Original article

Apple cultivation and its major challenging constraints in the Central Highlands of Madagascar

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Summary

Introduction – **Apple *Malus domestica* B. was imported to Madagascar in 1870 to be grown in the central highlands of this subtropical continental island of the Indian Ocean. Despite conditions that have been considered favourable for its cultivation, current bioclimatic constraints weaken the apple production.** *Materials and methods* – **Surveys of apple growers were carried out in the 5 main regions. In the survey, characteristics of the apple orchards, cultivation methods and constraints linked to production were asked. Periodic monitoring of the phenology of 25 identified varieties were also performed for 1 year.** *Results and discussion* – **The region of Vakinankaratra is the main producer of apples and has the higher varietal diversity (up to 8 varieties per grower). Growers multiply their own apple trees by stump bursting (44.61%) and grafting (45.57%), maintain their apple orchard (59.68%). Most of them associate apple orchards with other annual and perennial crop (59.92%) species. In the Amoron'i Mania region, the orchards installed around 1950 are still in the central zone without any renewal of the apple trees. The rest of the regions (Analamanga, Haute Matsiatra and Itasy) mostly grow apple for non-commercial purposes with rare cultural maintenance. Major constraints are *Deborrea malgassa* H. (Lepidoptera Psychidae) pest (63.51%). Ecological disturbances due to deforestation and climate change, where temperate zones are the most affected, could be at the origin of phytosanitary problems, particularly the aggravation of the attack of this Psychidae affecting apple growing.**

Keywords
apple, constraints, *Deborrea malgassa,* surveys

Significance of this study

What is already known on this subject?

- Apple cultivation is an important source of income for many farmers and plays an important role in the development of rural communities in the Central Highlands of Madagascar, however it is limited by diverse biotic and abiotic constraints. In addition, there is a lack of data about the current status of apple cultivation in Madagascar.

What are the new findings?

- This paper gives a global overview of apple cultivation in Madagascar and the current status of the main problems facing apple cultivation.

What is the expected impact on horticulture?

- A broad survey was conducted to clearly identify the major problems or concerns of apple cropping. Data collected will help to develop solutions based on identified issues.

Introduction

Apple (*Malus domestica* Borkh., Rosaceae) is one of the most cultivated temperate tree fruits in the world. Global production has over 93 Mt in 2021. China is the largest apple producing country globally, with the European Union and the United States not far behind (FAOSTAT, 2021). Apples originate from Asia Minor, the Caucasus, central Asia, Himalayan India, Pakistan and western China (Brown, 2011). The geographical distribution of apple is limited by its chilling requirement of greater than 1,000 h under 5 °C to 7 °C (Childers *et al.*, 1995). Currently there is a growing interest for apple cultivation in tropical areas such as in India, Brazil, Mexico, Pakistan, Egypt, South Africa, Morocco, Chile, Argentina, New Zealand and Australia (Childers *et al.*, 1995; Roche *et al.*, 1999; Ferree and Warrington, 2003) as potential production areas. Several apple cultivars are grown worldwide, however, a small proportion of these are grown commercially, among which some cultivars are available for subtropical climates (Turechek, 2004; Elzebroek, 2008). The leading varieties are 'Delicious' and 'Golden Delicious', which are grown in almost all apple-growing regions in the world (Childers *et al.*, 1995; Turechek, 2004).

Apple trees are cultivated in Madagascar. The climatic and the agroecological conditions of the Central Highlands are ideally suited to the cultivation of apple cultivars besides other temperate fruits (*Prunus domestica*, *Cidonia vulgaris*, *Armeniaca vulgaris*, ...). Madagascar ranks in 78th place worldwide apple producers with about 7.2 Kt production in 2021 (World Development Report, 2020; FAOSTAT, 2021). Apple tree was imported firstly in 1870 from Europe to Madagascar for diversification of fruit crops and then had been established for intensive production around 1931 (De la Bathie, 1931). In 1958, about 500,000 apple trees were planted through layering and cutting propagation methods,

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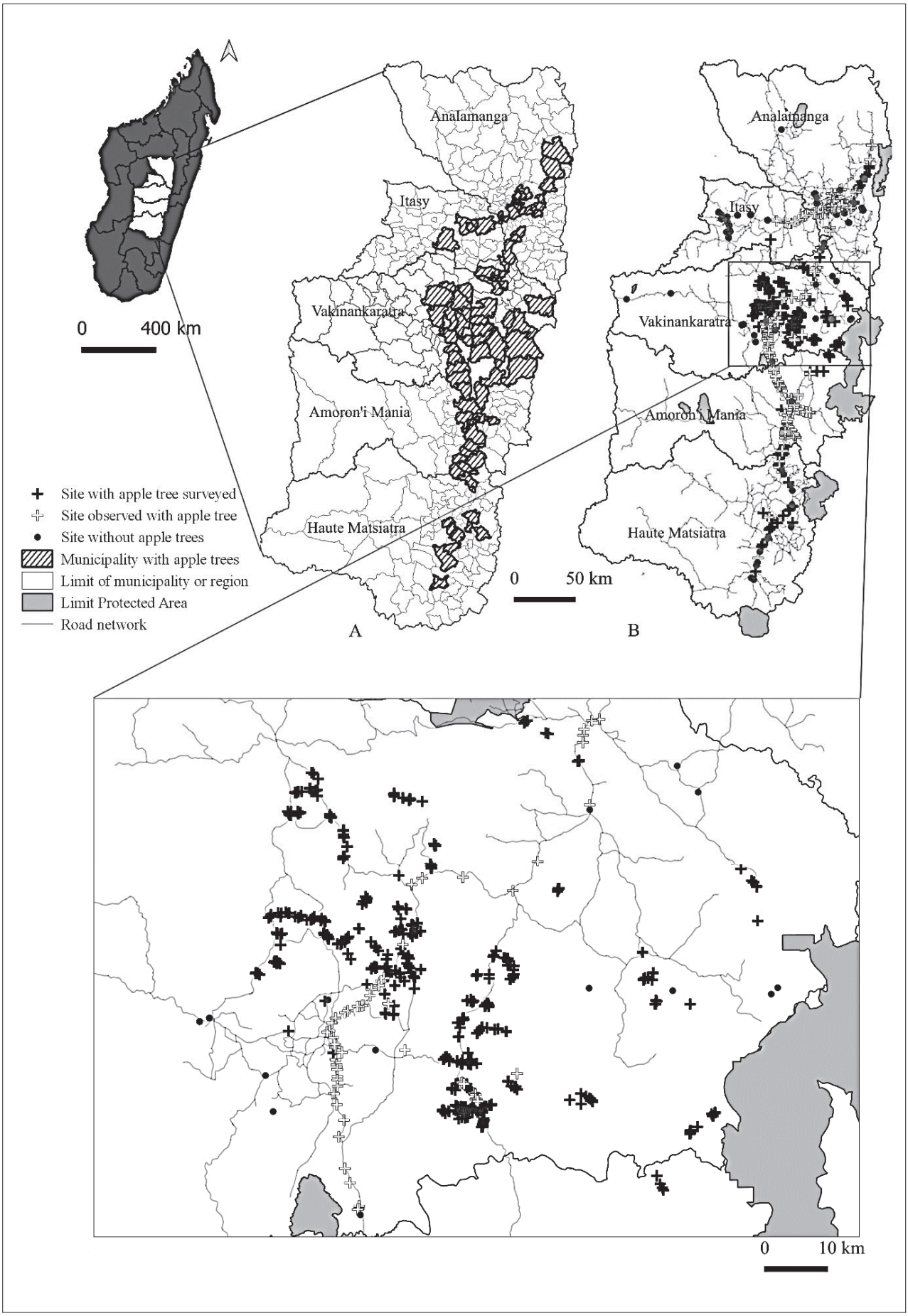


Figure 1. Distribution of apple tree in the five main regions in Madagascar. A. Distribution of municipalities having apple tree. B. Sampling site.

especially in Soanindrariny located in the Vakinankaratra region. More than 70 varieties of apple were imported by missionaries. Apple cultivation was later promoted through a number of projects for the development of apple sector. This sector is one of the economic resources for which the Central Highlands region is known. Indeed, apple cultivation is an important source of income for many farmers, plays a significant role in the rural communities' economy of these regions, and is of great value to counteract malnutrition by food diversification (Conti *et al.*, 2021; Rakotomanana *et al.*, 2020). In 2013, growers in Vakinankaratra region planted 1.5 million trees and the production of apples sold reached about 20.5 Kt in 2020 (according to data from Plateforme Pomme Vakinankaratra). Between 1995 and 2021, Madagascar exported about 6.8 Kt of fresh apples to neighboring islands, Europe and Jamaica, and about 5.9 Kt of by-products, such as juice, to neighboring islands, Europe, Arabia, South Africa, and Thailand (World Development Report, 2020; FAOSTAT, 2021).

Nonetheless, growers have been facing various difficulties and constraints affecting yields since the 1970s until today resulting in strong decrease in production, a reduction of 10.5 Kt to 5.4 Kt in 1984 with an average yield of 4 to 6 kg per plant and has levelled off at 5.7 Kt in 1990 (FAOSTAT, 2021). It should be pointed out that Madagascar is an island not immune to climate change, with temperature increases of +1.5 °C to 2 °C, changes in rainfall and intensification of drought (Tadross *et al.*, 2008; Nematchoua *et al.*, 2018). These ecological and climatic changes affect crops, especially in temperate fruits grown on the islands (Salama *et al.*, 2021). This study was carried out to assess the current status of apple cultivation and the production constraints at the level of the farmer in the five apple growing regions located in the Central Highlands of Madagascar including the Vakinankaratra, Analamanga, Itasy, Amoron'i Mania and Haute Matsiatra regions. The survey data and field observations are of great importance to develop solutions based on the problems identified to address production constraints.

Materials and methods

Description of the study area – ecology and climatic conditions of the surveyed regions

Madagascar is a large tropical continental island located in 12 to 26°S and 43 to 51°E, separated from Africa by the Mozambique Channel and bordered to the east by the Indian Ocean. Covering an area of 592,000 km^2, Madagascar is divided into 23 regions inhabited by 25 million people (INSTAT, 2020).

Surveys were conducted in five regions of the Central Highlands of Madagascar (Vakinankaratra, Analamanga, Itasy, Amoron'i Mania and Haute Matsiatra regions), in high altitudes (1,000 to 2,200 m), where apple growing is known to be the most abundant. These regions of highlands are characterized by a temperate altitude climate with a distinct seasonality of rainfall. Antananarivo (Analamanga), the capital (1,350 m) has five months hot and humid period set off by a cooler and drier season of about seven months. The average temperature in July at the height cool season in 14.4 °C. Antsirabe (Vakinankaratra) (1,476 m) and Fianarantsoa (Haute Matsiatra) (1,320 m) have a roughly similar climate to the capital. The main soil types in the highlands are ferralsols (dominant), lithosols, cambisols and gley soils (Braun *et al.*, 1997). Cyclones dumping extraordinary quantities of torrential rain periodically ravage the interior of the island (Gade, 1996).

Sampling and data collection techniques

Madagascar's territorial collectivities describe a region as a composition of districts, which are composed of municipalities, which are divided into fokontany. The survey was carried out using individual questionnaires, to investigate apple production and its major constraints. Respondents were smallholder apple farmers drawn from 10 households of apple farmers per producing fokontany chosen at random in each municipality. In case of less apple farmers in the fokontany as many apple farmers as possible have been surveyed. Surveys (n=836) were conducted from 2019 to 2022. The survey included main questions linked to the cultivation technics from planting to harvesting of apples, the choice of cultivar and rootstock used, the production (yield), the size of apple farms, and constraints related to apple production, particularly diseases and pests. At the same time, daily meteorological data from apple-growing areas were collected from two sites (Vakinankaratra region) using Tinytag Plus data loggers, and direct field observations were made as much as possible to supplement information collected through the surveys.

Phenological observations of existing varieties

Monitoring of phenological stages of several apple varieties was conducted for 12 months in 2021. The study of phenology was based on observations of 10 individual apple trees per variety (n=26) in two municipalities (Soanindrariny and Ambano) of the Vakinankaratra region, which are 60 km apart (Figure 1). Apple phenological stages noted were: induction and flower differentiation, budbreak, full bloom, fruit development and maturation as described in Petri *et al.* (2012). In order to determine the corresponding phenology on an approximate basis, a rating scale for plant organs (bud, leaf, flower, fruit) was established from 1 to 5, from the least to the most abundant. The high level of the scale (3 to 5) indicates the corresponding phenology except for dormancy. Observations and rating were done monthly.

Analysis of data

All Fokontany and data were georeferenced. Data were summarized using descriptive statistics and graphs that were computed in R software (R Development Core Team, 2021), and spatial distribution of sampling sites was processed using QGIS software (QGIS, 2023). An analysis of variance, a Tukey HSD (Honestly Significant Difference), a test of Pearson, and a general linear model (GLM), were used to test the relationships between the different factors of production and yield resulting from the conducted survey. The Growing Degree Days (GDD) of the 25 varieties for each phenological stage were calculated by taking the average daily maximum and minimum temperatures for each stage duration.

Results

Production areas

In total 50/410 municipalities and 108/4,814 fokontany surveyed contained apple culture. In total 836 growers were surveyed and 391 sites with apple trees were observed (Figure 1). Apple orchards were found in Central Highlands of Madagascar in altitudes between 1,022 and 2,165 m. The apple production areas concerned 46/410 municipalities of the 5 regions (Table 1a). Vakinankaratra is the main apple-producing region of the island was the most surveyed (n=768/836). Of the 768 surveyed growers, the highest orchard density is about 562.97 trees ha^{-1} and the

Table 1a. Surveys and apple orchard characteristics.

		Region				
		Analamanga	Itasy	Vakinankaratra	Amoron'i Mania	Haute Matsiatra
Survey	Number of apple grower surveyed/number of sites with apple tree observed	17/84	3/27	768/926	20/149	28/41
	Number of districts surveyed/ total number of districts	2/13	1/3	5/7	1/7	6/7
	Number of municipality surveyed/ total number of municipalities	7/134	2/53	20/86	5/55	12/82
Orchard characteristics	Total apple tree area (ha)	0.14	0.01	167.04	4.21	0.13
	Density (tree ha^{-1})	360.85±12.44	377.77±22.22	562.97±14.36*	396.78±1.56	358.67±5.80*
	Average age of orchard (y)	21.41±4.29	13.33±2.03	19.47±0.50	24.40±3.46	15.36±1.83
	Production (kg $tree^{-1}$)[1]	6.75±1.94	2.67±1.20	21.96±0.91*	19.03±4.24	1.10±0.31*

[1] Apple trees less than three years old have been removed from the yield calculation.
* Significant results ($P < 0.05$, ANOVA with Tukey's post-hoc analysis).

Table 1b. Apple breeding characteristics and crop management. Percentage of those surveyed having apple trees (%).

		Region				
		Analamanga	Itasy	Vakinankaratra	Amoron'i Mania	Haute Matsiatra
Reason for cultivation[2]	Source of income	0.00	0.00	54.17	35.00	0.00
	Self-consumption*	100.00	100.00	19.66	40.00	100.00
	Source of income + self-consumption	0.00	0.00	26.17	25.00	0.00
Variety (>10 trees)[1]	Fisakana ($n=1$)	0.00	0.00	100.00	0.00	0.00
	Golden Delicious ($n=44$)	0.00	0.00	100.00	0.00	0.00
	Maramena ($n=4$)	0.00	0.00	100.00	0.00	0.00
	Melrose ($n=9$)	0.00	0.00	100.00	0.00	0.00
	Mutsu ($n=1$)	0.00	0.00	100.00	0.00	0.00
	Norvégienne ($n=10$)	0.00	0.00	100.00	0.00	0.00
	Paoma mamy ($n=36$)	0.00	0.00	97.22	2.78	0.00
	Pommone ($n=6$)	0.00	0.00	100.00	0.00	0.00
	Reine des Reinettes ($n=8$)	0.00	0.00	100.00	0.00	0.00
	Reinette grise ($n=3$)	0.00	0.00	100.00	0.00	0.00
	Mixed varieties ($n=478$)	0.42	0.00	96.86	2.72	0.00
Origin of plants[2]	Local	29.41	66.67	95.57	75.00	64.29
	Out of the area	52.94	33.33	3.52	25.00	32.14
	NA**	17.65	0.00	0.91	0.00	3.57
Multiplication of plants[1]	Purchase of plants	20.00	5.71	31.43	2.86	40.00
	Cutting	0.00	0.00	50.00	50.00	0.00
	Stump bursting	1.47	0.24	91.20	4.40	2.69
	Grafting	0.00	0.00	100.00	0.00	0.00
	NA**	0.00	0.00	22.22	0.00	77.78
Rootstock[2]	Fisakana	0.00	0.00	0.79	0.00	0.00
	Maramena	0.00	0.00	5.25	0.00	0.00
	Poma mamy	0.00	0.00	67.19	0.00	0.00
	Pommone	0.00	0.00	1.57	0.00	0.00
	Reine des Reinettes	0.00	0.00	21.78	0.00	0.00
	Mixed varieties	0.00	0.00	3.41	0.00	0.00
Cultural maintenance[1]	Cleaning of plots	0.27	0.00	99.46	0.27	0.00
	Ridging	0.00	0.00	100.00	0.00	0.00
	Mixed (cleaning of plots/ridging/ fertilization/pruning and trimming)	0.00	0.00	98.21	1.79	0.00
	Pruning and trimming	0.00	0.00	100.00	0.00	0.00
	No maintenance	4.79	0.90	80.54	5.39	8.38

Table 1b. Continued.

		Region				
		Analamanga	Itasy	Vakinankaratra	Amoron'i Mania	Haute Matsiatra
Fertilizer[1]	Compost including other organic matter	0.00	0.00	98.84	1.16	0.00
	Dolomite	0.00	0.00	100.00	0.00	0.00
	Manure	0.00	0.00	100.00	0.00	0.00
	Mixed (manure + mowing)	8.33	0.00	91.67	0.00	0.00
	No fertilizer	2.59	0.49	89.32	3.07	4.53
Intercropping[1]	Monoculture	2.11	0.35	93.68	1.75	2.11
	Natural forest	0.00	0.00	0.00	100.00	0.00
	Pine forest and fruit crops	6.82	1.52	75.00	4.55	12.12
	Vegetable and forage crops	0.00	0.00	100.00	0.00	0.00
	Mixed (perennial and annual plants)	1.80	0.00	88.29	4.50	5.41
Pest[2]	*Deborrea malgassa* (Lepidoptera Psychidae) (*n* = 531)	5.00	23.53	0.00	0.00	68.49
	Diaspidiotus perniciosus (Hemiptera Diaspididae) (*n* = 22)	0.00	0.00	0.00	0.00	2.86
	Eriosoma lanigerum (Hemiptera Aphididae) (*n* = 5)	25.00	0.00	0.00	0.00	0.00
	Other Lepidoptera (*n* = 24)	0.00	0.00	0.00	0.00	3.13
	Ceratitis malagassa (Diptera Tephritidae) (*n* = 19)	0.00	0.00	0.00	0.00	2.47
	Fruit rot fungi (*Venturia inaequalis, Colletotrichum* sp.) (*n* = 107)	0.00	35.29	0.00	0.00	13.15
	Other fungal diseases (*n* = 170)	0.00	0.00	0.00	0.00	22.14
	NA** (*n* = 40)	5.00	0.00	0.00	0.00	5.08
	No pest (*n* = 213)	70.00	58.82	100.00	100.00	20.57
Pest control[2]	Prophylactic measures	0.00	0.00	0.13	0.00	0.00
	Mechanical control (weeding, cutting of diseased parts)	0.00	0.00	36.72	0.00	0.00
	Chemical control (deltamethrin, mancozeb, polyethrin)	0.00	0.00	1.95	0.00	0.00
	Mixed control	0.00	0.00	7.81	0.00	0.00
	No control	100.00	100.00	53.39	100.00	100.00
Other constraints linked to the crop[2]	Climatic factors (hail, global warming)	0.00	0.00	10.16	0.00	0.00
	Difficulty of the market	0.00	0.00	13.02	0.00	0.00
	Squatterization	0.00	0.00	0.00	5.00	0.00
	Stealing	0.00	0.00	1.56	0.00	0.00
	Lack of technical skills	23.53	0.00	6.64	20.00	3.57
	Bad road conditions	0.00	0.00	7.03	0.00	0.00
	Mixed constraint	5.00	0.00	5.99	5.00	0.00
	No constraint	76.47	100.00	55.60	70.00	96.43

[1] Means line reading; [2] means column reading.
* Mostly self-consumption but whenever opportunities arise, be used as a secondary income.
** NA means no answer and () contains total number.

best yield is about 21.96 kg tree^{-1} (Table 1a). Apple growing in the Amoron'i Mania region was constituted by the presence of orchards in the centre of the region. In the region of Haute Matsiatra, Itasy and Analamanga, we were not able to find commercial production areas, apple trees were mostly grown in garden with only a few trees (<10) for family consumption and secondary incomes whenever possible. In the five regions, surveyed growers declared on average orchard of 13- to 24-year-old. The oldest orchards were between 60 and 120 years old (*n* = 14). Orchards were mainly disposed with widely varying distances between trees of 3–7 m, depending on the region (*n* = 548).

Varieties

'Golden Delicious' (*n* = 538) and 'Paoma mamy' (which means "sweet apple") also called 'paoman-drazana' (which means ancestor's apple because it was the oldest introduced variety in the island) (*n* = 406) are the main cultivated varieties surveyed. Nonetheless, 25 varieties were observed. The greatest varietal diversity was found in Vakinankaratra region (maximum 8 varieties per orchard). The choice of cultivars is based on the availability of existing neighboring varieties from which growers take rootstocks and scions (64.23%). In addition, most of growers have inherited their orchards from their parents (25.36%). And there are

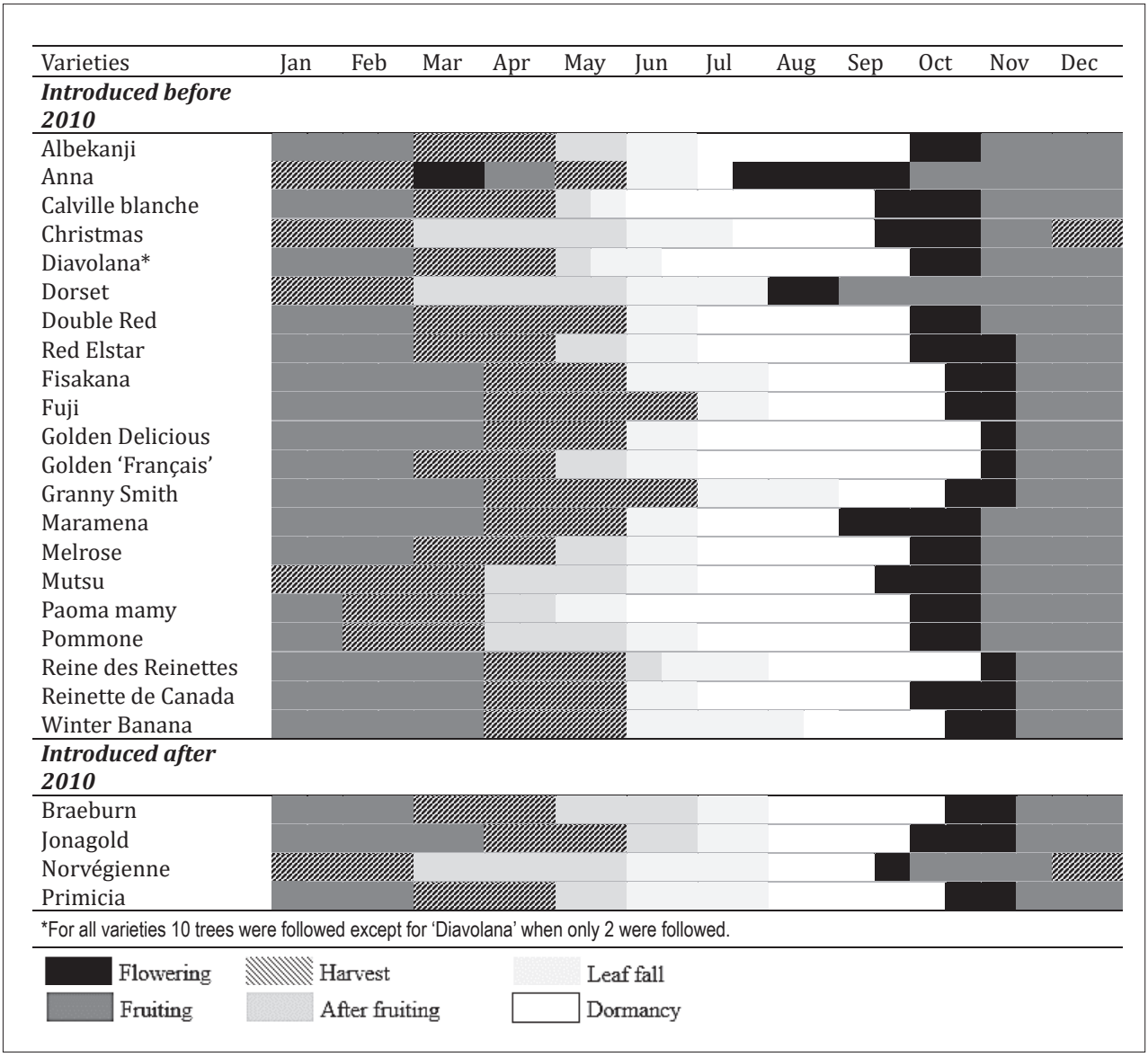


Figure 2. Phenological stage of apple varieties in the region of Vakinankaratra.

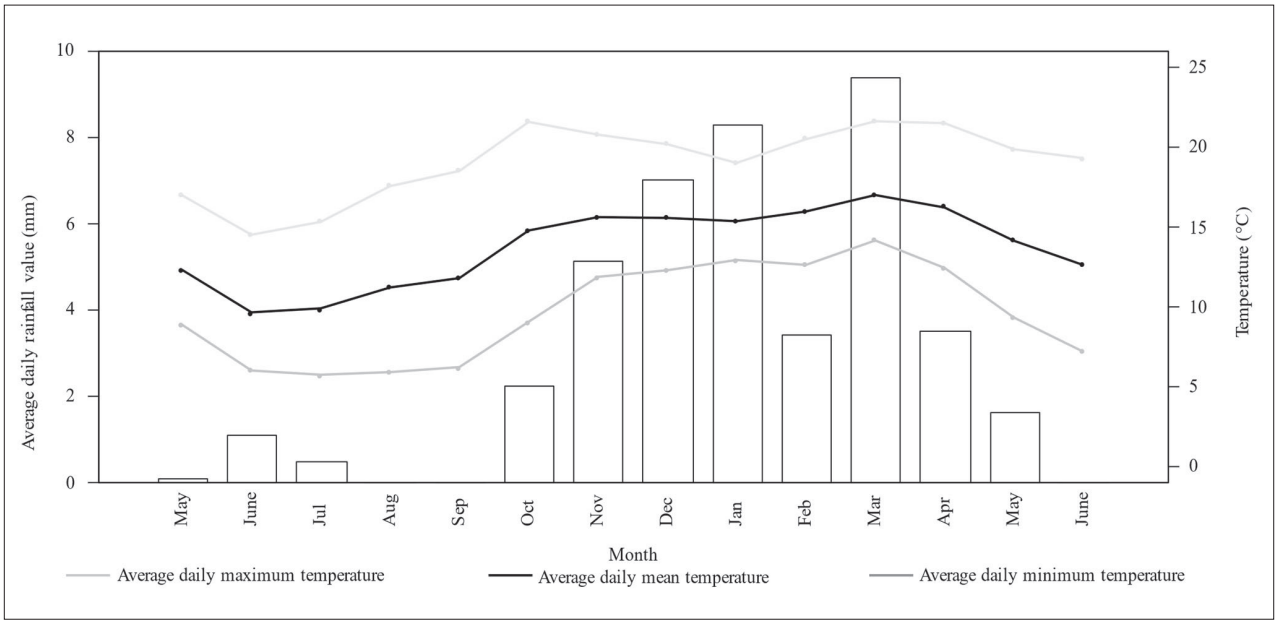


Figure 3. Umbrothermal diagram of Soanindrariny in 2022–2023.

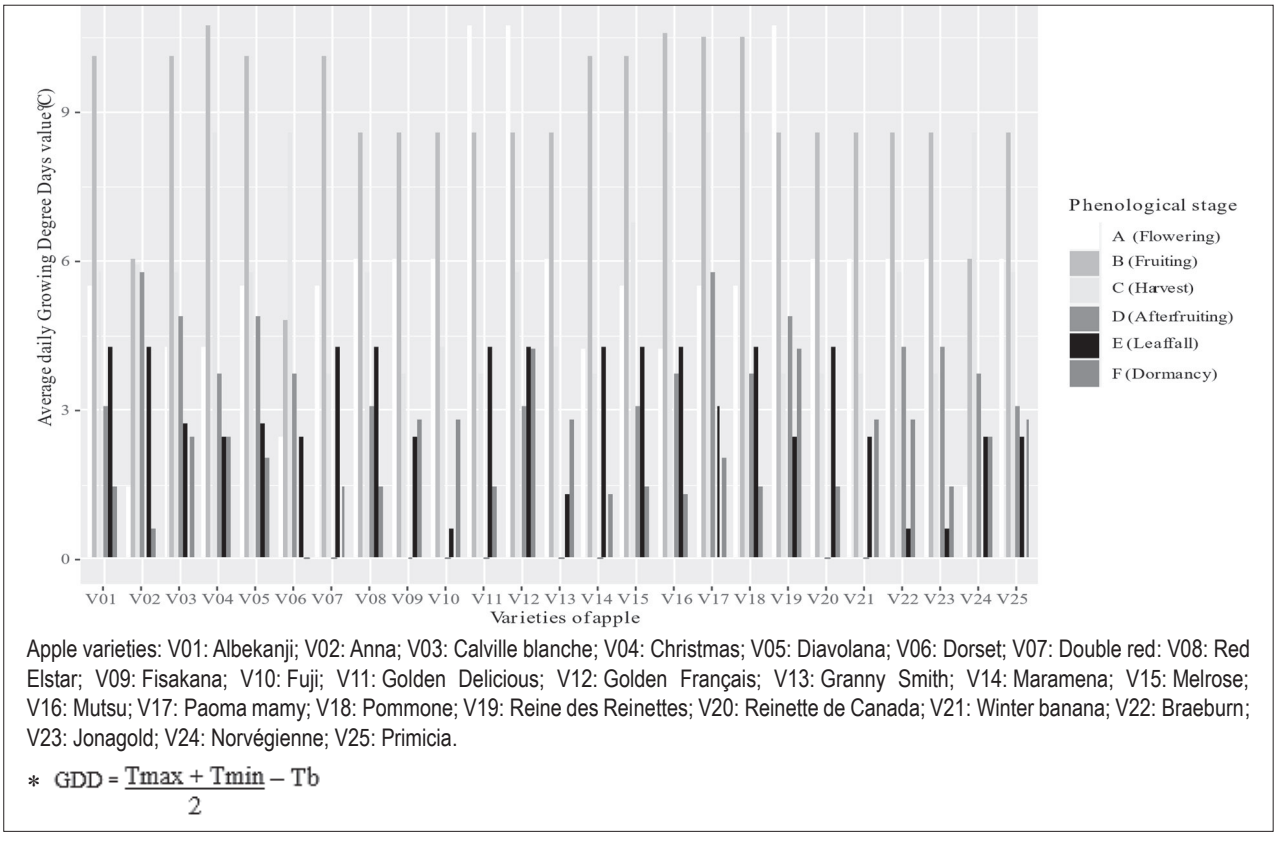
those who choose their cultivars because they are new, such as Norwegian and Anna (19.74%). In 17 municipalities from the Vakinankaratra, Amoron'i Mania and Haute Matsiatra regions, apple growers replanted and expanded their production areas (5 to 7 years ago) (n = 81). Early varieties were 'Anna' and 'Dorset', late varieties were 'Granny Smith' and 'Fuji'. The phenological stages from flowering to fruit ripening observed took place between September and May. Dormancy occurs from June to September. According to apple growers, the harvest period usually takes place in December for early varieties: 'Anna' (n = 4) and May for late varieties: 'Granny Smith' (n = 2), and the high season is from February to April (n = 19) (Figure 2). A rise in temperatures from September to April (Figure 3) corresponded to the fruiting stages (GDD, Figure 4), and the dormancy stage was synchronized with the cold period in apple-growing areas (GDD, Figure 4). In winter (June to August), temperatures can drop to 0 °C (-1.5 °C). Furthermore, annual rainfall exceeds 1,200 mm from December to April (Figure 3). According to growers, pollinating varieties were 'Golden Delicious' (64.35%), 'Granny Smith' (9.92%) and 'Reine des Reinettes' (6.34%) (Table 1).

Apple crop management

Vakinankaratra and Amoron'i Mania regions are considered as the main apple commercial production areas. In fact, 54.17% of production in the Vakinankaratra region and 35% of production in the Amoron'i Mania region were declared as grown for a source of income. The production in the three other regions was declared destined for self-consumption (100%) or secondary income whenever opportunities arise (Table 1b). Growers principally choose to generate their own apple trees: in the Vakinankaratra region by stump bursting in July and August (100%) and slit grafting (91.20%), in the Amoron'i Mania region by cuttings of the stump in December (50%). The three other regions preferred to purchase their apple trees locally or in other production areas (10 to 50 km from other growers). For the Vakinankaratra region, where growers multiply the apple trees by grafting, 'Paoma mamy' variety is mainly used as rootstock (67.19%) as it provides the most stump among other varieties according to surveyed growers. Also, the variety 'Reine des Reinettes' is declared by 21.78% of the surveyed growers used as rootstock, as it is supposed to give vigor to the plants (Table 1b).

The cultural maintenance (necessary care operations consisting in obtaining a good yield) of apple trees is rarely carried out by growers (Table 1b). If they are mainly practiced in the Vakinankaratra region, they consist of field cleaning (54.68%), pruning or trimming (14.84%), ridging (2.73%) during the dormancy phase especially for the 'Paoma mamy' in order to obtain more stumps for multiplication. Tools are "angady" (kind of spade; n = 61.84%), machete (1.55%), and pruning shears (0.24%). Fertilization, if applied, was for annual crops in intercropping. Vakinankaratra is the principal region which used organic fertilizer like manure (n = 119/218) from October to November. Compost and other organic materials (n = 98/218) were the second type of fertilizer (Table 1b).

The intercropping of apple orchards is very important for growers. Intercropping included perennial crops dominated by temperate fruits: *Prunus persica* and *Prunus domestica* (75% in the Vakinankaratra region), with forest plantations of *Pinus* sp. (0.36%). Annual intercrops consisted mainly in *Zea mays* (40.07%), but there were also *Phaseolus vulgaris*, *Solanum tuberosum* in the inter- and off-season, *Oryza sativa*, and *Manihot esculenta* reported. Intercropping with forage crops like *Penissetum* sp., *Brachiaria* sp. (0.12%) and vegetable crops like *Cucurbita* sp., or *Brassica* sp. (2.63%) were



Apple varieties: V01: Albekanji; V02: Anna; V03: Calville blanche; V04: Christmas; V05: Diavolana; V06: Dorset; V07: Double red: V08: Red Elstar; V09: Fisakana; V10: Fuji; V11: Golden Delicious; V12: Golden Français; V13: Granny Smith; V14: Maramena; V15: Melrose; V16: Mutsu; V17: Paoma mamy; V18: Pommone; V19: Reine des Reinettes; V20: Reinette de Canada; V21: Winter banana; V22: Braeburn; V23: Jonagold; V24: Norvégienne; V25: Primicia.

* $GDD = \frac{Tmax + Tmin}{2} - Tb$

Figure 4. Average daily Growing degree days value (°C) (GDD)* for apple varieties studied.

grown in the Vakinankaratra region. In the Amoron'i Mania, growers plant their apple trees within natural secondary forests (Table 1b).

Apple pests and diseases

In the surveys, *Deborrea malgassa* appeared to be the major problem for those who reported phytosanitary problems (63.51%) whose larvae are highly defoliating caterpillars. Other Lepidoptera species were also identified when performing the surveys like *Euproctis similis*, *Bunaea aslauga*, and *Parasa* sp. (2.87%) which larvae were found defoliating trees after apple harvest, but were not declared as a problem by apple growers. The San José scale *Diaspidiotus perniciosus* was also reported from the orchards of the Vakinankaratra region (2.63%) but the growers did not find it as a major problem for their production. The fruit fly, *Ceratitis malgassa*, was also reported as a minor constraint due to its low prevalence (2.27%), but causes damages to fruits whose larvae consume the pulp. The woolly aphid *Eriosoma lanigerum* attacks apple tree in the Amoron'i Mania region and reduces the orchard area of this zone (0.60%) (Table 1b).

Fruit rot fungi [*Venturia inaequalis*, *Colletotrichum* sp. (12.80%) and other fungal diseases (20.33%)] were the second problems after insect pests reported by growers on apple trees in the Vakinankaratra and Haute Matsiatra regions (Table 1b). They cause cracks and deformation on the heavily infected fruits, and can strongly affect the yield and the quality of the fruits. Corticolous lichens are colonizing the trunks and living branches of apple trees, they are not considered as a parasite, but disturb growers.

Control of these pests is done in the Vakinankaratra region (46.61%) and not done at all in other regions (Table 1b). Apple growers choose first mechanical ways such as manual harvesting of *D. malgassa* caterpillars (36.72%). The reported use of synthetic pesticides like insecticide and fungicide (1.95%) were low and often without knowledge of the active ingredients corresponding to which pests or diseases.

Table 2. Statistics from the generalized linear model used to analyze apple yield (kg ha^{-1}) as function of cropping practices and pests.

Cropping practices and pests	Yield	Df
Density	0.0005871***	4
Annual intercrop	5.353e-05***	1
Perennial intercrop	6.136e-05***	1
Fertilizer	0.1454	1
Cultural maintenance	0.01484*	1
Dm	0.002913**	1
Fungal diseases	0.0457*	1
Pest control	0.04764*	1
Age	0.005909**	5
Variety	0.07257	10

** and ***: highly significant results.
Data tested in the GLM only concern Vakinankaratra, apple trees less than three years old are removed (N=705). Fertilizer had no effect on yield. Age and other production factors such as density, the presence of annual intercrops (n=370), perennial intercrops (n=167), orchard maintenance (n=457), Dm presence and attack of *Deborrea malgassa* (n=491) and fungal diseases (n=231) as well as pest controls (n=332) influenced yield.

Harvest and production

The production of apple declared by growers was highly diverse with on average 21.96 kg tree^{-1} for the Vakinankaratra region or 19.03 kg tree^{-1} for the Amoron'i Mania region. The remaining regions declared in average less than 10 kg tree^{-1} (Table 1a).

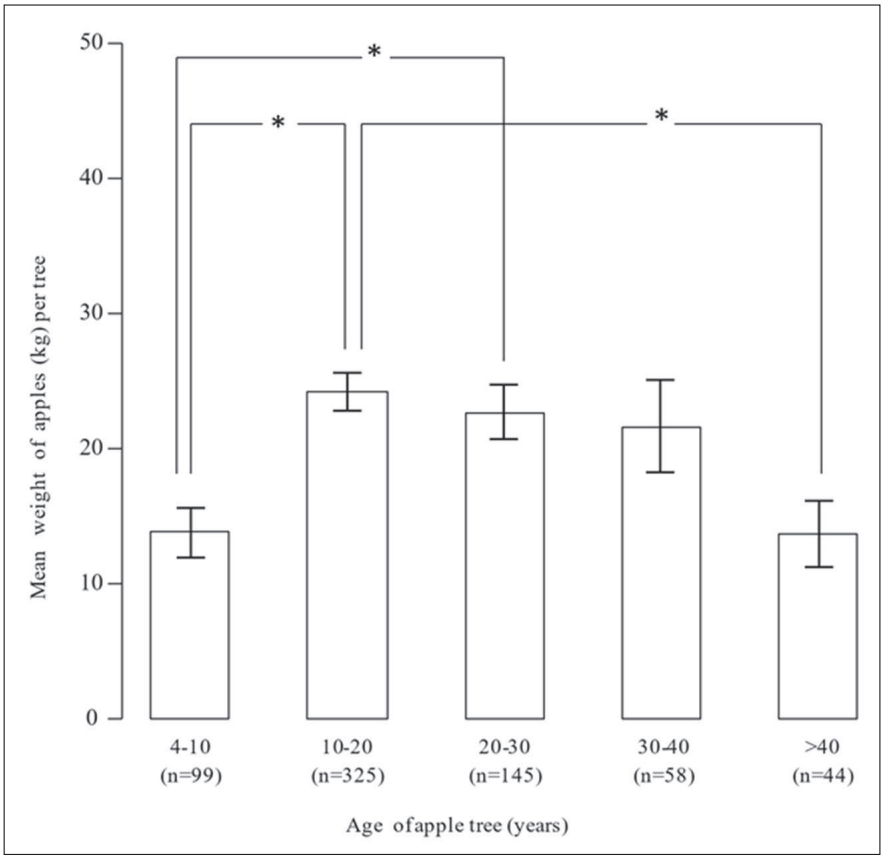


Figure 5a. Yield of apples (kg tree^{-1}) per class of age. Bars represent standard error. Data without age of apple are removed from calculation. Significant results were obtained by Tukey test.

The maximum of yield reported was 166.67 kg tree^{-1} (Table 1b). The high production (>100 kg tree^{-1}) was found in the Vakinankaratra region (n = 14). The majority of apple trees are in the 10–20-year age range (n = 325). The best production was found in orchards of 10 to 20 years and gradually decreased after 20 years (Figure 5a) (Tukey test, $P_{value} < 0.05$). There was a great diversity of apple varieties found in the Vakinankaratra region. Yield did not differ by variety but differed by age (Figure 3a). Even if the trees were young, the yield remained low (Figure 5b). The effect of density on yield was negative (Tukey test, $P < 0.05$).

Apple production was significantly influenced by crop management (Table 2; GLM analysis). The yield was significantly decreased by the presence of intercropping, or lack of orchard maintenance. The same goes for the choice of means of pests control, which decreases the yield because the use of phytosanitary products is without prior consultation or knowledge of the application dose. The yield also significantly decreased when orchards were attacked by pests or diseases, such as by *D. malgassa* (reported as the main pest by growers) and fungal diseases.

Other production-related constraints

In addition to biotic constraints, producers have encountered other constraints for the production of apple especially in the Vakinankaratra region. They complained about the difficulty of selling their production (13.02%) where the roads are very bad (7.03%) and not practicable in the rainy season, that corresponds to the main apple harvest time. Only the truckers which collect the apples could pick them up and dictate the price. It is a real problem for growers as they cannot sell their production at a higher price and are not motivated to improve cultural maintenance for higher yield.

Hail and global warming are also a problem felt by growers (10.16%) in the five regions surveyed.

Squatterization of land was also raised as a constraint for 5% of the apple growers in the Amoron'i Mania region (0.24%) (Table 1b). Another problem raised was the lack of technical skills in the Vakinankaratra, Analamanga, Haute Matsiatra and Amoron'i Mania regions (8.37%, n = 70). Because of this, some growers abandoned apple orchards. We could observe for example in the region of Analamanga in Anjepy the total replacement of apple orchards to annual or forest cultivations.

Discussion

Among about 70 varieties introduced in Madagascar from the 50's, we could only find 25 of them, which includes the most recent ones introduced after 2010 (n = 4), in the main region where apple is grown. Apple is grown in most temperate climates and needs a period of cold 1,200–1,500 hours of chilling below 7 °C depending on the type of cultivar to bloom and grow, and rainfall of 700–800 mm (Rai *et al.*, 2015). Most of these requirements can be found in the Highlands of Madagascar, thus still allowing low and medium chill apple varieties to grow. Nevertheless, the more the temperature rises, the more impact on yields is expected. Indeed, abnormal growth of the tree, flower initiation and fruit coloration along with deterioration in fruit texture and taste, and lower yield can be expected (Rai *et al.*, 2015). The Intergovernmental Panel on Climate Change (IPCC) has reported 1.5 °C rise in temperature in the world (Djalante, 2019). In fact, temperature sets several factors for apple growing altering phenology (flowering, blooming time, color, size and shapes), cycle of apple trees and physiology of fruits (Lin-Wang *et al.*, 2011). First, it sets the limits of the production areas (needing a winter period to cool down to break dormancy). Then, it controls the length of the growing season, which in turn

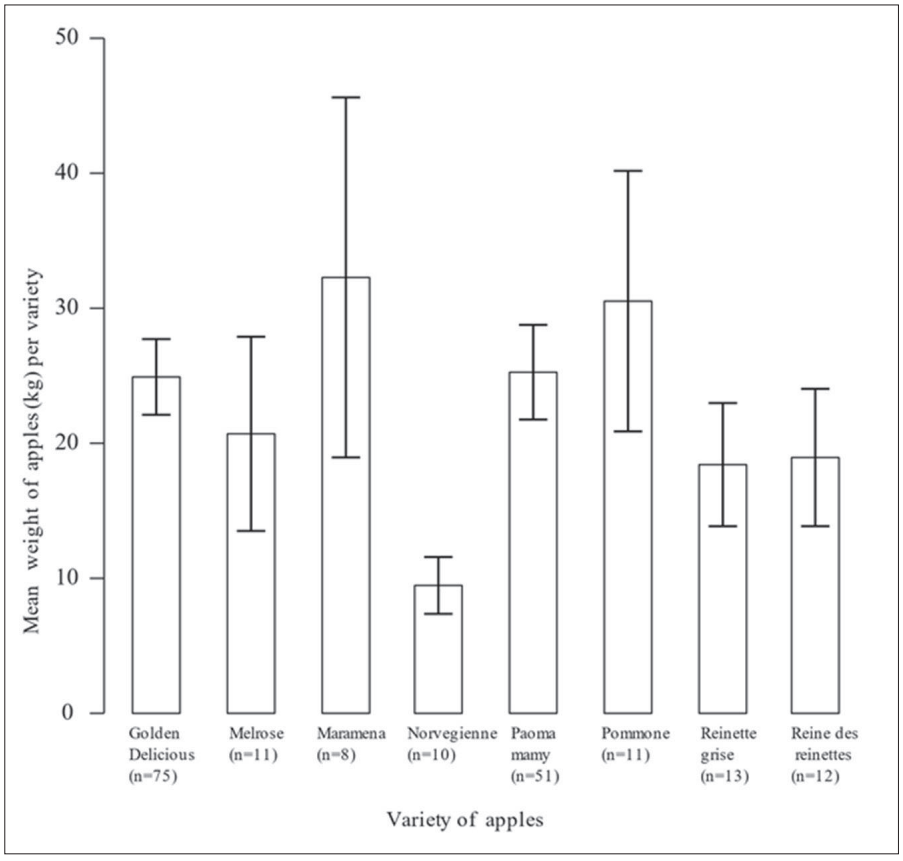


Figure 5b. Yield of apples (kg tree^{-1}) per variety (N = 191). Bars represent standard error. The calculation is based on the surveys only including monovariety plots. No significant differences were observed between varieties using Tukey test. For both graphs, data with apple trees less than three years old were removed as they were not yet productive. The calculation is based on Vakinankaratra region only.

limits the range of cultivars, alters the rate of development of all physiological processes (pollen tube growth, cell division and respiration). In addition, it can also favour the development of apple pests and diseases, so that warmer regions tend to have more diseases than cooler regions (Ferree and Warrington, 2003; Petri *et al*., 2012; Rai *et al*., 2015; Gitea *et al*., 2019; Nautiyal *et al*., 2020; El Yaacoubi *et al*., 2020). It can also affect yield and fruit quality (Singh *et al*., 2016) as recently reported in Germany (Pfleiderer *et al*., 2019), in the U.S.A. (Wolfe *et al*., 2018) or in Morocco (El Yaacoubi *et al*., 2020). For Madagascar, mean temperature increases of 1.1 to 2.68 °C throughout the island since the 1960's (Tadross *et al*., 2008). In Madagascar, we could observe during survey period the abandonment of the apple orchards in Soanindrariny to set up again towards the south east of the municipality in cooler areas. Agriculture is among the sectors vulnerable to climate change in Madagascar (Weiskopf *et al*., 2021). From 1990–2015, rising temperatures and multiple floods have led to a drop of more than 50% in agricultural production (Nematchoua *et al*., 2018). Furthermore, spring frosts, hails, summer droughts and unseasonal spring rain can lower the productivity and fruit quality (Rai *et al.*, 2015). Madagascar has a wide range of varieties, from early fruiting (produced from December) to late fruiting (until June). This offers growers a wide choice. In addition, it may be possible to develop new varieties that can produce outside these production seasons, but which can be adapted according to their GDD requirements and climatic conditions in Madagascar Highlands.

Growers in Vakinankaratra use the cultivation of apple tree by grafting. Propagation of apples is primarily through grafting (Turechek, 2004). The split grafting method was successful in apple production in 1900 during the first cultivation trials, which growers continue to use. Grafting is a technique often used but rootstocks are mostly sexually propagated with large variation and poor consistency like in China (Wang *et al*., 2019a). In Madagascar, the use of rootstocks was inspired by apple-growing countries (François, 1927). Tests on their compatibility with grafted plants are ambiguous. In the 1990's, clones were used by plant nursery and plant production centers. Growers currently use rootstocks without considering their sanitary state. However, the use of rootstocks requires a minimum of knowledge and training: grafting compatibility, reproductive capacity, dwarf, impacts on scion growth, *etc*. (Wang *et al*., 2019b). Unfortunately, growers do not have such a training in Madagascar. The stump bursting which had not been practiced before (François, 1927), has become the current method of obtaining rootstocks. Grafting of old apple trees was practiced in the 70's to rejuvenate the orchards, this practice is no longer used, but remains a possible option to save them. Renovating old apple trees by pruning is another solution for apple trees (Forshey, 1999).

Apple growers give very little importance to cultural maintenance and the application of fertilizers in orchards. However, it is necessary to increase yields and production quality. The success of apple culture and production depends on agronomic factors like the selection of appropriate scion and rootstock, irrigation and nutrition, pruning, crop-load and thinning, training system, biotic and abiotic factors: pollination, soil, temperature, light, humidity, and wind (Colavita *et al*., 2021). Apple production systems have changed extensively over the years in the world, for example high density plantings on dwarfing or semi-dwarfing rootstocks (Turechek, 2004) are now very often used in apple growing regions. Moreover, fruit thinning must be done and selection of appropriate scion and rootstock, *etc*. (Brown, 2011; Colavita *et al*., 2021). Nowadays, apple cultivation in agroecology is an improving practice using for example green fertilization (Dobrevska *et al.*, 2020). Maybe some of these techniques could be tested in Madagascar to see if it could be applied or adapted to increase the yield and quality of the production.

The intercropping of apple orchards is done by 65.91% of the growers. Associating intercrop species in orchard is a technic used by apple producers (Dupraz, 1994), because of their benefits depending on species: herbs or horticultural plants grown against pests (Song *et al*., 2013; Zhang *et al*., 2022), green manure crops (Ding *et al*., 2021), they can suppress weed growth and maintain soil fertility (Munde *et al*., 2011). As mentioned above, intercropping also contributes to income sources for growers. Sometimes it avoids the negative effects of resource competition on the fruit production (Wang *et al*., 2019a). Association of apple trees with Fabaceae are beneficial in terms of apple yield, whereas some associated species used are not suitable for apple growing, they are less so with Poaceae (Ahmad *et al*., 2018; Zada and Saljoqi, 2019) and can explain yield losses observed in several of these associations reported. These agroecological practices are well developed in Madagascar and training to improve some of them could greatly beneficiate some growers.

Apple pests were one of the major constraints for growers, among of them *D. malgassa.* It was declared a pest of temperate fruit trees in the 60's on the highlands of Madagascar (Appert, 1968) and endemic to the island (Scalercio and Malaisse, 2009). Reported reservoir hosts are mimosa (Frappa, 1937), pine, cypress, and other rosaceous plants (Quilici, 1984). Nevertheless, according to growers surveyed, the population of this insect has recently increased and the situation is getting worse in apple-growing regions affecting yields. Madagascar is one of the biodiversity hotspots where deforestation is generating an ecological problem. Habitat loss is estimated at >90% (Ganzhorn *et al*., 2001). This may be one of the causes of host switch of *D. malgassa*.

The woolly aphid *E. lanigerum* was observed. It was invasive in Madagascar since the 40's (Frappa, 1937), was observed in the Amoron'i Mania region, and is one of the important pests in the world on apple orchards (Nicholas *et al.*, 2003). Its control is in the priority research (Brown, 2011) in many countries, but in the island, it has never reached high population levels to impact the productions. During our surveys, we recorded for the first time in Madagascar the occurrence of *D. perniciosus*. This mealybug can induce leaf drop and degradation of the visual quality of the fruit, as well as dieback of the vegetation and is considered as a major pest on apple in many countries (Khan *et al*., 2020). Nonetheless, only a few orchards had this pest and populations were low with no impact reported by growers (except the visual ones). Apple scab, another major disease of apple in the world (Shafi *et al.*, 2019) and known from Madagascar was recorded but not reported as a main threat by growers.

Pest control is only carried out by growers in the Vakinankaratra region. This could be due to growers' ignorance of pest control methods, which leads them to use mechanical pest control and little chemical pest control. Nevertheless, pest control is required. Several strategies are possible. Currently, integrated pest management is promoted, even in apple orchards, by using biological, cultural, and physical control strategies (Zhou *et al.*, 2014; Shaw *et al.*, 2021).

Conclusion

Of the five apple-growing regions, only two are commercial: Amoron'i Mania and Vakinankaratra. Production factors like cultivation methods, presence of pests and diseases influence the yield, which is currently low. *Deborrea malgassa* is the main pest threat to apple growing in the Vakinankaratra region according to the surveyed producers. The species was little known before. Deforestation with climate change could be the reason for its change of host and its current outbreak in orchards. Apple growing in Madagascar is not only facing climate change but also ecological problems. This leads to changes in the phenological calendar of the apple trees, causing a decrease in apple yields and consequently a lack of food diversification for the population (Owen *et al*., 2021).

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References

Ahmad, S., Khan, P.A., Verma, D.K., Mir, N.H., Sharma, A., and Wani, S.A. (2018). Forage production and orchard floor management through grass/legume intercropping in apple based agroforestry systems. Intl. J. Chem. Studies *6*(1), 953–958.

Appert, J. (1968). Les insectes nuisibles aux cultures de Madagascar. Institut de Recherches Agronomiques Tropicales et des Cultures Vivrières. Bull. Agron. *22*.

Braun, A.R., Smaling, E.M., Muchugu, E.I., Shepherd, K.D., and Corbett, J.D. (1997). Maintenance and improvement of soil productivity in the highlands of Ethiopia, Kenya, Madagascar and Uganda: An inventory of spatial and non-spatial survey and research data on natural resources and land productivity. AHI Technical Report Series/ International Centre for Research in Agroforestry. African Highlands Initiative; no. *6*.

Brown, S. (2011). Apple. Fruit Breeding (Boston MA, U.S.A.: Springer), p. 8, 329–367. https://doi.org/10.1007/978-1-4419-0763-9_10

Childers, N., Morris, J., and Sibbett, G. (1995). Modern Fruit Science Horticulture Publication Grains (Florida, U.S.A.: Rutgers Publ.), 634 pp.

Colavita, G.M., Curetti, M., Raffo, D., Sosa, M.C., and Vita, L.I. (2021). Apple: Temperate Fruits (Apple Academic Press), p. 1–106.

Conti, M.V., Kalmpourtzidou, A., Lambiase, S., De Giuseppe, R., and Cena, H. (2021). Novel foods and sustainability as means to counteract malnutrition in Madagascar. Molecules *26*(8), 2142. https://doi.org/10.3390/molecules26082142.

De la Bathie, H. (1931). Les plantes introduites à Madagascar. J. Agric. Tradit. Bot. Appliquée *11*(121), 719–729. https://doi.org/10.3406/jatba.1931.5026.

Ding, T., Yan, Z., Zhang, W., and Duan, T. (2021). Green manure crops affected soil chemical properties and fungal diversity and community of apple orchard in the Loess Plateau of China. J. Soil. Sci. Plant Nutr. *21*(2), 1089–1102. https://doi.org/10.1007/s42729-021-00424-0.

Djalante, R. (2019). Key assessments from the IPCC special report on global warming of 1.5 °C and the implications for the Sendai framework for disaster risk reduction. Progr. Disaster Sci. *1*, 100001. https://doi.org/10.1016/j.pdisas.2019.100001.

Dobrevska, G., Dallev, M., Bileva, T., and Valcheva, E. (2020). Management practices for bioproduction of apples in the Plovdiv region. Agric. Sci. *12*(27), 92–97. https://doi.org/10.22620/agrisci.2020.27.014.

Dupraz, C. (1994). Les associations d'arbres et de cultures intercalaires annuelles sous climat tempéré. Revue Forestière Française *46*(S), 72–83.

El Yaacoubi, A., El Jaouhari, N., Bourioug, M., *et al.* (2020). Potential vulnerability of Moroccan apple orchard to climate change-induced phenological perturbations: Effects on yields and fruit quality. Intl. J. Biometeorol. *64*(3), 377–387. https://doi.org/10.1007/s00484-019-01821-y.

Elzebroek, A.T.G. (2008). Guide to Cultivated Plants (Wallingford, U.K.: CABI).

FAOSTAT (2018). Food Balance Sheets. https://www.fao.org/.

FAOSTAT (2021). Production, Crops and Livestock Products. Data from 1995 to 2021. https://www.fao.org/.

Ferree, D.C., and Warrington, I.J. (2003). Apples: Botany, Production, and Uses (U.S.A: CABI). https://doi.org/10.1017/S0014479704232057.

Forshey, C.G. (1999). Training and pruning apple trees. Cornell Cooperative Extension, Information Bulletin *112*.

François, E. (1927). La production des fruits à Madagascar. J. Agric. Tradit. Bot. Appliquée *7*(75), 713–724. https://doi.org/10.3406/jatba.1927.4576.

Frappa, C. (1937). Les principaux insectes nuisibles aux cultures de Madagascar. J. Agric. Tradit. Bot. Appliquée *17*(191), 513–516. https://doi.org/10.3406/jatba.1937.5764.

Gade, D.W. (1996). Deforestation and its effects in highland Madagascar. Mountain Res. and Developm. *16*(2), 101–116.

Ganzhorn, J.U., Lowry, P.P., Schatz, G.E., and Sommer, S. (2001). The biodiversity of Madagascar: One of the world's hottest hotspots on its way out. Oryx *35*(4), 346–348. https://doi.org/10.1046/j.1365-3008.2001.00201.x.

Gitea, M.A., Gitea, D., Tit, D.M., *et al.* (2019). Orchard management under the effects of climate change: Implications for apple, plum, and almond growing. Environm. Sci. Pollut. Res. *26*(10), 9908–9915. https://doi.org/10.1007/s11356-019-04214-1.

INSTAT (2020). Résultats Globaux de 2018 de Madagascar (Madagascar: Institut National de la Statistique). https://www.instat.mg/

Khan, A.A., Kundoo, A., Nissar, M., and Mushtaq, M. (2020). Sucking pests of temperate fruits. In Sucking Pests of Crops (Singapore: Springer), p. 369–409. https://doi.org/10.1007/978-981-15-6149-8_12.

Lin-Wang, K., Micheletti, D., Palmer, J., *et al.* (2011). High temperature reduces apple fruit colour via modulation of the anthocyanin regulatory complex. Plant Cell Environm. *34*(7), 1176–1190. https://doi.org/10.1111/j.1365-3040.2011.02316.x.

Munde, G., Hiwale, B., Nainwad, R., and Dheware, R. (2011). Effect of intercrops on growth and yield of custard apple. Asian J. Hortic. *6*(1), 29–31.

Nautiyal, P., Bhaskar, R., Papnai, G., Joshi, N., and Supyal, V. (2020). Impact of climate change on apple phenology and adaptability of Anna variety (low chilling cultivar) in lower hills of Uttarakhand. Intl. J. Curr. Microbiol. Appl. Sci. *9*(9), 453–460. https://doi.org/10.20546/ijcmas.2020.909.057.

Nematchoua, M.K., Ricciardi, P., Orosa, J.A., and Buratti, C. (2018). A detailed study of climate change and some vulnerabilities in Indian Ocean: A case of Madagascar island. Sust. Cities Soc. *41*, 886–898. https://doi.org/10.1016/j.scs.2018.05.040.

Nicholas, A.H., Spooner-Hart, R.N., and Vickers, R.A. (2003). Control of woolly aphid, *Eriosoma lanigerum* (Hausmann) (Hemiptera: Pemphigidae) on mature apple trees using insecticide soil-root drenches. Australian J. Entomol. *42*(1), 6–11. https://doi.org/10.1046/j.1440-6055.2003.00336.x.

Owen, E., Farris, Z., Razoliarivelo, H.L., Griffin, J., and Farris, A. (2021). Impact of a diet diversification and health and nutrition counseling program in Madagascar. World Nutr. *12*(2), 21–31. https://doi.org/10.26596/wn.202112221-31.

Petri, J.L., Hawerroth, F.J., Leite, G.B., Couto, M., and Francescatto, P. (2012). Apple phenology in subtropical climate conditions. In Phenology and Climate Change, Xiaoyang Zhang, ed. (Croatia: InTech), p. 195–216.

Pfleiderer, P., Menke, I., and Schleussner, C.F. (2019). Increasing risks of apple tree frost damage under climate change. Climate Change *157*(3), 515–525. https://doi.org/10.1007/s10584-019-02570-y.

QGIS.org. (2023). QGIS Geographic Information System. QGIS Association. http://www.qgis.org.

Quilici, S. (1984). Situation phytosanitaire des productions fruitières à Madagascar. Rapport Technique Entomologie (Reunion: GERDAT-IRAT).

R Development Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, V. (Austria). https://www.R-project.org/.

Rai, R., Joshi, S., Roy, S., Singh, O., Samir, M., and Chandra A. (2015). Implications of changing climate on productivity of temperate fruit crops with special reference to apple. J. Hortic. *2*(2), 135–141. https://doi.org/10.4172/2376-0354.1000135.

Rakotomanana, H., Hildebrand, D., Gates, G.E., Thomas, D.G., Fawbush, F., and Stoecker, B.J. (2020). Maternal knowledge, attitudes, and practices of complementary feeding and child undernutrition in the Vakinankaratra region of Madagascar: A mixed-methods study. Curr. Dev. Nutr. *4*(11), nzaa162. https://doi.org/10.1093/cdn/nzaa162.

Roche, M., McKenna, M., and Le Heron, R. (1999). Making fruitful comparisons: Southern hemisphere producers and the global apple industry. Tijdschrift Econ. Soc. Geogr. *90*(4), 410–426. https://doi.org/10.1111/1467-9663.00082.

Salama, A.M., Ezzat, A., El-Ramady, H., *et al.* (2021). Temperate fruit trees under climate change: Challenges for dormancy and chilling requirements in warm winter regions. Horticulturae *7*(4). https://doi.org/10.3390/horticulturae7040086.

Scalercio, S., and Malaisse, F. (2009). Between species and ethnospecies: edible Psychidae in Tropical Africa. Entomologie Faunistique 62(1), 17–24.

Shafi, S.M., Sheikh, M., Nabi, S., Mir, M., Ahmad, N., Mir, J., Raja, W., Rasool, R., and Masoodi, K. (2019). An overview of apple scab, its cause and management strategies. EC Microbiol. *15*, 1–4.

Shaw, B., Nagy, C., and Fountain, M.T. (2021). Organic control strategies for use in IPM of invertebrate pests in apple and pear orchards. Insects *12*(12), 1106. https://doi.org/10.3390/insects12121106.

Singh, N., Sharma, D., and Chand, H. (2016). Impact of climate change on apple production in India: A review. Curr. World Environm. *11*(1), 251. https://doi.org/10.12944/CWE.11.1.31.

Song, B., Tang, G., Sang, X., Zhang, J., Yao, Y., and Wiggins, N. (2013). Intercropping with aromatic plants hindered the occurrence of *Aphis citricola* in an apple orchard system by shifting predator-prey abundances. Biocontrol Sci. Technol. *23*(4), 381–395. https://doi.org/10.1080/09583157.2013.763904.

Tadross, M., Randriamarolaza, L., Rabefitia, Z., and Zheng, K. (2008). Climate change in Madagascar; Recent past and future (Washington DC, U.S.A.: World Bank).

Turechek, W.W. (2004). Apple diseases and their management. Diseases Fruits Veg. Diagn. Manag. *1*, 1–108. https://doi.org/10.1007/1-4020-2606-4_1.

Wang, Y., Li, W., Xu, X., Qiu, C., Wu, T., Wei, Q., Ma, F., and Han, Z. (2019a). Progress of apple rootstock breeding and its use. Hortic. Plant J. *5*(5), 183–191. https://doi.org/10.1016/j.hpj.2019.06.001.

Wang, Z., Cao, Q., and Shen, Y. (2019b). Modeling light availability for crop strips planted within apple orchard. Agric. Syst. *170*, 28–38. https://doi.org/10.1016/j.agsy.2018.12.010.

Weiskopf, S., Cushing, J., Morelli, T.L., and Myers, B. (2021). Climate change risks and adaptation options for Madagascar. Ecol. Soc. *26*(4). https://doi.org/10.5751/ES-12816-260436.

Wolfe, D.W., De Gaetano, A.T., Peck, G.M., *et al.* (2018). Unique challenges and opportunities for northeastern US crop production in a changing climate. Clim. Change *146*(1), 231–245. https://doi.org/10.1007/s10584-017-2109-7.

World Development Report (2020). https://www.worldbank.org/en/publication/wdr2020.

Zada, H., and Saljoqi, A.U.R. (2019). Habitat manipulation through intercropping for the management of codling moth *Cydia pomonella* (L.) (Lepidoptera: Tortricidae) in Swat Pakistan. Pak. J. Zool. *51*(4). https://doi.org/10.17582/journal.pjz/2019.51.4.1537.1545.

Zhang, X., Ouyang, F., Su, J., Li, Z., Yuan, Y., Sun, Y., Sarkar, S.C., Xiao, Y., and Ge, F. (2022). Intercropping flowering plants facilitate conservation, movement and biocontrol performance of predators in insecticide-free apple orchard. Agric. Ecosyst. Environm. *340*, 108157. https://doi.org/10.1016/j.agee.2022.108157.

Zhou, H., Yu, Y., Tan, X., Chen, A., and Feng, J. (2014). Biological control of insect pests in apple orchards in China. Biol. Control *68*, 47–56. https://doi.org/10.1016/j.biocontrol.2013.06.009.

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