



# Assessment of the importance of climate, land, and soil on the global supply for agricultural products and global food security: Evidence from Madagascar

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## ABSTRACT

Sub-Saharan Africa is home to 63.00% of the global food-insecure people (IPC/CH Phase 3 or above) and endowed with more than 50.00% of uncultivated land. The production environment in the region is subject to numerous constraints imposed by climate, physical infrastructure, and human activities. This study highlights the importance of countries' natural endowment and crop-specific requirements, namely soil and climate characteristics, on agricultural trade and food security. To analyze the global supply of crops, we based our research on the comparative advantage theory with the factor endowment approach. We found that the climate in the tropical region lowered the soil quality and the agricultural productivity in the region. Compared to most developing Asian countries, least developed countries from Africa, including Madagascar, struggle with soil management which lowers their comparative advantage in the agricultural sector. We also found that the crops' requirements give a comparative advantage to well-endowed countries. This research exposed that the climate and soil combined, along with the geography variables are important for the international trade pattern. It also brings light to the importance of international trade in the achievement of global food security. Our findings suggested that foreign direct investment (FDI) can be used to boost the global agricultural sector and improve global food security. For Madagascar in particular, we found that FDI could help the country sustain the global supply of spices, specifically vanilla, cloves, and cocoa.

## 1. Introduction

According to the Integrated Food Security Phase Classification (IPC), Sub-Saharan Africa is home to 63.00% of the global population suffering from food crises (IPC/CH Phase 3 or above). For instance, in Madagascar, a tropical Sub-Saharan African country, the 8.99 million (representing 63.83 % of total workforce) agricultural producers fail to satisfy the local food demand (World Bank, 2020). Agricultural production in Madagascar is threatened by numerous factors, among which a significant rainfall variation due to climate change is one of the most concerning (Tanteliniaina et al., 2020). Climate change constitutes a threat for the African agricultural productivity (Kanianska, 2016), by 2030, climate change will decrease agricultural productivity by one-

quarter to one-third (Ortiz-Bobea et al., 2021; World Bank, 2020). Furthermore, climate change is known to alter the soil quality, hence the agricultural productivity (Jaja, 2016; Nachtergaele et al., 2009). In the early 2000s, climate change has degraded 75.00 % of the African soil, costing up to 10.00% of the GDP of African economies (Hamidov et al., 2018; Nkonya et al., 2011; Pareek, 2017).

Say's law draws attention to the importance of the interaction between climate factors and soil characteristics in international trade (Say, 2017). More specifically, classical economists highlighted that the ability to purchase a product from the market depends first on its availability on the market. Thereby, by decreasing the agricultural productivity, the negative effect of climate on soil decreases crop availability on the international market. Therefore, analyzing the

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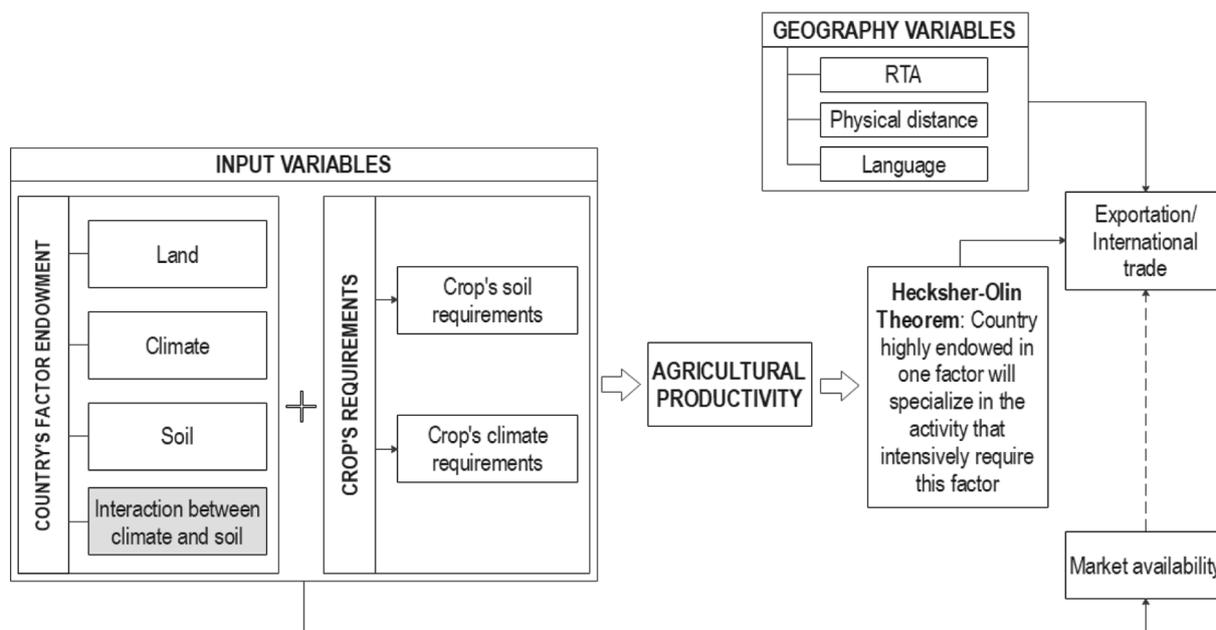


Fig. 1. Conceptual framework.

importance of countries' natural-resources endowment (land, soil and climate characteristics) on the global supply of crops, given the crops' specific agro-ecological requirements namely soil and climate, is of great importance in order to implement solid and sustainable policies and end the persisting global food insecurity.

The relationship between soil characteristics and agricultural productivity is already well established in the agricultural sciences literature but less so in economics. Previous research investigated the impact of land, climate, and labor productivity on agricultural trade patterns (Andrianarimanana and Yongjian, 2021; Costinot et al., 2012; Heerman, 2020; Reimer and Li, 2010; Xu, 2015). However, these authors independently analyzed each factor, except for Heerman (2020) who built a model using countries' land productivity and climate characteristics. Heerman's work defined agricultural international trade according to countries' climate endowment and crops specific requirements. Therefore, the global production system is shaped according to countries' strengths in producing crops given climate variables. Put simply, tropical countries tend to specialize in the production and exportation of tropical intensive crops. Previous scholars also found that climate can alter soil quality which induces significant production loss (Corwin, 2021; Panagos et al., 2018). Yet, hardly any research in the agricultural economic field investigated the relationship between countries' soil characteristics and international trade patterns. Although an updated work by Heerman and Sheldon (2022) introduced soil variables into their original model but without clearly specifying soil's importance to international trade, which motivates the need for a research that digs deeper into the importance of soil's characteristics in the global agricultural trade.

To our best knowledge, this is among the first attempt to evaluate the combined effect of climate and soil characteristics on the global supply of crops. Accordingly, this study contributes to highlighting the importance of soil and climate on global trade of agricultural products and global food security. Furthermore, since climate change is recognized as a threat to global food security, the majority of global food strategies and policies mainly focus on strengthening producers' resilience, in particular for staple food production (De pinto et al., 2016). However, increasing the household's consumption power is also another strategy to improve food access. Thus, this study emphasizes the contribution of cash and exportation crops to achieving global food security. Cash and exportation crops increase households' consumption power resulting to

a better access to healthy and nutritious food (Minten and Barrett, 2008; Taylor et al., 2019). Finally, this study empirically assess how soil texture and pH contribute to shape international trade.

The remainder of this paper is organized as follows. In section 2, we present the data and the implementation of the factor endowment model using a multinomial logistic approach. We present the data in section 3. In section 4, we return the result of the importance of countries' natural endowment and crop-specific requirements on agricultural trade and food security. We explain the policy implications of this study in section 5 and draw a conclusion of the research in section 6.

## 2. Methodology

### 2.1. Data

We considered the bilateral relationship between Madagascar and its top trade partners. Selecting countries based on top exporters and importers is a sampling method that helps to understand the general pattern of international trade given a specific context and was already been used by previous scholars (Abafita and Tadesse, 2021; Wang et al., 2021). Thus, we selected 11 countries which are: Canada, China, France, Germany, India, Indonesia, Japan, Madagascar, Malaysia, Thailand, and the U.S which hold about 85.00% of the total agricultural share of Madagascar. From the 90 crops traded between them, we selected 21 crops (areca, bananas, cashew, cloves, cocoa, coconuts, coffee, eggplants, fruits, other tropical fruits, ginger, mangoes, nutmeg, papayas, pepper, pineapples, plantains, pumpkins, spices, tea, and vanilla) based on the comparative advantage of Madagascar following the selection concept of Costinot and Donaldson (2012). In other words, we selected crops that have higher tropical requirements than temperate requirements (Section 2.3.2) as Madagascar is a tropical country. We also introduced rice because it is Madagascar's staple food and among the comparative disadvantage crops in our model (FAO, 2020).

We collected the data from open access and reliable sources. Climate data were downloaded from the global ecological zones (GAEZ version 3.0) (FAO, 2020a). The soil data were collected from the Harmonized World Soil Database (HWSD version 1.2). The HWSD is the most reliable updated global soil database compiled using data up to 2008 (Nachtergaele et al., 2009). Geography-related variables were obtained from CEPII (2020) and the CIA factbook (2020). The bilateral trade data were

gathered from FAO (2020a). We used cross-sectional data at the time of 2012, the year of the release of GAEZ version 3. As global soil degradation between 2001 and 2012 was estimated to be about 2.5%, we assumed that the soil erosion between 2009 and 2012 was not statistically significant (Borrelli et al., 2017). It should be noted that these data sources are widely used by economic researchers and were already checked for outliers (Costinot et al., 2012; FAO, 2020b; Heerman, 2020; Jayne et al., 2014; Reimer and Li, 2010; Tombe, 2015).

## 2.2. The factor endowment model

### 2.2.1. Conceptual framework

To understand the relationship between soil, climate, and international trade, our research is drawn on the comparative advantage theory with a factor endowment approach (Heckscher et al., 1991; Heerman, 2020). As most of the research on agricultural international trade overlook the importance of natural resource endowment, the model introduced in this paper considered countries' factor endowment in land, climate, and soil. The selection of these three factors was self-evident because agricultural activities are land-based (Kanianska, 2016), highly dependent on climate (Mihalescu and Bruno Soares, 2020), and soil is among the main production environment to grow crops (Gomes et al., 2019). However, Sivakumar et al., (2015) highlighted that climate factors (e.g. rainfall, temperature, wind, etc.) reduced soil productivity by increasing soil erosion and decreasing soil quality (absorption quality and roots-soil relationship) (Jin et al., 2021; Raj et al., 2019). Thus, by introducing the interaction between soil and climate variables in the model, the approach used in this study is able to capture the relationship between factor endowment in a dynamic production system. At the same time, we added the crop-specific agroecological requirements (soil and climate) to the model as additional decision variables that drives the international trade of crops. It captures how the production environment of the producer countries influence the exportation and importation of each crop. We also introduced geography variables (as dummy) such as regional trade agreement (RTA), language, and distance into the model, because they are deemed important in international trade. The conceptual framework is summarized in Fig. 1. Overall, the approach introduced in this study is important because it allows an understanding of how different externalities from the production environment shape the global supply of crops which is crucial for the achievement of global food security.

### 2.2.2. The model

The comparative advantage theory is an extension of Adam Smith's absolute advantage theory (Smith, 1776). It allowed a country to export a product without necessarily having the lowest production cost. Initiated by Ricardo in 1817, scholars investigated international trade using labor productivity, capital productivity, and technology (Dornbusch et al., 1977; Eaton and Kortum, 2002; Heckscher et al., 1991; Ricardo, 1817). More recent studies unpacked the comparative advantage by investigating the interaction between countries and industries' characteristics (Chor, 2010; Heerman, 2020). This recent advancement allows countries with different factor endowments to use their best attribute given the characteristics of the products to enhance their competitiveness. In other words, countries well-endowed in given factors are better off specializing in the production of a product that intensively requires these factors (Deardorff, 2007). This paper used a comparative advantage theory with a factor endowment approach (Chor, 2010; Heckscher et al., 1991; Heerman, 2020); to highlight the determinants of the international supply of crops.

We considered a world with  $N$  countries trading  $j$  crops with each other. We used index  $n$  to denote the importer country and  $i$  the exporter country. Each crop  $j$  produced a continuum of varieties  $k_j$  [0,1] for final consumption. The production cost follows the law of Constant Return to Scale with a nested Cobb-Douglass production function. Solving the production function, we obtained the expression for marginal cost  $a^{1-}$

$^{\alpha}c_i/z_i$ . However, because the transportation of goods from country  $i$  to country  $n$  is not free of cost, we added a transportation cost  $d_{ni}$ . We obtained the expression of the price  $p_{ni}$  for a crop  $j$  produced locally by the exporter  $i$  and sold to country  $n$  in Eq. (1).

$$p_{ni}(j) = \frac{\tilde{a}_i c_i}{z_i(j)} d_{ni} \tag{1}$$

Where:  $p_{ni}(j)$  is the price of crop  $j$  that country  $n$  pays to  $i$ ,

$c_i$  is the production cost of crop  $j$  in country  $i$ .

$\tilde{a}_i$  is the specific effect of land productivity

$z_i(j)$  is the productivity of the exporter  $i$  in producing crop  $j$ , that follow a Fréchet distribution  $Fi(z) = e^{-Tiz^{-\theta}}$

$d_{ni}$  is the transportation cost that follows Samuelson's standard assumption  $d_{ni} > 1$  for every  $n \neq i$ ; and  $d_{ii} = 0$  for every  $n = i$ ; and the triangular inequality  $d_{ni} \leq d_{nk}d_{ki}$

The real world violates the assumption of perfect competition. Country  $n$  always seeks the minimum price to supply its market. Country  $n$  willingness to pay for crop  $j$  is given by  $p_n(j)$  in Eq. (2).

$$p_n(j) = \min\{p_{ni}(j); i = 1, \dots, N\} \tag{2}$$

Finally, following the proprieties of Heerman's (2020) model, the probability of country  $i$  supplying the market of country  $n$  with the lowest price is equal to the fraction of goods that country  $n$  purchases from producers  $i$  as given in Eq. (3).

$$\Pr(p_{ni} \leq p_{ni1}) = \frac{X_{ni}}{X_n} = \frac{T_i (\tilde{a}_i c_i d_{ni})^{-\theta}}{\sum T_i \tilde{a}_i^{-\theta} c_i^{-\theta} d_{ni}^{-\theta} p^{\theta}} \tag{3}$$

## 2.3. Empirical implementation

Our empirical implementation followed Heerman's (2020) principles<sup>1</sup>. Heerman (2020)' s work analyzed countries' performance in exporting crops given countries' agroecological endowments. More specifically, countries with similar agroecological attributes will have a similar set of crops to export as such, tropical-climate-abundant countries have a higher comparative advantage in tropical-climate-intensive crops. However, implementing crop-specific characteristics allow the model to shape specifically the set of crops that require a more complex production environment. As a result, even if countries shared similar agroecological attributes, crops specific characteristics will shape the set of crops to be produced differently.

First, we decomposed the specific effect of the production environment to get Eq. (4). Second, we allowed the soil and climate characteristics of the country to have a specific effect on agricultural productivity. We obtained the crop-specific requirements denoted by  $Trop_j$  and  $S_j$ , respectively. Thus, an interaction term between the country's characteristics and the product's specific requirements was introduced. This interaction term captures the effectiveness of the production environment in answering the crops' specific requirements.

$$\ln(a_i(j)) = \beta_1 X_i + \beta_2 X_i Trop_j + \beta_3 X_i S_j \tag{4}$$

where:  $X_i$  describes country  $i$ 's agro-ecological characteristics,

$Trop_j$  is the crop  $j$ -specific climate requirements, and

$S_j$  is the crop  $j$ -specific soil requirements.

$\beta_x$  is the vector of coefficients for country characteristics, and crops agro-ecological requirements.

<sup>1</sup> The focus of the paper is to understand the global trade pattern; therefore, we did not display the equilibrium conditions.

**Table 1**  
Statistics of the consumer choice for the dummies (%).

Variables	Dummies	Alternatives <sup>1</sup>				
		①	②	③		
<b>Geography variables</b>	<b>Sharing Border (B<sub>ni</sub>)</b>	0	89.03	100.00	96.95	
		1	10.97	0.00	3.05	
	<b>Distance (D<sub>ni</sub>)</b>	<b>Nearest</b>		11.81	23.29	6.89
		<b>Farthest</b>		54.22	76.71	69.84
	<b>Sharing an RTA</b>	0		58.76	69.86	66.18
		1		41.24	30.14	33.82
<b>Sharing Language (I<sub>ni</sub>)</b>	0		79.22	67.12	85.31	
	1		20.78	32.88	14.69	
<b>Products dummies</b>	<b>Vanilla</b>	0	96.20	86.30	95.43	
		1	3.80	13.70	4.57	
	<b>Cloves</b>	0	95.99	86.30	95.55	
		1	4.01	13.70	4.45	
	<b>Cocoa</b>	0	96.10	87.67	95.43	
		1	3.90	12.33	4.57	
	<b>Rice</b>	0	93.57	95.89	96.53	
		1	6.43	4.11	3.47	

<sup>1</sup> The Alternatives are described in Section 2.3.4. Source: Authors' computation using the geography data from CEPII (2020) and the CIA factbook (2020) and the bilateral trade data from FAO, (2020b).

2.3.1. Exporter characteristics

We defined  $X_i = [AL_i \text{ trop}_i \text{ pH}_i \text{ text}_i]$ , where  $AL_i$  is the available arable land in country  $i$ ,  $\text{Trop}_i$  represents the percentage of land of country  $i$  located in the tropical climate zone,  $\text{pH}_i$  is the share of soil with the preferential pH ( $\text{pH}_{[5.50, 7.20]}$ ) of country  $i$ , and  $\text{text}_i$  is the share of soil in the country  $i$  with a loam texture. We used  $\text{pH}_{[5.50, 7.20]}$  and loam texture because they provide the most favorable production environment for most crops (Jaja, 2016; Nachtergaele et al., 2009). The composition of loam texture on the textural triangle is about 40% sand, 40% silt, and 20% clay (Jaja, 2016). From the agronomic standpoint, soil structure affects plant growth because it influences the infiltration, percolation, retention of water, soil aeration, and mechanical impedance to root growth.

2.3.2. Crops requirements

The climate requirement  $\text{Trop}_j$  of crop  $j$  denotes the ideal climate for crop  $j$  to grow (Heerman, 2020). We obtained  $\text{Trop}_j$  using Eq. (5).

$$\text{Trop}_j = \sum_{i=1}^I w_i(j) \times \text{trop}_i \tag{5}$$

where  $w_i(j)$  is the share of country  $i$  in terms of global crop  $j$  production value. Crops were selected if their tropical requirement is higher than their temperate requirement. We substituted  $\text{Trop}_i$  by the share of the country in the temperate zone to obtain the temperate requirement.

The soil requirement of the crop  $j$  proxies the ideal soil characteristics (pH and texture) to grow crop  $j$ . We obtained pH ( $\text{pH}_j$ ) and texture ( $\text{text}_j$ ) requirements by running a Pearson correlation between the value of production of crop  $j$  and producer soil characteristics as in Eq. (6).

$$r_j = \frac{i(\sum x_j y_j) - (\sum x_j)(\sum y_j)}{\sqrt{[i \sum x_j^2 - (\sum x_j)^2][i \sum y_j^2 - (\sum y_j)^2]}} \tag{6}$$

where:

- $y_j$  is the total production of crop  $j$  in exporter country  $i$ ,
- $x_j$  is the soil characteristic variables (pH and texture).

A positive correlation coefficient means that soil characteristic (pH and texture) positively impacts the production of the crop  $j$  and a negative coefficient reflects a negative impact. The correlation coefficient ranges from 0 to |1|. A coefficient close to 1 means a strong

correlation between the soil characteristic and the production of crop  $j$ .

2.3.3. The geography variables

When modeling the international trade pattern, it is important to introduce geography variables into the model. We used dummies to get the geography variable  $d_{ni}$  (Eaton and Kortum, 2002).

$\ln(d_{ni}) = b_{ni} + l_{ni} + \sum d_{ni} + rta_{ni}$ , where  $b_{ni}$ ,  $l_{ni}$ ,  $d_{ni}$ , and  $rta_{ni}$  denotes border, language, physical distance interval, and Regional Trade Agreement (RTA), respectively. For the RTA, we used the European Union, Global System of Trade Preferences among Developing Countries, and other bilateral relationships that exist among each pair of countries.

Finally, from Eq. (2) we obtained Eq. (7), the final equation to be estimated:

$$\pi_{ni} = \frac{\exp\{S_i + X_i(E_j)' + X_i(S_j)' + d_{ni}\}}{\sum_{l=1}^I \exp\{S_i + X_i(E_j)' + X_i(S_j)' + d_{ni}\}} \tag{7}$$

2.3.4. The multinomial logistic estimation

We specified Eq. (7) as a multinomial logistic model to capture how countries' endowment and crop-specific requirements contribute to shaping the international trade pattern of crops. The dependent variables have to be categorical variables representing a set of alternatives for decision-makers. In this study the alternatives are set as follows:

- (1) The exporter country is one of Canada, China, France, Germany, Indonesia, India, Japan, Malaysia, Thailand, and the United States;
- (2) Madagascar is the exporter country. We chose to draw a conclusion based on Madagascar because firstly it shares many similarities with other African countries so, our findings can be scaled up to the regional context of Africa. For instance, the majority of Sub-Saharan African countries including Madagascar struggle in the production of staple food despite their potential (FAO, 2020b). Secondly, Madagascar is the first supplier of Vanilla, the second most expensive spice in the world after Safran.
- (3) there is no export (no trade).

The alternatives were tested using a Wald test to make sure that no alternative should be combined. The choice of the implementation method was done carefully after testing for Independence of Irrelevant Alternatives (IIA). Several methods have been suggested by the literature to relax the IIA assumptions, such as the nested model, conditional logit model, and mixed logit model (Seshadri and Ugander, 2020). However, the nested and conditional logit models do not allow capturing the specific influence of crop requirements on the choice of the importer. Moreover, by adding the soil variables to our model and because international trade data is typical with numerous zero values, converging the mixed logit model is challenging. Thus, as the IIA assumptions were not violated, and to capture countries' soil endowment and crop-specific soil requirements, the multinomial logistic estimation methods were suitable. We performed a Hausman test to verify the IIA assumption (Hausman, 1978). It is noteworthy that we used the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) to assess and select the best model.

2.3.5. The revealed comparative advantage

The RCA metric explains the trade patterns using the relative difference in productivity (Balassa, 1965). We used the RCA to highlight the comparative advantage of Madagascar. The ratio is obtained using Eq. (8).

$$RCA_{Aj} = \frac{X_{Aj}}{\sum_{c \in P} X_{Ac}} / \frac{X_{wj}}{\sum_{c \in P} X_{wc}} \tag{8}$$

**Table 2**  
Statistical descriptive of the quantitative variables.

	Alternative <sup>1</sup>	Mean	SD	Max	Min
Arable land ( $X_i$ in millions Ha)	①	66.25	63.99	156.46	0.88
	②	3.50	0.00	3.50	3.50
	③	42.74	53.57	156.46	0.88
Share of tropical land ( $trop_i$ in %)	①	0.46	0.46	1.00	0.00
	②	0.97	0.00	0.97	0.97
	③	0.39	0.47	1.00	0.00
Share of soil with the pH <sub>[5.50, 7.20]</sub> (in %)	①	0.29	0.15	0.47	0.03
	②	0.25	0.00	0.25	0.25
	③	0.31	0.13	0.47	0.03
Share of soil with loam Texture Text <sub>i</sub> (in %)	①	0.36	0.25	0.74	0.00
	②	0.58	0.00	0.58	0.58
	③	0.36	0.22	0.74	0.00
Crop Tropical Requirement Trop <sub>j</sub>	①	0.49	0.25	0.99	0.03
	②	0.53	0.25	0.97	0.03
	③	0.52	0.26	0.99	0.03
Crop pH requirement pH <sub>j</sub>	①	-0.09	0.07	0.11	-0.22
	②	-0.07	0.07	0.11	-0.22
	③	-0.07	0.09	0.11	-0.22
Crop texture Requirement Text <sub>j</sub>	①	-0.07	0.08	0.11	-0.22
	②	-0.07	0.09	0.09	-0.22
	③	-0.05	0.09	0.11	-0.22

Note: pH<sub>[5.50, 7.20]</sub> and Text<sub>i</sub> were estimated using the data from HSWD (Nachtergaele et al., 2009); Trop<sub>j</sub> was obtained using the data from GAEZ (FAO, 2020a) and the production data from FAO (FAO, 2020b); pH<sub>j</sub> and text<sub>j</sub> were obtained using data from HSWD version 1.2 (Nachtergaele et al., 2009) and production data from FAO (FAO, 2020b). Source: Authors' computation.

<sup>1</sup> The Alternatives are described in Section 2.3.4;

where: P is the set of all crops,

$X_{Aj}$  is the total export of country A for crop  $j$ ,  $X_{wj}$  is the global exports of crop  $j$ ,  
 $\sum_{c \in P} X_{Aj}$  is the total exports of country A, and  $\sum_{c \in P} X_{Aj}$  is the global exports.

A country is a competitive exporter of a crop  $j$  relative to another country if  $RCA > 1$  (Eq. (8)). RCA only explains trade according to the volume traded. It provides limited information on the factors that shape the international trade pattern. Therefore, we only used RCA to select crops to be used in the model as dummies to capture the strength of Madagascar in the international market. The country fixed effect was also introduced to capture the demand for crops.

### 3. Descriptive statistics

#### 3.1. Description of the alternatives

The sample distribution is as follows: 36.00%, 3.00%, and 62.00% of the data are from the first, second, and third alternatives, respectively.

**Table 3**  
Product characteristics.

Product	Trop <sub>j</sub>	pH <sub>j</sub>	Text <sub>j</sub>	Product	Trop <sub>j</sub>	pH <sub>j</sub>	Text <sub>j</sub>
Areca nuts	1.00	-0.16	0.11	Nutmeg	0.18	-0.08	-0.01
Bananas	0.25	-0.16	0.02	Papayas	0.45	-0.10	-0.10
Cashew nuts	0.97	-0.04	-0.22	Pepper	0.62	-0.12	-0.16
Cloves	0.87	0.03	0.08	Pineapples	0.19	-0.21	-0.09
Cocoa	0.49	-0.1	-0.17	Plantains	0.46	0.06	-0.05
Coconuts	0.8	-0.14	-0.14	Pumpkins	0.52	-0.01	0.02
Coffee	0.73	-0.12	-0.21	Rice	0.03	-0.14	-0.16
Eggplants	0.25	0.11	0.09	Spices	0.2	-0.07	-0.02
Fruit	0.33	-0.11	-0.02	Tea	0.55	-0.06	-0.04
Ginger	0.63	-0.22	-0.04	Tropical Fruit	0.57	0.03	-0.09
Mangoes	0.68	-0.07	-0.06	Vanilla	0.51	0.00	-0.08

Note: Trop<sub>j</sub> was obtained using the data from GAEZ (FAO, 2020a) and the production data from FAO (FAO, 2020b); pH<sub>j</sub> and text<sub>j</sub> were obtained using data from HSWD version 1.2 (Nachtergaele et al., 2009) and production data from FAO (FAO, 2020b). Source: Authors' computation using the climate data from GAEZ version 3.0 (FAO, 2020a), the soil data from HSWD version 1.2 (Nachtergaele et al., 2009), and the production data from (FAO, 2020b).

According to Table 1, for the first alternative, 10.97% of the trading countries share a border; 41.24% have an RTA; 20.78% speak the same language; and 54.22% of the partners are located far from each other (within more than 6,000 miles). For the second alternative (Madagascar): 30.14% have an RTA; 67.17% of the partners do not speak French, the official language of Madagascar; the island does not share a border with any country; and 76.71% of the sample are located at more than 6,000 miles away from Madagascar. For the third alternative *i.e.* no trade: 3.05% share a border; 69.84% are located at more than 6,000 miles; 33.82% have an RTA; and 15.00% share the same language.

According to Table 2, the country in the first alternative has the highest mean of arable land (66.25 million Ha). Madagascar has the lowest arable land available (3.50 million Ha) but is well endowed in tropical land (97.00%) compared to the mean endowment of countries in the first alternative (46.00%). For both the first and second alternatives, soil with the pH<sub>[5.50, 7.20]</sub> represents around 30.00% of the total soil. However, Madagascar has a higher share of loam soil (58.00%). We also found that Madagascar exports more products that require a tropical climate. For both alternatives, there is a negative relationship, but with a weak effect (with a maximum coefficient of correlation of 0.11), between countries' characteristics and products' soil requirements.

#### 3.2. Crops requirements

Among the 21 crops we selected, 12 crops are tropical intensive which means that they prefer tropical climates with  $trop_j > 0.50$ . Only eggplants, plantains, cloves, tropical fruits, and vanilla have a positive correlation with the soil pH. The productivity of these 5 crops is optimum with pH<sub>[5.50, 7.20]</sub> (Table 3). We also found that areca, eggplants, cloves, pumpkins, and bananas prefer soil with a loam texture.

#### 3.3. The revealed comparative advantage of Madagascar

For Madagascar in particular, spices have the highest RCA metric (613.10). For decades, Madagascar leads the international vanilla market holding about 55.00% of the global supply (ITC, 2020). Moreover, the country's competitiveness in the international cloves market is relatively high and holds about 25.00% of the global supply of cloves. The third product with a relatively high RCA (7.50) is cocoa.

### 4. Results and discussion

#### 4.1. Empirical results

The significant estimates (p-value < 0.05) from the multinomial logistic regression are shown in Table 4. Model (3) (Appendix – Table A.1) gives the best estimates with the lowest value of AIC (3,275.16) and BIC (-626.66). The Wald test suggested that the alternatives should not be

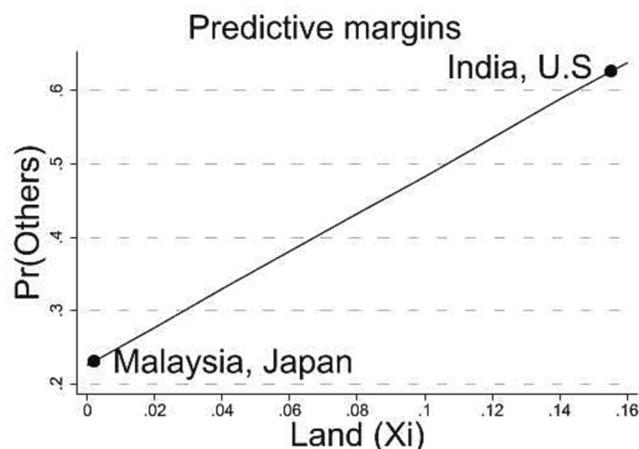
**Table 4**  
Estimates from multinomial logistic regression.<sup>1</sup>

	Coef.	RRR	Standard Error	P > z	[95% conf. interval]	
<b>Madagascar</b>						
RTA	1.62	5.08	5.08	0.01	0.45	2.80
Language $l_{ni}$	2.17	8.75	8.75	0.00	0.96	3.38
Dist - 5	-4.49	0.01	0.01	0.00	-6.23	-2.75
Vanilla	5.20	181.28	181.28	0.00	2.88	7.52
Cloves	8.13	>>1		0.00	5.11	11.16
Cocoa	2.76	15.81	15.81	0.00	0.92	4.60
<b>Partner country</b>						
RTA	0.60	1.82	1.82	0.00	0.35	0.85
Border $b_{ni}$	0.70	2.01	2.01	0.00	0.28	1.12
Language $l_{ni}$	0.46	1.58	1.58	0.00	0.20	0.71
Dist - 4	-1.23	0.29	0.29	0.00	-1.59	-0.88
Dist - 5	-1.21	0.30	0.30	0.00	-1.47	-0.95
Arable land $X_i$	12.60	>>1		0.00	10.62	14.58
$trop_j$	-2.68	0.07	0.07	0.00	-3.67	-1.68
$Text_j$	-7.41	0.00	0.00	0.00	-11.16	-3.65
$pH_i$	-3.62	0.03	0.03	0.05	-7.27	0.02
$trop_i \# Text_i$	-1.63	0.20	0.20	0.00	-2.57	-0.68
$trop_i \# trop_j$	2.30	9.96	9.96	0.00	1.48	3.12
$trop_i \# text_j$	3.00	20.07	20.08	0.04	0.17	5.83
$pH_i \# trop_j$	2.60	13.44	13.44	0.02	0.37	4.82
$pH_i \# Text_j$	16.21	>>1		0.02	2.60	29.82
Cloves	0.96	2.62	2.62	0.00	0.43	1.49
Cocoa	-0.56	0.57	0.57	0.02	-1.02	-0.10

Legend: RRR: Relative Risk Ratio;  $l_{ni}$ : country n and i share language;  $b_{ni}$ : country n and i share border; Dist-5: Distance higher than 6000 miles; Dist-4: Distance between 3000 and 6000 miles;  $X_i$ : Arable Land;  $trop_j$ : crop tropical requirement;  $text_j$ : crop loam texture requirement;  $pH_i$ : share of soil with  $pH_{[5.50,7.20]}$ ;  $trop_i \# Text_i$ : interaction term between country tropical share and the share of soil with loam texture;  $trop_i \# trop_j$ : interaction term between country tropical share and crop tropical requirement;  $trop_i \# text_j$ : interaction term between country tropical share and crop loam texture requirement;  $pH_i \# trop_j$ : interaction term between the share of soil with  $pH_{[5.50,7.20]}$  and crop tropical requirement;  $pH_i \# Text_j$ : interaction term between the share of soil with  $pH_{[5.50,7.20]}$  and crop loam texture requirement. Source: Authors' computation using data from GAEZ version 3.0 (FAO, 2020a), HWSN (Nachtergaele et al., 2009), CEPII (2020) and the CIA factbook (2020), and FAOSTAT (FAO, 2020b).

<sup>1</sup> Setting different alternatives, namely, splitting the first alternative into two sub-groups: sub-group 1: a group of countries with tropical share > 0.50 and sub-group 2: a group of countries with tropical share < 0.50 return the following results: (1) The border and RTA are only significant for non-tropical countries, (2) The sign of the significant variables did not change (3) Tropical region has the highest probability to export tropical crops. Also, it should be noted that regrouping all tropical countries together did not change the sign of the significant variables.

combined (p-value = 0.00) so we kept the alternatives separated. The Hausman test showed that the IIA assumption was not violated (chi-square = 0.00 and p-value = 1.00). According to Table A.1, for all four models, the traditional gravity variables are consistent in signs which means that the RTA, language, and border variables significantly contribute to strengthening the bilateral relationship. Madagascar being an island, does not share a border with any countries, thus the border variable is not significant. However, we found that the negative effect of physical distance on the choice of exporter decreases with distance, which means that the choice of suppliers is not driven by distance. On the other hand, the long distance between suppliers and consumers of tropical products, on average 12,000 miles, and the low concentration of supplying market (0.04) implied that few countries are exporting tropical products (ITC, 2020). This suggests that even if the distance does not have a significant effect on the choice of supplier, it affects the volume traded between countries.



**Fig. 2.** Land endowment and the probability to be selected as exporters. Note: Predictive margins of countries from the first alternative to be selected as exporters given their land endowment. Countries with the highest and lowest predictive margins are displayed in the figure. Sources: Authors' computation using the data from (FAO, 2020b).

**4.2. Countries' agro-ecological endowment and the global supply of crops**

Considering the first alternative, the land variable significantly increases the relative log odds of choosing a country from this alternative as exporters relative to no trade. In other words, the probability of a country being selected as an exporter increases with land availability. Ceteris paribus, India's probability to be selected as an exporter (Pr (India) = 0.63) is higher than Malaysia or Japan (Pr (Malaysia, Japan) = 0.22) (Fig. 2).

The results also highlight that the more the countries of the first alternative are endowed with loam soil, the lower their probability to be selected as an exporter (Fig. 3 (b)). The interaction between countries' tropical endowment (Fig. 3 (a)) and soil texture characteristics weakens the positive effect of countries' tropical endowment on the probability to export crops relative to no trade (Fig. 3 (c)). More specifically, by holding all other variables constant, Indonesia's ( $Text_i = 0.40$ ) probability to be selected as an exporter decreased by about 0.12 points while Thailand's probability ( $Text_i = 0.00$ ) increased by 0.15 points. It shows that in the tropical zone, extreme weather lowered soil quality, thereby reduced the productivity and total production (Fageria and Baligar, 2008; Harter, 2007). Fig. 3 (c) shows that a Tropical country endowed with more than 60.00% of loam soil is expected to have a lower probability to export crops compared to non-tropical countries. Thereby, the tropical production environment is expected to weaken the comparative advantage of countries endowed with more than 60.00% loam soil. Furthermore, it is expected that tropical countries endowed with more than 80.00% of tropical land and loam texture will have a relatively low probability to export relative to no trade (Pr = 0.13).

Madagascar shares similarities with the tropical islands from the first alternatives, therefore we related their results to the case of Madagascar<sup>2</sup>. The island is endowed with 58.00 % of loam soil which is relatively equal to the above threshold of 60.00% and one of the highest among the tropical countries considered in this study. Moreover, the negative sign of the pH variable (Model 4) indicates that soil quality in Madagascar is low. Therefore, this study showed that Madagascar's probability to export crops relative to no trade is lowered by the negative impact of climate on soil quality which is reducing the productivity.

Overall, the most important problems with tropical soil management are erosion, aridity, and excess of water (Chang, 1977; Fujii, 2014;

<sup>2</sup> Data availability did not allow Madagascar's endowment to vary, therefore, the fixed value of endowment variables impacted the significance level.

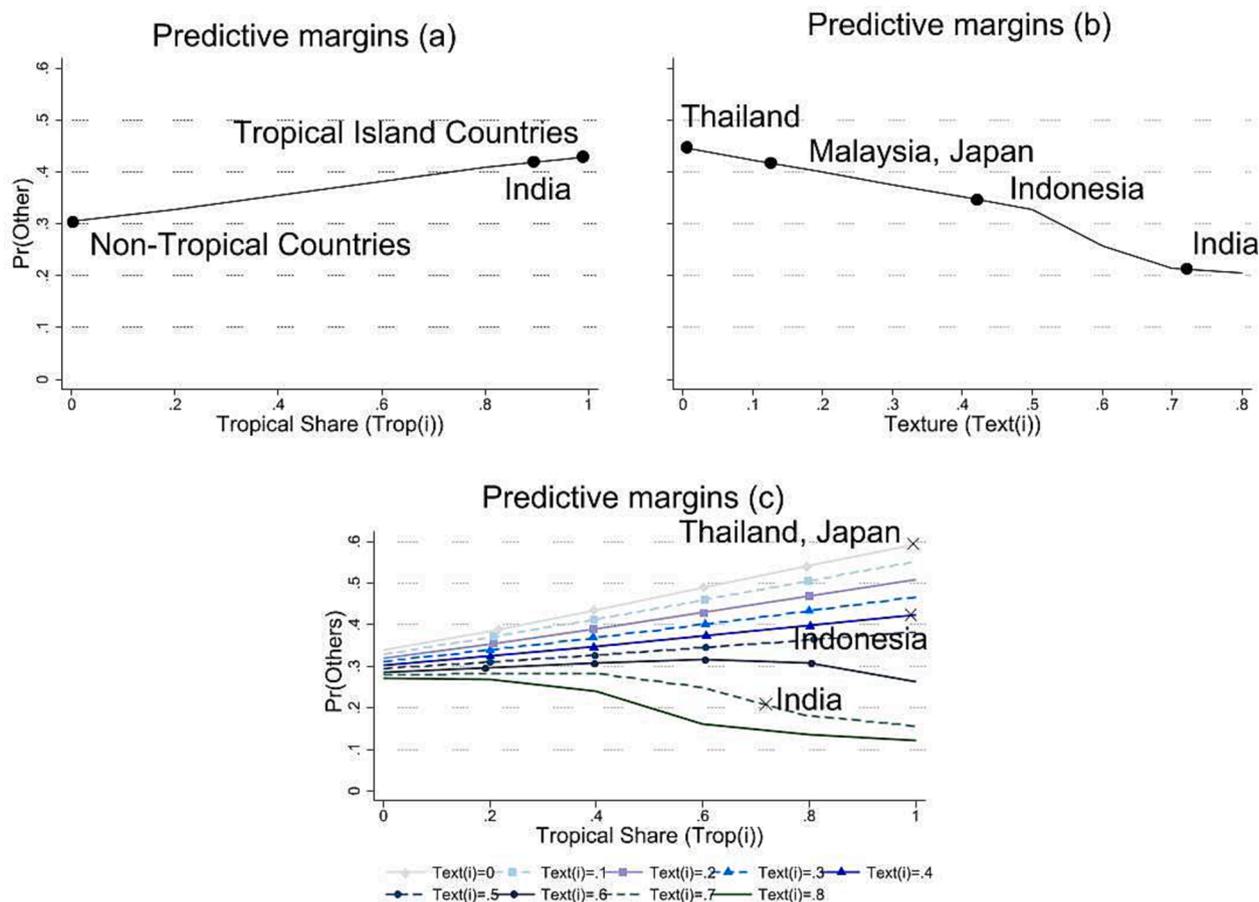


Fig. 3. Tropical soil endowment, and the probability to be selected as exporters. Note: Fig. 3(a) displays the predictive margins of countries from the first alternative to be selected as exporter given their endowment in tropical land. Fig. 3(b) presents the predictive margins of countries from the first alternatives to be selected as exporter given their endowment in soil with loam texture. Fig. 3(c) shows the predictive margins of countries from the first alternative to be selected as exporter given the interaction between the production environment (i.e. countries tropical land endowment and crops requirement in soil texture). Source: Authors' computation using the data from GAEZ version 3.0 (FAO, 2020a), HSWD version 1.2 (Nachtergaele et al., 2009), and (FAO, 2020b).

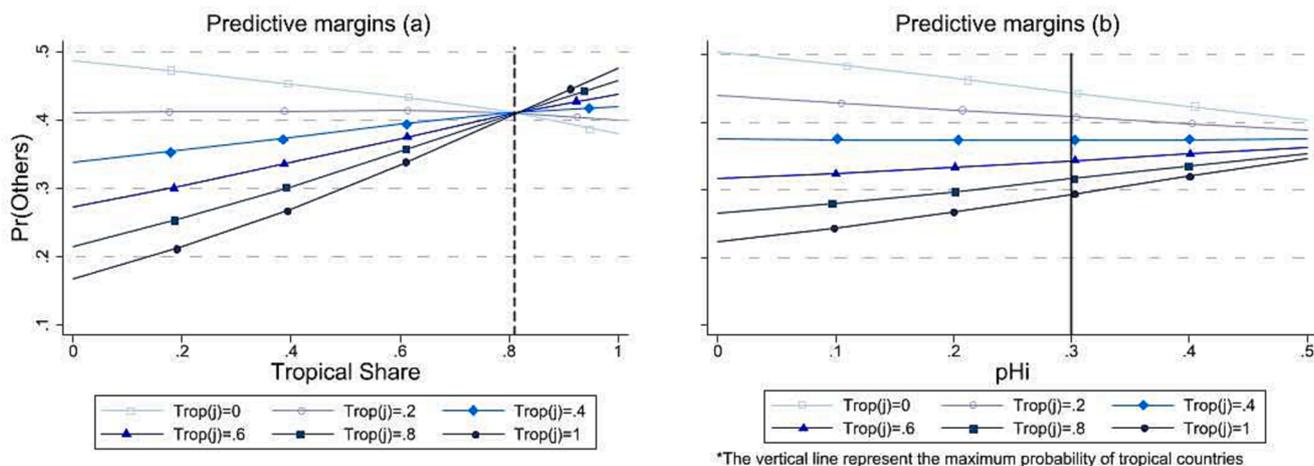


Fig. 4. Crops' tropical requirements and the probability to be selected as an exporter. Note: Fig. 4(a) presents the predictive margins of countries from the first alternative to be selected as exporter given the interaction between countries tropical land endowment and crops tropical requirement. Fig. 4(b) shows the predictive margins of countries from the first alternative to be selected as exporter given the interaction between countries endowment in soil with pH<sub>[5.50, 7.20]</sub> and crops tropical requirement. Source: Authors' computation using the data from GAEZ version 3.0 (FAO, 2020a), HSWD version 1.2 (Nachtergaele et al., 2009), and (FAO, 2020b).

Harter, 2007; Igwe, 2011). In addition, climate change brings further challenge to the already existing problems. But, better soil management with the use of additional input and adequate infrastructure can improve

productivity in tropical regions. Yet, soil management is still a challenging aspect for producers in LDCs, especially in Madagascar. Producers from these regions have a low budget and most of the time,

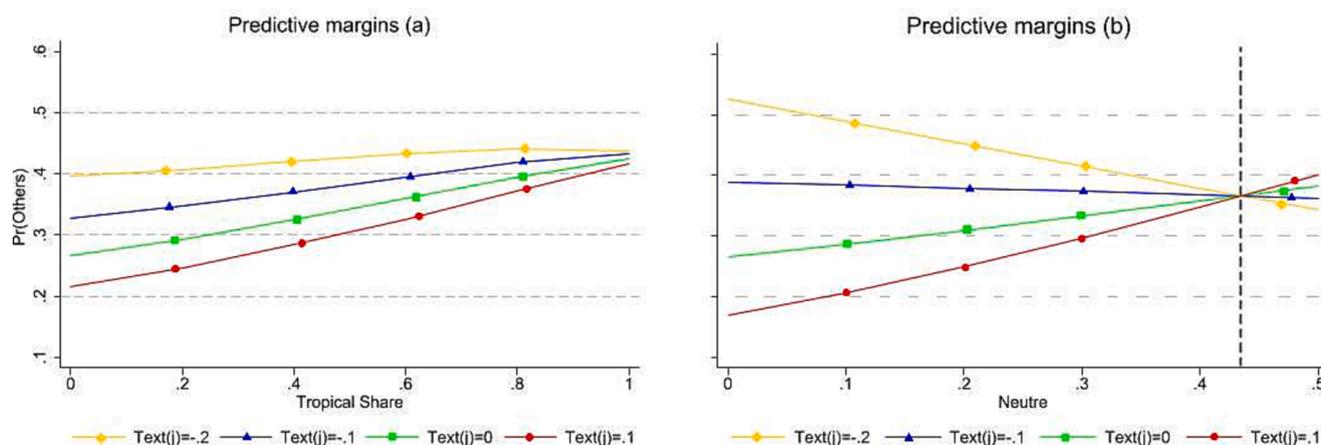


Fig. 5. Crops Texture requirements and the probability to be selected as exporter. Note: Fig. 5(a) displays the predictive margins of countries from the first alternative to be selected as exporter given the interaction between countries tropical land endowment and crops soil texture requirement. Fig. 5(b) presents the predictive margins of countries from the first alternative to be selected as exporter given the interaction between countries endowment in soil with pH<sub>[5.50, 7.20]</sub> and crops soil texture requirement. Source: Authors' computation using data from GAEZ version 3.0 (FAO, 2020a), HSWD version 1.2 (Nachtergaele et al., 2009), and (FAO, 2020b).

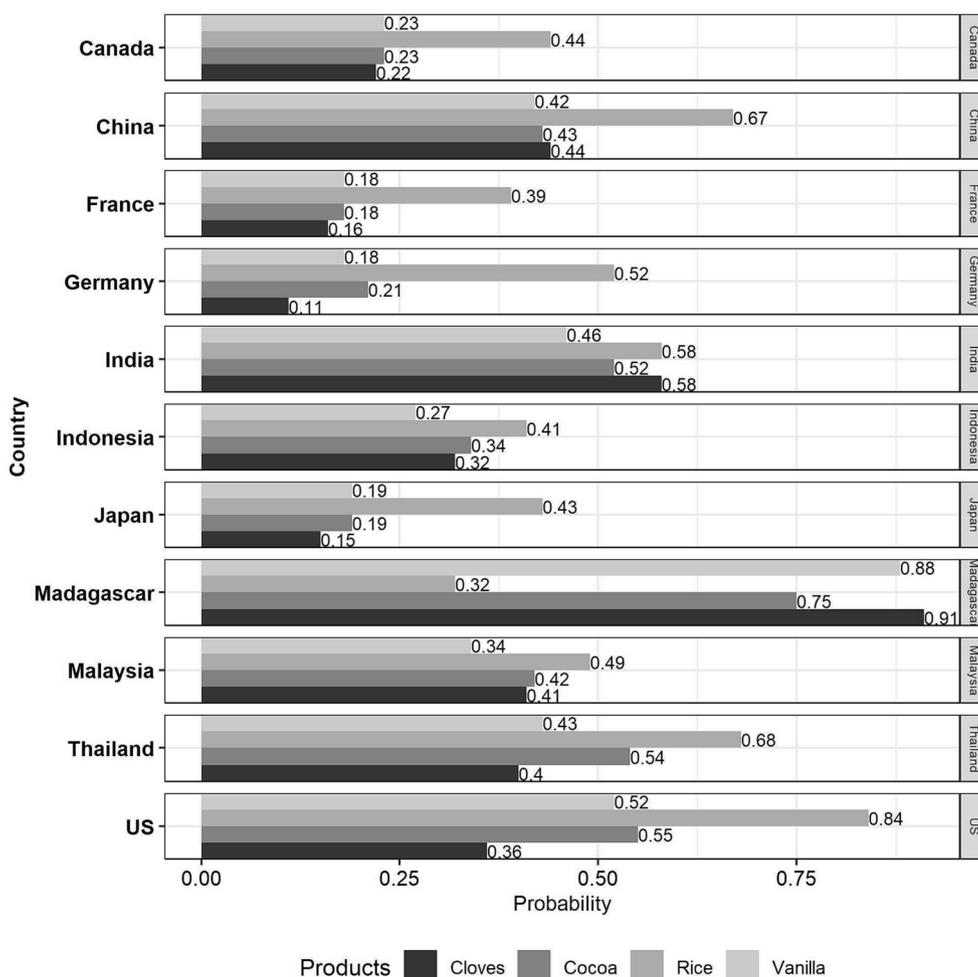


Fig. 6. Probabilities of Cloves, Cocoa, Rice, Vanilla to be exported by the countries selected in this study.

purchasing additional input to improve the soil texture and pH is beyond their budget line (Yoon et al., 2020).

### 4.3. Crops' specific requirements and the global supply of crops

#### 4.3.1. Crops tropical requirements

Fig. 4 (a) shows that only tropical countries endowed with more than 80.00% of tropical land have a higher probability to export tropical

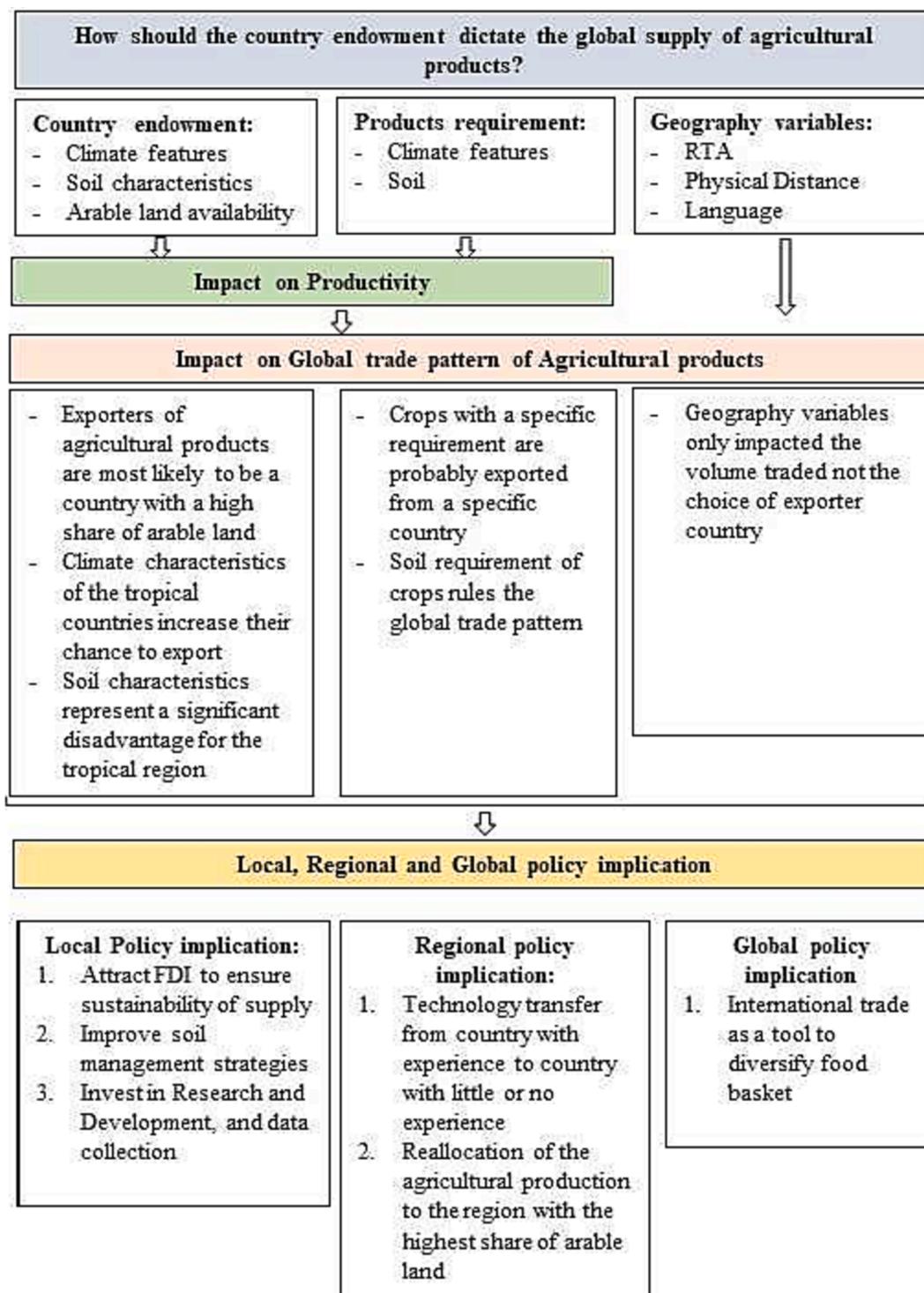


Fig. A.1. Overview of the findings and the policy implications.

intensive crops relative to no trade ( $Trop_j > 0.50$ ). Previous research showed that the tropical region is more suitable for tropical crops like rubber, cocoa, and palm tree rather than staple food (Danthu et al., 2014; Gallup and Sachs, 2000; Heerman, 2020; Minten and Barrett, 2008). Regarding countries' soil  $pH_{[5.50, 7.20]}$ , tropical intensive crops ( $Trop_j > 0.50$ ) are most likely to be traded by countries well-endowed with neutral soil (Fig. 4 (b)). Considering our sample, all tropical countries' endowment with neutral soil is lower than 30.00%. It suggests that poor soil quality in the tropical region lowers the probability of a tropical country to export tropical intensive crops relative to no trade. It

is straightforward to see that for tropical countries ( $pH_i = 0.30$ ), given  $pH$  requirements, the more crops are tropical intensive, the lower their probability to be exported by tropical countries compared to non-intensive tropical crops (Fig. 3 (b)). Previous research in the agriculture field already highlighted this dependence of productivity on soil characteristics, especially  $pH$  and texture (Liu et al., 2015; Nachtergaele et al., 2009; Nurudin et al., 2013). Hence, it is worth noting that the increasing shape of the curve in Fig. 3(b) suggests that increasing the share of soil with  $pH_{[5.50, 7.20]}$  in tropical countries would increase the probability of tropical countries to export tropical intensive crops, then

**Table A1**  
Empirical results of the remaining variables and models.

Model	(1)	(2)	(3)	(4)
AIC	3398.30	3359.92	3275.16	3309.00
BIC	-600.92	-601.41	-626.66	-573.61
<b>Madagascar</b>				
RTA	<b>1.09**</b> (2.98)	<b>1.09**</b> (2.96)	<b>1.62**</b> (5.08)	<b>1.61**</b> (5.02)
$b_{ni}$	1.07 (2.92)	1.06 (2.88)	-3.67 (0.03)	0.73 (2.08)
$l_{ni}$	<b>1.52***</b> (4.59)	<b>1.51***</b> (4.54)	<b>2.17***</b> (8.75)	<b>2.18***</b> (8.88)
Dist-2	-5.29 (0.00)	-5.29 (0.01)		-5.44 (0.00)
Dist-3	-0.12 (0.89)	-0.08 (0.92)		-1.85 (0.16)
Dist-4	-4.30 (0.01)	-4.28 (0.01)	-4.86 (0.01)	-5.04 (0.01)
Dist-5	<b>-3.20***</b> (0.04)	<b>-3.19***</b> (0.04)	<b>-4.49***</b> (0.01)	<b>-4.50***</b> (0.01)
$X_i$	-97.16 (0.00)	-98.61 (0.00)	-173.08 (0.00)	-310.37 (0.00)
$trop_i$	-16.09 (0.00)	-16.40 (0.00)	-30.49 (0.00)	-54.34 (0.00)
$Text_i$	114.59 ( $\gg 1$ )	116.40 ( $\gg 1$ )	11.67 ( $\gg 1$ )	48.18 ( $\gg 1$ )
$pH_i$	-179.39 (0.00)	-182.22 (0.00)		-72.65 (0.00)
$trop_j$	0.22 (1.25)	0.030 (1.34)	4.61 ( $> 1$ )	-4.37 (0.01)
$Text_j$	<b>-3.17*</b> (0.04)		-6.82 (0.00)	-1.93 (0.15)
$pH_i$		1.12 (3.09)	-33.58 (0.00)	<b>-3.85**</b> (0.02)
$trop_i \# Text_i$			86.06 ( $\gg 1$ )	
$trop_i \# trop_j$			-2.08 (0.13)	1.34 ( $\gg 1$ )
$trop_i \# text_j$			-11.85 (0.00)	-10.31 (0.00)
$trop_i \# pH_j$			18.71 ( $\gg 1$ )	-3.93 (0.00)
$text_i \# text_j$			28.80 ( $\gg 1$ )	19.24 ( $\gg 1$ )
$text_i \# pH_j$				-1.14 (0.32)
$pH_i \# trop_j$			-20.44 (0.00)	1.81 (6.09)
$pH_i \# Text_j$			-39.01 (0.00)	-42.25 (0.00)
$pH_i \# pH_j$			39.46 (0.00)	-84.75 (0.00)
Vanilla			<b>5.20***</b> (181.28)	<b>5.20***</b> (182.11)
Cloves			<b>8.13***</b> ( $\gg 1$ )	<b>8.14***</b> ( $\gg 1$ )
Cocoa			<b>2.76***</b> (15.81)	<b>2.76***</b> (15.73)
Rice			-1.99 (0.14)	-1.99 (0.11)
Trop FE			-0.30 (0.74)	-0.30 (0.74)
Cons.	-4.03 (0.01)	-3.83 (0.02)		-10.43 (0.00)
<b>Partner country</b>				
RTA	<b>0.42***</b> (1.52)	<b>0.43***</b> (1.53)	<b>0.60***</b> (1.82)	<b>0.54***</b> (1.71)
$b_{ni}$	<b>0.68***</b> (1.97)	<b>0.69***</b> (2.00)	<b>0.70***</b> (2.01)	<b>0.55**</b> (1.73)
$l_{ni}$	<b>0.58***</b> (1.78)	<b>0.59***</b> (1.80)	<b>0.46***</b> (1.58)	<b>0.49***</b> (1.63)
Dist-2	<b>0.47***</b> (1.60)	<b>0.48</b> (1.62)		0.44 (1.56)
Dist-3	-0.29 (0.74)	-0.30 (0.74)		-0.31 (0.74)
Dist-4	<b>-1.15***</b> (0.32)	<b>-1.17***</b> (0.00)	<b>-1.23***</b> (0.29)	<b>-1.14***</b> (0.32)
Dist-5	<b>-1.06***</b> (0.34)	<b>-1.08***</b> (0.34)	<b>-1.21***</b> (0.30)	<b>-1.19</b> (0.30)
$X_i$	<b>12.17***</b> ( $\gg 1$ )	<b>12.43***</b> ( $\gg 1$ )	<b>12.60***</b> ( $\gg 1$ )	<b>13.74***</b> ( $\gg 1$ )
$trop_i$	<b>0.87***</b> (2.39)	<b>0.89***</b> (2.42)	0.18 (1.19)	0.42 (1.53)
$Text_i$	<b>-1.77***</b> (0.17)	<b>-1.83***</b> (0.16)	-0.71 (0.49)	<b>-1.75***</b> (0.17)
$pH_i$	0.88 (2.41)	0.92 (2.50)		1.38 (3.98)
$trop_j$	<b>-0.63***</b> (0.53)	<b>-0.52***</b> (0.60)	<b>-2.68***</b> (0.07)	<b>-2.65***</b> (0.00)
$Text_j$				

**Table A1 (continued)**

Model	(1)	(2)	(3)	(4)
AIC	3398.30	3359.92	3275.16	3309.00
BIC	-600.92	-601.41	-626.66	-573.61
	<b>-2.03***</b> (0.13)		<b>-7.41***</b> (0.00)	<b>-7.46***</b> (0.00)
$pH_i$		<b>-4.06***</b> (0.02)	<b>-3.62**</b> (0.03)	<b>-3.95**</b> (0.02)
$trop_i \# Text_i$			<b>-1.63***</b> (0.20)	<b>-2.75***</b> (0.06)
$trop_i \# trop_j$			<b>2.30***</b> (9.96)	<b>2.29***</b> (4.39)
$trop_i \# text_j$			<b>3.00**</b> (20.08)	<b>3.01**</b> (20.22)
$trop_i \# pH_j$			-2.11 (0.14)	-1.91 (0.15)
$text_i \# text_j$			-3.15 (0.04)	-3.04 (0.05)
$text_i \# pH_j$				-1.14 (0.32)
$pH_i \# trop_j$			<b>2.60***</b> (13.44)	<b>2.54***</b> (12.69)
$pH_i \# Text_j$			<b>16.21***</b> ( $\gg 1$ )	<b>16.19***</b> ( $\gg 1$ )
$pH_i \# pH_j$			1.00 (2.71)	3.11 (22.35)
Vanilla			0.05 (1.06)	0.06 (1.06)
Cloves			<b>0.96***</b> (2.62)	<b>0.97***</b> (2.63)
Cocoa			<b>-0.56**</b> (0.57)	<b>-0.56**</b> (0.57)
Rice			-0.16 (0.85)	-0.16 (0.85)
Trop FE			<b>-0.40***</b> (0.67)	<b>-0.38***</b> (0.68)
Cons.	<b>-0.46*</b> (0.15)	<b>-0.72***</b> (0.49)	-0.03 (0.97)	-0.24 (0.79)

\*p < 0.1 \*\*p < 0.05 \*\*\*p < 0.01.

Note: This table returns the results of all models computed in this paper. The results from this table were used to select the best model given their AIC and BIC score.

increase the global supply of tropical crops.

#### 4.3.2. Crops texture requirements

The Models from Table 4 display that crops' soil requirements significantly decreased the probability of a country being selected as an exporter relative to no trade. Thereby, by holding all other variables constant, countries are better off exporting crops with  $pH_j < 0.00$  and  $Text_j < 0.00$  (Table 3). The increasing shape observed in Fig. 5 (a) suggests that tropical countries have a higher probability to export crops compared to non-tropical countries regarding crop texture requirements. At the same time, crops that are less intensive to loam texture ( $Text_j < 0.00$ ) (See Table 3) are expected to have a higher probability to be exported relative to no trade. The production environment (soil acidity, erosion, etc) in the tropical regions makes it difficult for agricultural activities to thrive without external human intervention (Gurmessa, 2021), which induces an additional production cost that might harm the international competitiveness of LDCs in the tropical zone. Fig. 5 (b) highlights that by considering the soil  $pH_{[5.50, 7.20]}$  endowment, some tropical countries like Madagascar, Japan, and India can lose their comparative advantage to export crops with  $Text_j < 0.00$  (See Table 3). In fact, since Madagascar, Japan, and India's soil  $pH_{[5.50, 7.20]}$  endowment ( $pH_{[5.50, 7.20]} = 0.30$ ) is higher than the  $pH_{[5.50, 7.20]}$  endowment in countries like Germany and the US, they are expected to have a lower probability to export crops that are not loam texture intensive ( $Text_j < 0.00$ ). Overall, our results suggest that the less complex the crop requirements are, the higher its probability to be traded by tropical countries. Also, for a tropical intensive crop to have a higher probability to be traded, the exporter country should have a share in neutral soil i.e.  $pH_{[5.50, 7.20]}$  higher than 43.00%.

#### 4.4. The comparative advantage of Madagascar

Consistent with the results in Section 4.1, we found that Madagascar

has the highest probability to export crops such as vanilla, cloves, and cocoa, with a probability equal to 0.88, 0.90, and 0.75, respectively (Fig. 6). According to Table 4, Madagascar is the only country favored for the global supply of vanilla (coefficients of the dummies are higher for Madagascar). These results support the results found from the RCA metrics. Moreover, crops like cloves, cocoa, and vanilla require a specific production environment that not all tropical countries can satisfy. Thereby, the trade pattern of these crops can be assimilated to a relaxation of the factor endowment theory related to fuel endowment (Bergstrand, 1989). Yet, Madagascar does not hold a monopoly on the global market of these products, however, the country's production environment makes Madagascar a major international actor in the market of the set of crops.

The negative, even insignificant coefficient of the rice dummy variable for Madagascar reflects the unfulfillment of the rice demand by the local market (Appendix). Annually, the country needs to import rice to fulfill the demand (about 180 million USD in 2020) (Dostie et al., 2002; ITC, 2020; Minten and Barrett, 2008; Moser et al., 2009). Among the country sample, Madagascar has the lowest probability for the exportation of rice (0.32) because the producers in Madagascar fail to control the production environment (i.e. the combined effect of soil and climate). However, by referring to Fig. 6, we can see that countries like Thailand succeeded to overcome the negative effect of tropical climate on rice productivity.

## 5. Policy implications

According to our findings, this section introduces the policy contributions of our research (Fig. A.1). The policies suggested in this section were drawn from our results and can be scaled up to the African continent and other LDCs located in the tropical zone.

The global arable land per capita is continuously decreasing. It went from 0.25 ha per capita in 1990 to 0.18 ha per capita in 2020 (World Bank, 2020). However, with the actual rapid population growth, the global demand for food and crops is continuously increasing and puts pressure on land (Blum, 2013; Kaniaska, 2016). Moreover, the increasing demand for proteins and bio-energy crops combined with rapid urbanization has reduced the size of agricultural land that was formerly dedicated to food production (Bai et al., 2016; Tan et al., 2005). To satisfy the increasing demand for food, the Asian continent increased the use of fertilizers and irrigation, while most African producers focused on the increase of arable land. Compared to other countries, the rate of urbanization in the African continent is still low (40.00%) and the continent holds more than half of the total uncultivated land (Chang, 1977; IFAD, 2020; Jayne et al., 2014; Kaniaska, 2016). Therefore, developed countries that are facing arable land scarcity are recommended to reallocate their agricultural production to LDCs. This reallocation of production is expected: (1) in short term, to supply the local market, and (2) in long term, to produce bio-energy crops and satisfy the global demand for proteins and organic foods.

On the other hand, African policies should focus on the attraction of FDI to improve their agricultural sector in the cultivation of staple food. They should seek investors from Asia, especially those who have experience in staple food production. To guarantee global and local food security, countries like Madagascar should be aware that without proper soil management, tropical soil is not suitable for the production of staple food (Chang, 1977; Fujii, 2014; Harter, 2007). Our analysis showed that Asian countries located in the tropical zone have a great experience in soil management. Hence, a transfer of technology from developing countries in tropical Asia to Madagascar, through FDI, would increase the productivity of staple food in Madagascar.

The lack of capital in the African continent impedes most African countries to increase their cultivated land. They require external help from multinational enterprises to fully exploit their available land. With the support from multinational enterprises, the probability for the African region to supply the international market with crops would

significantly increase.

International food policy should focus on the agricultural sector, especially in LDCs. To improve food security in LDCs and the rest of the world, international cooperation between LDCs and developed countries is strongly advised. In the short term, to prevent a future decline in the global supply of tropical products, developed countries are encouraged to invest in the agricultural sector. As an illustration, in Madagascar, the production of vanilla and cloves is threatened by aging input (Danthu et al., 2014), natural disasters (cyclones, floods, and seasonal droughts), market threats (asymmetric information, lack of fertilizer supply, and price volatility), and human threats (slash and burn agriculture, and thief). All of those issues are negatively affecting the international supply of vanilla (Rakotonanahary and Cao, 2020). Thereby, the vanilla sector requires fundamental reform going from the development of new seeds to the use of fertilizers to the market regulation. These solutions require capital that Madagascar alone cannot provide, thus require strong international cooperation.

International trade can, directly and indirectly, contribute to the improvement of the nutrient intake in LDCs. Local policymakers could use the added value from their countries' comparative advantage (eg. vanilla for Madagascar) and increase their importation of fruits, vegetables, and nuts from other countries to diversify the basket of consumption. In Madagascar, about 70,000 households are growing the second most expensive spice in the world, so vanilla, like any other cash crop, guarantees an increase in income and ensures better access to diversified food.

Local governments of the countries in the tropical zone should call for external capital to help them build infrastructure related to agriculture namely road, energy, irrigation, etc. This will inhibit the negative influence of climate (erosion and leaching) and improve productivity (Danthu et al., 2014, 2014; Minten and Barrett, 2008). Moreover, the infrastructure development attracts FDI (Andrianarimanana and Yongjian, 2021; Dunning, 1988; Minten and Barrett, 2008; Morea and Balzarini, 2019), and the implementation of new infrastructure such as processing plants, and storage plants will increase the added value of the raw products.

Finally, one of the major challenges for policymakers in the LCDs is the lack of research and data unavailability, especially updated soil data. The lack of research in the region limits the effective implementation of local policy. To alleviate poverty and achieve global food security, research on agriculture in the LCDs must significantly increase in the following years. Hence, scientists and policymakers should join their effort to improve the productivity of the agricultural sector. On the other hand, the local government should increase its investment in agricultural research and development to develop adequate and specific policies.

## 6. Conclusion

Most people threatened by food insecurity are located in Sub-Saharan Africa and LDCs. The present study aimed to highlight the importance of natural-resources endowment (land, soil, and climate characteristics) on the global supply of crops given the crops' specific agroecological requirements, specifically soil and climate. Our results showed that the global market of crops is mainly driven by the country's endowment and the crops' requirements. For Madagascar in particular, the production environment gives the country a high probability to export vanilla, cloves, and cocoa. Our study also showed that the international supply of crops is threatened by the climate, soil characteristics as well as the lack of capital in most LDCs in the tropical zone. Therefore, in order to meet the increasing demand for food, strong collaboration between developed countries and LDCs is greatly advised. Even drawn from the case of Madagascar, our findings and the policy implications we suggested in this study can be extended to LDCs in Africa and LDCs in the tropical zone. However, our research was limited by data availability, especially in LDCs. For instance, with more micro-level

data on LDCs, the mixed logit approach could have been used to get country-specific estimates. Given the importance of the impact of climate change on food security, we encourage future research to further explore the effect of climate change in tropical regions on the international supply of tropical products.

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## CRedit authorship contribution statement

**Mihasina Harinaivo Andrianarimanana:** Conceptualization, Data curation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Pu Yongjian:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Mirindra Finaritra Rabezahary Tantelinaina:** Validation, Methodology, Visualization, Writing - review & editing.

## Declaration of Competing Interest

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

## Data availability:

Data are all available online as presented in section 2.1.

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## Appendix

See Table A1.

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