lower wood charcoal
368 consumption per capita than in Toliara. The cost of gas cylinders is higher in Toliara (~1000
369 km from Antananarivo) due to the extra cost linked to transportation. Furthermore, the nature
370 of the staple foods consumed in each town also may explain this difference: dry cassava,
371 which takes more than one hour to cook, is the staple food of the *Masikoro*, *Mahafaly* and
372 *Tanalana*, the dominant ethnic groups in Toliara, while rice, which can be cooked in a few
373 minutes, is the staple food in Antananarivo. Moreover, because of their busier schedules,

374 some inhabitants of the capital prefer street food for lunch or even dinner rather than
375 preparing meals at home (Charpin et al., 2019).

376 The annual wood charcoal consumption per capita in the study site is higher than that of rural
377 and urban areas in Kenya (95-130 kg/year per capita; Kituyi et al., 2001) and Kampong
378 Thom Province in Cambodia (120 kg/year per capita; Top et al., 2003), while it is comparable
379 to that of the rural area of Yedashe township in Myanmar (280 kg/year per capita; Win et al.,
380 2018). This variation of annual wood charcoal consumption per capita at the international
381 level also may be explained by the availability of alternative energy sources, with those who
382 use wood charcoal exclusively having a higher consumption rate, and by the nature of the
383 country/population's staple foods with cooking durations that may vary.

384

385 4.3. Ranobe and Behompy forests, to the north of Toliara town, are the main current wood
386 charcoal production sites

387 Wood charcoal supplies for Toliara town mainly pass through the transport axes from the
388 north: RN9 (54% annual weight), Maromiandra (11%) and Miary (5%); the flows of wood
389 charcoal from RN7 (24%) and Mahavatsy harbour (7%) are less important (Fig. 3).

390 Consequently, the current wood charcoal production sites supplying Toliara town are Ranobe
391 forest and the Behompy xerophytic thickets that are connected to Toliara town by the first
392 three transport axes (Fig. 1). The dry forest of Mikea has been spared so far because of its
393 relative remoteness (>50 km north of Toliara town), but the recent asphaltting of the RN9 over
394 a distance of about 100 km from Toliara could change this relatively protected situation.

395 The importance of the xerophytic thickets of the Belomotse Plateau crossed by the RN7 as a
396 charcoal production site is on the decline. This forest was the main wood charcoal production
397 site supplying Toliara town in the 1990s (Mana et al., 2001). Wood charcoal production and
398 slash-and-burn agriculture have exhausted the woody resources of the xerophytic thickets of
399 this RN7 site to the point that in some locations the roots of the shrubs are dug up to be used
400 as wood charcoal biomass (Randriamalala et al., 2017a).

401 The share of the xerophytic thickets south of Toliara in the town's wood charcoal supply is
402 low (7%; Mahavatsy II harbour; Fig. 1). The relative inaccessibility of the corresponding
403 production sites by road may explain this phenomenon; pirogues are used to cross a
404 distance of 30-35 km by sea. The depletion of woody resources on the Belomotse Plateau
405 has shifted wood charcoal production sites to the Ranobe dry forest and the Behompy
406 xerophytic thickets. When these are exhausted, the pressures on the xerophytic thickets
407 south of Toliara town and on the Mikea dry forests to the north could exacerbate and
408 accelerate their degradation or even their disappearance.

409

410 4.4. Implication for wood charcoal governance in southwest Madagascar

411 Toliara town's annual consumption of wood charcoal has increased by more than 600%
412 since 1991 and by more than 130% in the last 10 years (Tab. 3). This annual consumption is
413 increasing with population growth while the forest resources supplying wood charcoal
414 biomass are shrinking year by year (annual forest loss >1%; Randriamalala et al., 2015). A
415 periodic update (every 5-10 years) of this annual wood charcoal consumption is necessary.
416 Forest management authority agents with the support of the police forces could undertake
417 such updates.

418 To date, no accurate study has assessed the balance between wood collection for wood
419 charcoal production and the annual increase in biomass from the forests of the wood
420 charcoal production sites supplying Toliara town. Only Randriamalala et al. (2017b) have
421 made this balance assessment for xerophytic thickets located south of Toliara town, which
422 account for less than 7% of the city's wood charcoal annual supply (Mahavatsy harbour; Fig.
423 3). They showed that wood charcoal production at their site would result in the
424 disappearance of wood charcoal species in less than 20 years. The use of shrub roots to
425 produce wood charcoal at some sites of the Belomotse Plateau (RN7 axis; Fig. 3;
426 Randriamalala et al., 2017a) confirms this lack of sustainability of wood charcoal production
427 in southwestern Madagascar, which will lead to the disappearance of wood charcoal species
428 within a finite period. Consequently, the transfer of forest management to local communities

429 for wood charcoal production purposes, and the biomass resources economy (improved kiln
 430 design) promoted by the fuelwood supply strategy in Toliara may not be sufficient. An
 431 increase in wood charcoal biomass supply through the plantation of fast-growing exotic
 432 species is necessary to complete this strategy.

433 Tab. 3. Increase in wood charcoal annual consumption for the town of Toliara

Years	Wood charcoal annual consumption (t)	Wood charcoal methods	Sources
1991	7 029	Value chain survey	ABETOL (2007)
2000	10 372	Value chain survey	
2007	33 391	Flow observation	
2017-2018	43 460	Flow observation	This study

434

435 Tree planting has been promoted by NGOs operating in southwestern Madagascar (WWF
 436 and GIZ; Randriamalala et al., 2017b). A community tree plantation program was undertaken
 437 30-90 km north of Toliara town, where annual rainfall is higher (P=600-800 mm/year), during
 438 the 2008-2011 period (WWF, 2011). *Eucalyptus camaldulensis* and *Acacia mangium* tree
 439 species were planted on plots with a total area of about 400 ha (Randriamalala et al., 2017b).
 440 Results were mixed, while the survival rate of the trees planted was generally under 50%
 441 (Randriamalala et al., 2017b). However, the program demonstrated that tree plantations in
 442 the semi-arid southwestern region of Madagascar are possible because the mortality was
 443 essentially due to poor organisation (late planting period at the end of the rainy season and
 444 lack of plantation monitoring). This kind of tree plantation could be undertaken successfully if
 445 these organisational problems are solved (Hervé et al., 2021a). Moreover, this tree plantation
 446 can also be done in the savannahs to the north of the study site where the climatic conditions
 447 are wetter (P>800 mm/year). About 56 000 ha of Eucalyptus plantations would be needed to
 448 produce the woody biomass for total wood charcoal production if we consider carbonisation
 449 yield of 0.125 (Ramaroson, 2014), an annual wood increment of 10 m³/ha of eucalyptus
 450 plantations (WWF/CIRAD, 2006) and a mass of 0.6 t for 01 m³ of wood pile (WWF/CIRAD,
 451 2006). The implementation of this kind of large scale tree plantation would require a strong
 452 political will from the State. Indeed, reforestation is not yet a priority in environmental policies

453 in Madagascar. It takes a back seat to the financing of protected areas and is generally
454 included in the restoration activity of natural forests. Finally, this area of 56,000 ha does not
455 take into account the contribution of natural dry forests. Assessments of annual biomass
456 increment of southwestern Madagasy dry forests should be made in order to estimate more
457 accurately the area of tree plantation to be implemented.

458

459 5. Conclusion

460 The transportation axis observation method to estimate the annual wood charcoal
461 consumption of Toliara town is reliable and can be replicated in other towns in Madagascar
462 and other developing countries. However, it must be done periodically because wood
463 charcoal consumption increases with population size. Sustainable wood charcoal production
464 from xerophytic thickets vegetation around Toliara town seems to be unrealistic, so it is
465 recommended to intensify the plantation of fast-growing exotic species to decrease the
466 pressure on the native forest. Moreover, the sustainability of the wood charcoal supply for
467 Toliara town should be evaluated in order to estimate accurately the annual deficit between
468 wood charcoal biomass production and wood charcoal urban demand.

469

470 6. Acknowledgements

471 We wish to thank the VALSE Project “Valorisation durable des formations sèches côtières”
472 from UE/COI Biodiversity and the JEA/EXPLORE project “Exploitation et régénération des
473 forêts malgaches” from IRD, which financed the fieldwork from 2017 to 2018.

474

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