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Final report

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1 Acknowledgments

The whole consortium of the project is really indebted to ACIAR and the SLAM Program for having given us the opportunity to run this SRA project. It was a great opportunity for working all together, International, and national scientists, on 3 main relevant topics related to soil management/soil health, farming systems and SBPDs.

Despite the pandemic Covid 19 outbreak, most of the activities were undertaken with some delays (thanks to Dr James Quilty for his acceptation to allocate a no-additional funding 6-month extension to the SRA On-Farm) and we believe that most of the expected results have been delivered.

We look forward continuing these research activities in the frame of the new 5-year V-Scope project ACIAR is financially supporting from February 2021 on coffee and black pepper production in the Central Highlands in Vietnam.

2 Executive summary

Coffee and black pepper production in the Central Highlands of Vietnam are threatened by a range of issues related to inefficient and unsustainable production practices, declining soil health and increasing pest and disease pressures, resulting in declining productivity. Despite some initial research on these problems, there is still a lack of clarity on the extent and interaction of the various factors driving productivity decline in both commodities. This project was aiming to deliver a situational analysis of on-farm coffee and black pepper production in 3 target provinces in the Central Highlands of Vietnam. The project investigated the farming systems that rely on coffee and black pepper production and examined the distribution of soil and plant health and agronomic factors that are constraining production in the region.

A more thorough understanding of current management practices for coffee and pepper is still needed to adapt inputs to crop needs and soil health status. This is especially the case for pepper farming systems, where management practices have been much less documented than coffee. In terms of livelihood indicators, information is lacking for both coffee and pepper production systems. Another key aspect is the lack of information at landscape level: production should be targeted to locations that are best suitable. Pepper seems declining in Gia Lai, and the reasons for this should be better understood, to take appropriate action. This involves a need for a better understanding of environmental drivers and issues from the research side. Future work on coffee and pepper farming systems improvement in the Central Highlands will need to be based on a solid primary data collection to cover all dimensions of sustainable intensification (productivity, economic, environment, human condition and social domains), which will then allow identifying the relevant techniques and system targeting to ensure positive impact.

Our preliminary analysis of secondary data about coffee plantations in Dak Lak suggest that the association coffee – black pepper is not accurate because too favourable for nematodes and meanwhile, the intensive management with chemical inputs is also a way to promote SBPD such as nematodes. Through our investigations in Gai Lai province, it seems that the seedlings of both coffee and black pepper are totally healthy and totally deprived of any SBPD. Indeed, this shall be confirmed by further investigations in nurseries of Dak Lak and Dak Nong Provinces, but it suggests that in most cases, the SBPD are already in the fields and the seedlings do not play any role in spreading the diseases. Surprisingly, regarding black pepper, it seems that *Phytophthora* is not the main pathogenic fungi damaging the plantations. Obviously, *Pythium* and *Phytopythium* already described in the literature as SBPD of other crops are a serious problem in the black pepper plantations in Central Highlands. It is important to take this into consideration for further developments of any strategies to control the main SBPD affecting the black pepper production in Vietnam.

There are already good geospatial data available from NIAPP on land use (including coffee and pepper), soil types and coffee and pepper suitability. However, improvements in terms of accuracy and frequency of map production can be achieved at relatively low cost. The land cover classification method using Sentinel satellite imagery showed a good potential to discriminate between coffee/black pepper from other land use classes. Based on the coffee and pepper land use map by NIAPP, we identified 6 agroclimatic zones that are differentiated by climatic variables and elevation. Further research is required to better understand how these agroclimatic zones affect coffee and pepper growth and development. Climate change is increasingly affecting Robusta and pepper production in the Central Highlands. This requires a mechanistic understanding of crop response to long-term climate trends such as increasing temperature and changing precipitation patterns but also climate variability with increasing extremes (e.g. drought).

3 Background

Coffee and black pepper production in the Central Highlands of Vietnam are threatened by a range of issues related to inefficient and unsustainable production practices, declining soil health and increasing pest and disease pressures, resulting in declining productivity. Despite some initial research on these problems, there is still a lack of clarity on the extent and interaction of the various factors driving productivity decline in both commodities. It is therefore necessary to quickly develop a clear understanding of the on-farm issues effecting coffee and black pepper production in this region. This project aimed to deliver a situational analysis of on-farm coffee and black pepper production in 3 target provinces in the Central Highlands of Vietnam. The project investigated the farming systems that relied on coffee and black pepper production and examined the distribution of soil and plant health and agronomic factors that were constraining production in the region. This project undertook in conjunction with an investigation and situational analysis of the coffee and black pepper markets and value chains in Vietnam, AGB/2018/175.

History of coffee and black pepper production in Vietnam and current situation:

Vietnam is the number one producer of Robusta coffee globally. Across the country there are approximately 650,000 ha of plantations generally concentrated in the Central Highlands with the majority managed by smallholders (<2 ha) as the main source of income for most coffee farming households.Vietnam produces annually in the range of 1.3 - 1.7 million tons of Robusta coffee beans. At a national level, the coffee sector supports about 1 million direct and indirect jobs and has been contributing in the range of 2.5 to 3.5 billion USD annually to the Vietnamese economy over the last 5 years.

Vietnam is also the number one producer of black pepper in the world, with production also concentrated in the Central Highlands. According to figure of the General Statistics Office of Vietnam, the pepper planting area in Vietnam is estimated around 152,000 hectares with a productivity of about 240,000 tonnes, accounting for 48% of the world total volume. In 2017, Vietnam exported 215,000 tonnes of black pepper and pepper products with a turnover of nearly 120 million USD. Enthusiasm for spice usage continues to increase unabated around the world. Due to growth of the middle class, particularly in areas of Asia, Latin America, and Africa, some experts predict that pepper demand will double in the next 30 years from the current 500,000 tonnes to one million metric tonnes.

Despite being the centre of production in Vietnam, the sustainability of both coffee and pepper in the Central Highlands of Vietnam are being challenged by a range of issues. Both coffee and pepper are often grown on the same farm in this region. The expansion of coffee and pepper production in recent years has been ineffectively managed and has resulted in deforestation in some areas and inappropriate land use selection. Ineffective farm management in the region has resulted in declining plant health, soil fertility and soil health, and increased pest and pathogen pressures. Additionally, there is widespread overuse of fertilizers, pesticides and other inputs. These factors are having detrimental impacts on coffee and pepper productivity and are potentially limiting access to high value markets.

Urgent problems on-farm in coffee and black pepper production in Central Highlands of Vietnam

1. *Coffee and pepper plants have been dying off for the two last years*. According to the Vietnamese government, over 3,200 ha of pepper plantations have already died and this number will likely increase due to pests and plant pathogens under inappropriate climate conditions. The Central Highlands Agriculture and Forest Science Institute (WASI) has predicted that approximately 3,000 ha of pepper plantations are currently infected seriously with disease.

2. In recent years, *pepper production area has expanded significantly* because of the high price of pepper. Instead of growing and/or replanting coffee, which is also facing very serious problems with pests and plant pathogens, farmers switched to growing pepper. As the price of pepper falls and as many pepper plantations have very poor plant health, farmers are again switching to other crops, mainly fruit trees. However, farmers do not know whether the soil-borne pests and diseases effecting pepper may also affect fruit trees. Without understanding of the pest and pathogen populations within the environment farmers are unable to make informed decisions on suitable crops and varieties, which can have direct and serious consequences for the agricultural sector in the Central Highlands.

3. The unmanaged expansion of coffee and pepper has resulted in farmers establishing production areas in *unsuitable land* with poor drainage that frequently floods. They also did not pay attention to the variety of black pepper planted nor to options for optimizing and sustaining production. This has most probably contributed to enhancing the pest and plant disease issues. In addition, the intensive management with overuse of mineral fertilisers and pesticides is a likely cause of soil health decline.

4. The Central Highlands region is prone to the effects of *El Nino*. An *El Nino* event in the dry season, November to April, will see areas within the region suffer serious water shortages. For instance, in the eastern and south eastern districts of Gia Lai Province and the eastern part of Đak Lak Province, the possibility of serious water shortages and severe drought is likely to occur. An *El Nino* event in 2018 saw these areas receive only 60-70% of their average rainfall.

Consultations with Vietnamese Ministries (MARD, MOST) and a scoping mission (November 2018) with in-depth discussions with provincial authorities and local stakeholders of the coffee and pepper value chains in the 3 provinces (Gia Lai, Dak Nong and Dak Lak) confirmed the need to document current dynamics (coffee area expansion, coffee intercropping with pepper and fruit trees) and pressing issues (build-up of soil-borne pests and diseases, soil fertility decline).

4 Objectives

In conjunction with AGB/2018/175, the SRA had identified priority research, development and collaboration opportunities for sustainable, inclusive and competitive coffee and black pepper farming systems in the 3 target provinces of the Central Highlands of Vietnam. The project characterised coffee and black pepper farming systems in these 3 provinces, collecting baseline information and undertaking a situation analysis to provide clarity on the extent and severity of the problems affecting production.

To achieve this, the project had 3 major objectives:

1. **Farming system characterisation**: characterise coffee and black pepper farming systems and livelihoods in the Central Highlands of Vietnam
2. **Soil health**: assess soil health and soil-borne pests and diseases (SBPD) status in coffee and black pepper farming systems to gain knowledge on the importance of these constraints and identify opportunities to restore soil and plant health.
3. **Production area analysis**: utilising geospatial data develop a framework and pilot the system to test the capability of mapping coffee and pepper plantations within the 3 target provinces

General outputs/outcomes

A series of diagnoses, reports, literature reviews and analyses identified priority research, development and collaboration opportunities in coffee and pepper production in the Central Highlands of Vietnam.

The build-up of a strong scientific team spirit between Vietnamese, Australian and international institutions.

An expected engagement and co-investment from the private sector and local authorities into the development of sustainable coffee and pepper production systems in the Central Highlands of Vietnam.

About the partnership

The work was undertaken by a multidisciplinary team involving both International and National partners led by CIAT. International collaborative partners include ICRAF and Deakin University in Melbourne. In conjunction with AGB/2018/175 and through well-established relationships with relevant Vietnamese Institutions running projects on both black pepper and coffee funded by the Vietnamese governments and the private sector, a consortium brought together a wide range of technical research disciplines in soil and crop science, agronomy, integrated crop management, climate change adaptation, plant protection, social science, agribusiness and economics. The Western Highlands Agriculture and Forestry Science Institute (WASI) is the primary Vietnamese collaborative partner in this project, mainly through the Pepper Research and Development Center (PRDC) in Pleiku. Meanwhile despite their non-official involvement within the SRA, we had got strong support from the Plant Protection Research Institute. The private sector was also supposed to support the project by giving us an access to their data bases, but it was not successful.

Objective 1.

1. **Set of indicators**

To characterize coffee and black-pepper based systems in a broad system perspective, i.e. including all activities for each production system and their interactions, a set of indicators was agreed upon by the project team and validated by local partners during a project workshop organized in Buon Ma Thuot in September 2019. The set included both quantitative and qualitative indicators, with information on areas, productivity, system management (biomass use, use of inputs, water use), income, risks, land issues, opportunities, ethnic groups, generational and gender issues, and constraints.

2. Data collection

An inventory of current and past projects was mapped for the provinces of interest for the period 2010-2020. Secondary data was collected from partners and past projects, i.e. public sector (DARD (Department of Agriculture and Rural Development), provincial and national databases), on-going projects, and private sector (farmers' networks of McCormick and OLAM, ECOM…). As data sharing can be a sensitive matter, a visit to partners in the Central Highlands was carried out for face-to-face discussions. The datasets were then evaluated for their quality, the coverage of the three provinces of interest and their potential use. Three datasets were selected and cleaned. Descriptive analysis was performed in R statistical computing environment (v 3.4.1). A brief literature review completed the data collection.

Objective 2.

1. Analysis of secondary data

Secondary data analysis for coffee in Dak Lak (ECOM data base). ECOM provided us 4 databases for the 4 following regions: Dak Lak, Dak Nong, Gia Lai, Lam Dong. Each database includes information on farm identity, field management practices, diseases tally and farm costs but none on soil fertility. These data were about coffee plantation in 2015. According to the objective 2, our focus were the analysis of field management practices and soil-borne pests and diseases. We chose to work on Dak Lak database only because the number of fields was higher and statistically interpretable compare with the other regions.

Data are mostly qualitative. For the disease incidence, fields were divided in 4 classes: 0%,1-10%, 11-25% and 26-50% according to the 5 types of soil-borne pests and diseases.

- « Nematodes » which regroup all species of nematodes.
- « Leaf rust », caused by the fungal pathogen *Hemileia vastatrix*.
- « *Pseudomonas synrigiae* », responsible of Bacterial blight.
- « Coffee Berry borer » (*Hypothenemus hampei*), a damaging beetle of coffee.
- « Die-back » which is a progressive decline most caused by bacteria and fungus.

Firstly, we investigated the effect of intercropping on soil-borne pests and diseases incidence. Secondly, the correlation between amount of fertilizer and diseases incidence was assessed. Finally, we have crossed these two factors to highlight a possible correlation between intercropping and fertilizer effects.

To study intercropping effect on disease incidence we chose to merge the classes 11-25% and 26-50% in one class « affected fields ». For each kind of intercropping we calculated the proportion of affected fields P(A):

$P_i(A) = nia/Ni$ where *Ni* is the number of fields for the cropping system *i* and *nia* the number of affected fields for cropping system. We used a statistic test at level $P<0.05$ to make proportion comparison.

To understand the relationships between fertilizer amounts and diseases incidence we plot the rate of fertilizer used for the four classes of incidence. We used a mean comparison statistical test to compare fertilizers rate means of consecutive classes. The results showed that there are more trustable for classes 1-10% and 11-25% because of the highest number of fields

2. Presence of SBPD in the seedlings at the nursery: case study in Gai Lai Province

Nurseries investigated:

Location: Tinh nursery (1) and Duc nursery (2), Thuy Duong (3), Pleiku city, Gia Lai province, Vietnam

<u>Tinh nursery:</u>

a. Potting mixture: soil and cow dung (ratio 3:1). It means 3 soil and 1 cow dung. The soil treated by solarization around 1-2 months before mixing to composted cow dung. There were no fungicides and nematicides applied to potting mixture to reduce total costs.

b. Fertilization

DAP (18% N – 46% P_2O_5) around 4 – 5 kg was diluted in 200 litres clean water, then applied to 10,000 seedlings/cuttings, 30 days interval. Around 4 – 5 times in total.

UREA (46% N): 3-5kg/200 litres of water, spraying to 10,000 seedlings/cuttings.

c. Disease management:

Coffee: after planting to plastic bags, baby plants were treated with a chemical fungicide **Anvil 5SC** (active ingredient: 50g/L *Hexaconazole;* 30 minutes), two times (10 – 15 days interval).

Black pepper: cuttings harvested from mother gardens then transported to nursery. Then, they were cut into two to three nodes. The cuttings were dipped into the chemical fungicide **Anvil 5SC** (same protocol than for coffee seedlings).

When disease incidence was detected (normally saw leaf symptoms) Anvil 5SC or Tilt super 300EC (150g/litre *Difenoconazole 1*50g/litre *Propiconazole*) application (7 days interval) until stopping the symptoms.

Duc Nursery:

a. Potting mixture: 1 m^3 soil + 0.3 m^3 cow dung. The soil was treated by solarization around 1-2 months before mixing to composted cow dung. There were no fungicides and nematicides applied to potting mixture to reduce total costs.

b. Fertilization

- DAP (18% N – 46% P_2O_5) around 2-3kg was diluted in 200 litres clean water, and sprayed on 10,000 seedlings, 30 days interval. 4 times in total.

- NPK (25 N – 25 P_2O_5 – 5 K_2O), 3 – 4 kg applied through potting mixture to 10,000 seedlings, 30 days interval.

c. Disease management:

Coffee: after planting to plastic bags, baby plants were treated with **Anvil 5SC** or **Tilt Super 300 EC**, two times (10 – 15 days interval).

Black pepper: cuttings harvested from mother gardens then transported to nursery. Then, they were cut into two to three nodes. The cuttings were dipped in **Anvil 5SC** or **Tilt Super 300 EC** around 30 minutes to kill fungi.

When disease incidence was noticed (normally saw leaf symptoms) **Anvil 5SC** or **Tilt super 300EC** application (7 days interval) until stopping the symptoms.

Shade regulation (for both Tinh and Duc nurseries)

0 – 30 days of planting: 50% of shade (regulate by shade net)

30 – 90 days of planting: 20 – 30 % of shade

90 – 120 days and ready for field planting: 0% of shade, that means 100% sunlight to train baby plants ready for planting in fields.

Thuy Duong:

a. Potting mixture

Soil 80% mixed to Cow dung 20 %. In one m^3 of potting mixture will contain 5 kg of Fused Calcium Magnesium Phosphate (15% - 18% of P_2O_5).

Soil treatment: Soil was transferred to nursery site and left on the site for about 7 – 8 months. There was no solarization treatment.

b. Fertilization

Application of one commercial bio-inoculant (Tricho), every two weeks, 50 kg applied for 40,000 seedlings.

NPK (20 N – 5 P_2O_5 – 6 K_2O) was applied every three weeks. About 50 kg applied for 100,000 seedlings

Urea (46% N), every three weeks: 50 kg applied for 140,000 seedlings.

DAP, every four weeks, 20 kg/260 litters of water, applied to 40,000 seedlings.

c. Pest

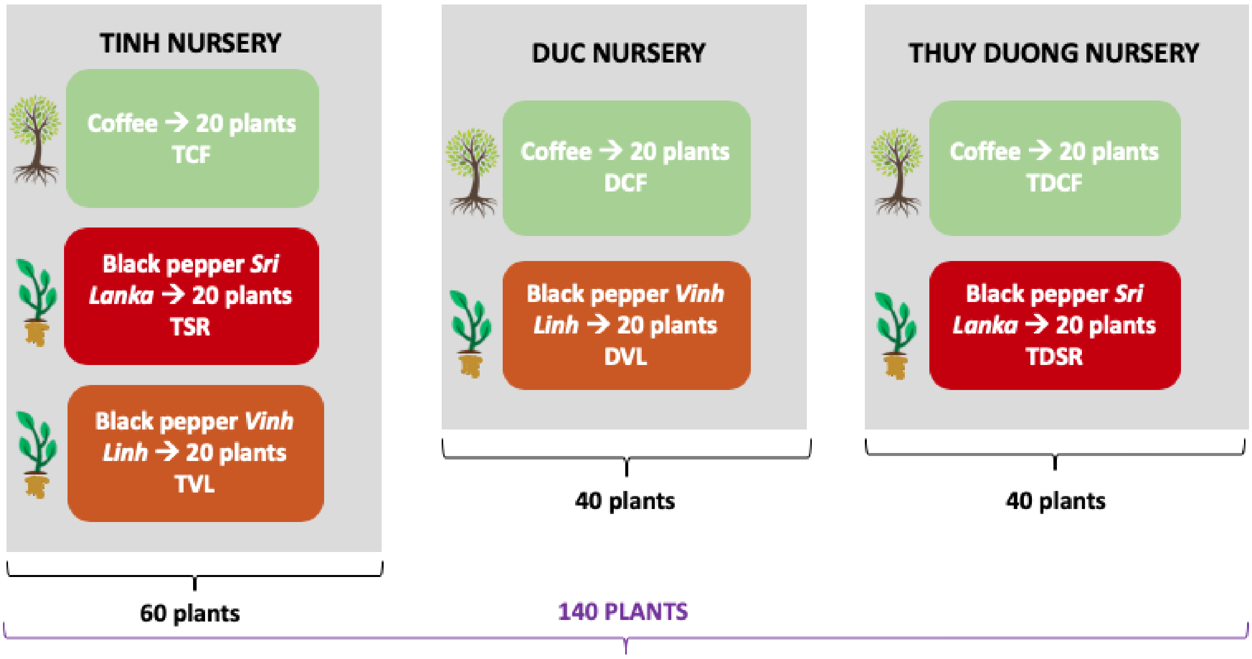
and disease management

Application of 2 bio-inoculants produced by the company Dien Trang: Tricho and Nema. A total of 3 applications were practiced.

The sampling was carried out as follows:

A total of 140 plants were harvested from the 3 nurseries:

- 60 plants of coffee → 20 plants per nursery
- 80 plants of black pepper as one nursery had 2 varieties (Vinh Linh and Sri Lanka) → 20 or 40 plants per nursery



For each nursery, 5 plastic bags of each commodity were collected, and the soil was analysed by the soil laboratory of the Pepper Research and Development Center in Pleiku. The soil parameters measured were pH, Organic C, N total and Available P.

Every plant/seedling were treated as follows:

From each pot:

- 200 g of soil + roots were stored at 4°C for searching nematodes such as *Pratylenchus* and *Meloidogyne* for coffee or pathogenic fungus (Oomycetes) for black pepper.
- 50 g of soil were stored at -80°C for possible further NGS analyses.

3. Preliminary investigations on SBPD affecting black pepper in the 3 regions (Dak Nong, Dak Lak and Gai Lai).

In September, a soil and root samplings were carried out in monocropping black pepper plantations of the 3 regions (Dak Nong, Dak Lak and Gai Lai). The objectives were to characterize the soil characteristics of soil in these plantations with regards to the tree species used as life pole for black pepper. Meanwhile, to initiate some preliminary investigations on the pathogenic fungus affecting black pepper.

For each province, we have identified one district and tried to standardize as much as we can the plantations where we harvested the samples (monocropping, same age of the plantations, the same size of the plantations). The sampling was done in the District of Dak Song (Province of Dak Nong), in the District of Cu Kuin (Province of Dak Lak) and in the District of Dak Doa (Province of Gai Lai).

The soil and the root samples were harvested all around the trunk of the black pepper from 0 to 30 cm depth. In total per plantation, 12 trees were sampled (distributed in 3 different rows).

From the root and soil samples, we tried to count the number of pathogenic fungi, to grow and isolate some on Potato Carrot Agar (PCA). All the isolates were purified and morphologically characterized.

4. Literature review entitled “Manage pepper and coffee soil pests and diseases in the Central Highlands in Vietnam by using microbial agents and increasing soil health”.

The overall objective was to gather into the same document the whole information already published about the main SBPD affecting both commodities (coffee and black pepper), the strategies in terms of biocontrol for controlling these SBPD and to list possible agroecological practices aiming to enhance soil health for a more sustainable coffee and black pepper production.

5. Preliminary investigations on the commercial bio-inoculants available in Vietnam to control SBPD such as nematodes and pathogenic fungi.

a. Data collection

Secondary data was obtained from annual reports of the company, market research reports, industrial websites. Meanwhile we run some direct interviews with companies specializing in the production of bio-inoculants listed and officially recognized by the Ministry of Agriculture and Development (MARD).

b. Interviews

Questionnaires were developed and used to interview various bio-inoculants companies. The interviews were done on phone, while for other companies, the questionnaires were emailed to the companies to be filled out. The most important part for the project was about the production and the products available currently on the market. Indeed, we asked for results about field testings, but it was very tricky to get such information from these companies.

c. Bio-inoculants produced by other partners

We noticed that many bio-inoculants available for farmers are not coming from the private sector. Universities and/or Research Institutes have developed their own bio-inoculants and farmers can purchase them for their farms. For instance, Tay Nguyen University in Dak Lak Province has several categories of bio-inoculants farmers buy in Central Highlands. We tried to contact these partners as much as we can for completing our list of bio-inoculants available in Vietnam. It is interesting to notice that most of the time, these products are not in stock but only produced when there are orders coming up. On the other hand, the private companies have always some stock available to reply to the demand.

d. Purchase of all the bio-inoculants and preliminary investigations on some of them

A final list of these products was obtained with all the recommendations of the manufacturers / Universities / Research Institutes and we purchased all of them for further laboratory investigations. Some preliminary results about the microbial content of some of these products have been obtained through an isolation and sequencing of the microorganisms contained in each of them.

Objective 3.

1. Pilot land cover classification using remote sensing

In order to conduct our pilot, the the Dak Song District in the Dak Nong province has been selected. Sentinel 1 and sentinel 2 top of atmosphere images for the year 2017 and 2018 have been used and completed with slope information from the SRTM dataset (Jarvis et al. 2008). Sentinel 2 images have been corrected for terrain effect and the clouds were removed. Two years composite were computed taking the temporal mean, median, 20 percentile, 80 percentile and standard deviation of each pixels of each available band, creating a stack of layers. In order to train the model, a training sample, containing 14830 GPS points was collected in Central Highlands and in the Dak Song district using high resolution satellite imagery as show in the table:

Class	Dak Song	Central Highlands
Coffee	971	4336
Black pepper	1583	1817
Seasonal agriculture	469	2545
Rubber	140	1307
Water	259	547
Urban	385	607
Forest	170	3239
Low vegetation	37	286
Other	0	146
Total	4014	14830

A convolutional neural network taking the full stack of image and receiving as input a square of 65 meters around the central GPS points was trained. The neural network needs to classify the central pixel of the image and give a score for each category between coffee, black pepper, seasonal agriculture, rubber, water, urban, forest, low vegetation. The highest score determining the mapped category. The point in the other categories where not used for this given map. After training, the neural network was used to generate a map.

2. Geospatial and yield data

Two types of yield data were collected: i) farm level yield data from ECOM for the year 2015 and ii) district and provincial level yield data from the General Statistics Office of Vietnam (GSOV) for a period of 19 years (2000-2018). The farm level data from ECOM was provided without GPS locations but with reference at village level. The yield data used by Kath et al. (2020) with 10 years of observations are unfortunately not accessible due to data protection issues. Geospatial data were collected from various sources (table 1). In order to identify agroecological zones that can inform coffee and pepper agronomy and land use planning, relevant environmental criteria need to be selected. Yield time series distributed along the environmental gradients of the Central Highlands where coffee and pepper are grown is only available for coffee. Unfortunately, no appropriate pepper time series were identified. Some private sector companies do have additional data sets that might be relevant but accessing these takes time and confidentiality agreements.

Table 1: Geospatial data available for defining agroecological zones of coffee and black pepper growing areas in the Central Highlands of Vietnam

Name	Type of data	Year/Temporary extend	Resolution	Source
Climate (Rainfall, temperature)	Map/Raster	1970-2000 (Climatology)	30 seconds grid (~1 km^2)	WorldClim version 2.1
Climate (Rainfall, temperature, solar radiation, etc.)	Raster	1958-present (monthly values for individual years)	(~4 km^2)	TerraClimate

Name	Type of data	Year/Temporary extend	Resolution	Source
Climate	Raster	1981-present (hourly)	(~9 km^2)	ECMWF
National soil map	Map/Vector	Not defined	1:1,000,000	NIAPP
Dak Lak soil map	Map/Vector	Not defined	1:100,000	NIAPP
Landuse map	Map/Vector	2015	1:100,000	NIAPP
Digital Eveletion Model (DEM)	Map/Raster	2000 – 2013	30 m x 30 m	ASTER version 3 (released 2019)
Forest inventory	Map/Vector	2017	1:100,000	VNFOREST (MARD)
Agroecological zoning	Map/Vector	Not defined	Not defined	NIAPP
Landuse	Statistical table	2018; 2015	N/A	GSO
Suitability maps for coffee Robusta	Map/Raster	2019	30 m x 30 m	ICRAF

3. Weather sensitivities of coffee yield

Crop specific agroclimatic zones should be based on relevant climate variables to which the crops are sensitive. For a first assessment of relevant climate variables and sensitivities, we used the yield time series provided by GSOV (2000-2018). The long-term trend due to improvement in management was removed and the yield anomaly calculated. Monthly climate data were collected from the ERA5-Land (ECMWF 2018) with a spatial resolution of about 10 km. Because the yield data is at the district and provincial scale, the climate data was projected to the resolution of the selected administrative levels. Multiple linear regression has been used to assess the effect of weather on district and provincial level yield, with regularization techniques such as PCA and leave-one-out to avoid overfitting.

4. Agroclimatic zoning

Based on the land use maps provided by NIAPP, climate variables were extracted at locations indicated to grow coffee and pepper. These climate variables were used to derive agroclimatic zones (ACZ) using clustering analysis. The ACZ in combination with other classified maps (e.g., soil types and slope classes) indicate zones with homogeneous environmental conditions.

5. Spatial distribution of pest and disease incidence

Based on the ECOM database for 2015, the incidence of the coffee berry borer, nematode, leaf rust and die back was related to the ACZ defined in 3.4.

5 Achievements against activities and outputs/milestones

Objective 1: To carry out a situational analysis of coffee and black pepper farming systems and livelihoods in three provinces of the Central Highlands of Vietnam

no.	activity	outputs/ milestones	completion date	comments
1.1	defining a set of biophysical and socio-economic indicators for farming system management, resource use and farmers' livelihoods	Set of indicators defined	October 2019	Contributions of ICRAF, CIRAD and WASI
1.2	collect secondary data from partners and past projects	Databases evaluated	June 2020	Contributions of ICRAF, CIRAD and WASI
1.3	identify possible entry points for research on system efficiency and sustainable production initiatives	Preliminary findings and system characterizatio n	December 2020	Contributions of ICRAF, CIRAD and WASI

PC = partner country, A = Australia

Objective 2: To provide knowledge from the literature and from the ground about the soil /plant health issues of black pepper and coffee from the nurseries to the field.

no.	activity	outputs/ milestones	completion date	comments
2.1	Secondary data analysis	Intercropping coffee / black pepper increases the nematode's thread for coffee	February 2020	Contribution of WASI

2.2	SBPDs in black pepper plantations	*Pythium* and/or *Phytopythium* seem to be responsible of more damages in the black pepper plantations than *Phytophthora*	November 2020	Contribution of WASI - PRDC + PPRI and Deakin University
2.3	SBPDs in nurseries	In Gai Lai, the seedlings (coffee and black pepper) from 3 of the main nurseries were healthy (almost deprived of any SBPDs)	August 2020	Contribution of WASI - PRDC & PPRI
2.4	Literature review on SPBD affecting coffee and black pepper plantations: strategies for controlling them	A full document has been produced and will be used for preparing a mini review to submit to an International journal	November 2020	Contribution of Deakin University, WASI - PRDC & PRRI
2.5	Listing of the bio-inoculants available in Vietnam for controlling nematodes and *Phytophthora*	List established and preliminary investigations on the quality of these bio-inoculants	October 2020	Contribution of WASI - PRDC

PC = partner country, A = Australia

Objective 3: To analyse spatial distribution of coffee and black pepper production

no.	activity	outputs/ milestones	completion date	comments
2.1	Pilot mapping of coffee and black pepper production using remote sensing	Land cover classification for Dak Song District based on 10 m resolution Sentinel data	October 2020	

2.2	Coffee yield – climate analysis	Weather sensitivity of coffee yield – Manuscript submitted to Agricultural and Forest Meteorology	June 2020	Manuscript is under review
2.3	Agroecological zoning	Map of AEZ for case study area	August 2020	Contribution from ICRAF, NIAPP and ECOM
2.4	Spatial distribution of SBPD incidence	Relationship between nematodes incidence and climate	October 2020	Only limited data available on SBPD incidence through ECOM

PC = partner country, A = Australia

6 Key results and discussion

Objective 1

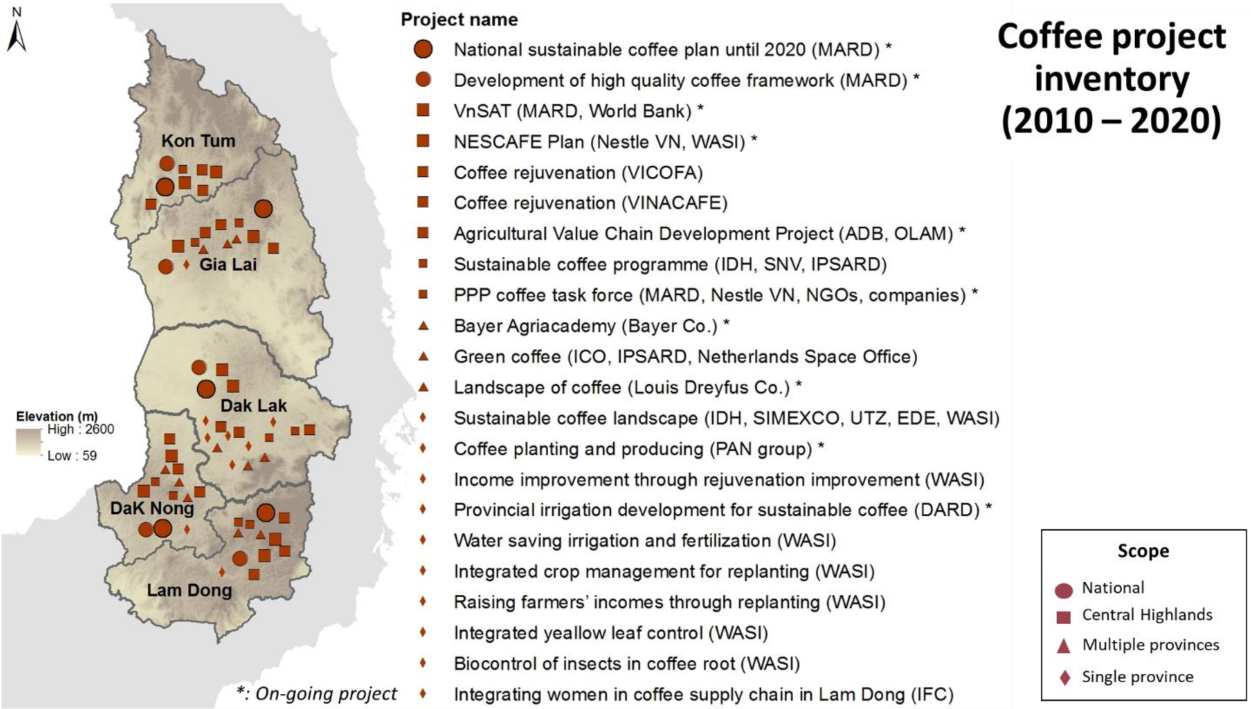
1. Set of indicators

The list of indicators selected by the project team is presented in Annexes. It includes three scales (farm, community, and value chain) with several components for each. Briefly, the list covers household members description, productive assets, details on crops and livestock management, soil characteristics, system performance, access to information, communal resources, description of value chain actors, commodity prices and post-harvest processing details for coffee and pepper.

2. Databases availability, quality and usefulness

Numerous coffee projects were conducted in the five provinces of the Central Highlands over the last ten years (Figure 1A). Scope ranged from national to provincial level. Stakeholders included government institutions (MARD, IPSARD, NIAPP), national research centers (WASI), NGOs (SNV), international donors (WB, ADB…) and private companies (Nestlé, IDH, SIMEXCO, OILAM, Vinacafe…). The landscape was less crowded for pepper (Figure 1B), mainly projects at provincial scale led by research institutions (WASI, ILRI…), with the exception of two projects led by MARD at national and regional level. Beside the PPP pepper task force involving IDH at regional level, the private sector is only present in the provinces of Dak Lak and Dak Nong. This is about to change, with the raising interest of the spices giant McCormick in the region.

(A)



(B)

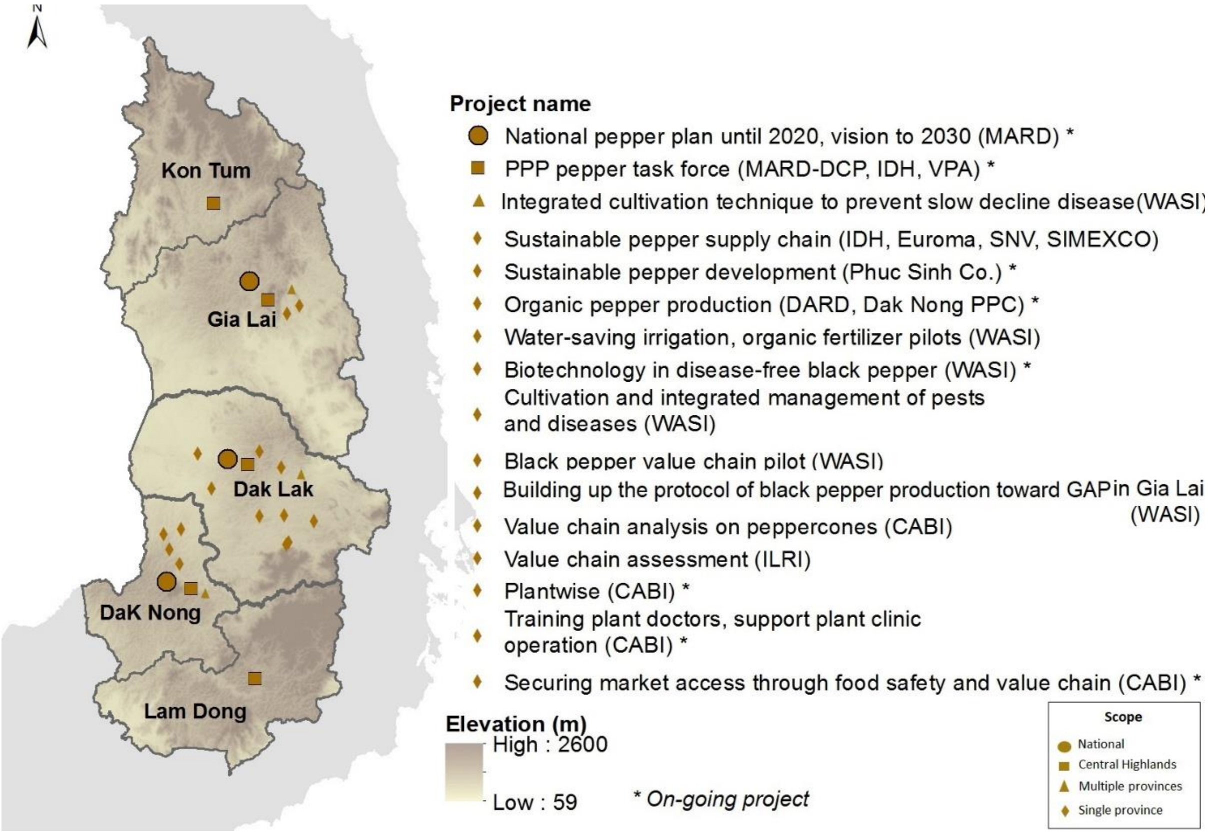


Figure 1. Inventory of past and current projects, for coffee (A) and pepper (B)

Three databases were selected for further analysis: ECOM (as it offers a good base for coffee farmers, with a lot of details on management and cost of production), Pepper WASI (Bang so lieu NVTX - a good base for pepper farmers, including some VC info), and the Hands and Minds database (good info for general performance of both pepper and coffee farmers). The other databases had major flaws (unclear crops, unclear structure, lack of geographical information…) or did not have an added value.

The databases have been cleaned and uploaded to the project Google Drive folder[1]. An overview of the type of data available with each of the selected database is presented in Table 1. Geographical information was missing for all datasets. Only the WASI database included market information. There was a major gap in social indicators (incl. livelihood options, innovation capacities, gender…), market linkages information, as well as farm performance indicators in general.

In terms of coverage, most of the information came from the district of Cu Mgar (ECOM database; Figure 2). It was not possible to merge the three datasets selected neither on a thematic not on a geographic base, and the data available did not cover all the indicators needed for a complete farming system characterization at this stage However, when analysing separately each dataset, a general overview of coffee and pepper-related agronomic and economic information can be obtained.

Table 1. Characteristics of the databases selected against the type of indicators needed

[1] https://drive.google.com/drive/folders/1QVZnt9aBqLJaLR51gBvjhEq35o_E8lHB

Source of data	Province	District	Commune	No. of household (HH)	Year	Available data							
						GPS	Farmer profile	Farming system	Farm management	Production cost	Selling price	Profit	Market
ECOM	Dak Lak	Cu Mgar (4124)	Ea Tar	909	2015	x	v	v	v	v	x	x	x
			Cu Dlie M'nong	881									
			Ea Hding	405									
			Ea Kiet	265									
			Ea Kpam	281									
			Ea Kueh	542									
			Quang Phu	623									
			Quang Tien	218									
	Dak Nong	Dak Glong (193)	Dak Ha	97		x	v	v	v	v	x	x	x
			Quang Son	96									
		Dak R'lap (412)	Dak Ru	56									
			Dak Wer	98									
			Nhan Co	77									
			Quang Tin	181									
		Gia Nghia (393)	Dak Nia	171									
			Nghia Duc	61									
			Nghia Phu	102									
			Nghia Tan	14									
			Nghia Trung	45									
	Gia Lai	Chu Se (387)	Bo Ngoong	148		x	v	v	v	v	x	x	x
			Chu Pong	61									
			Ia Tiem	178									
		Dak Doa (502)	Ia Bang	325									
			Ia Pet	177									
WASI	Gia Lai	Duc Co (19)	Ia Din	3	2018	x	x	v	v	v	v	v	v
			Ia Dok	1									
			Ia Dom	9									
			Ia Kha	1									
			Ia Lang	1									
			Ia Nan	4									
		Chu Se (11)	Chu Se Town	11									
		Cu Kuin (45)	N/A	45									
		Mang Yang (17)	N/A	17									
	Dak Nong	Dak Song (40)	Thuan Hanh	40									
Hands and minds	Dak Lak	Ea Kar (153)	Ea Tyh	153	2015	x	v	x	x	v	v	v	x
	Dak Nong	Krong No (157)	Dak Dro	157									

	800-1000
	600-800
	400-600
	200-400
	100-200
	< 100

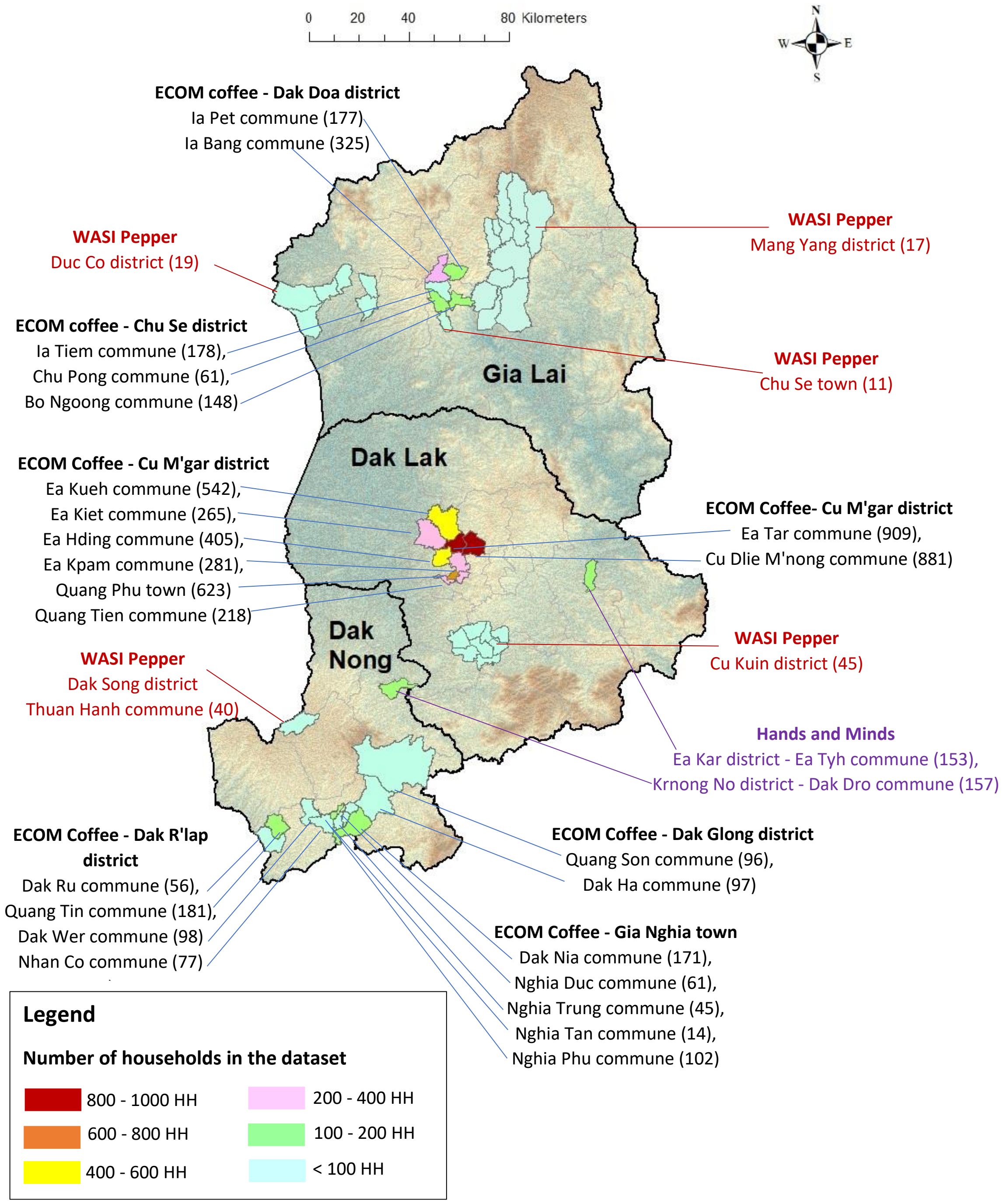


Figure 2. Map of the coverage of the datasets selected to characterize three provinces of the Central Highlands

3. Characterising coffee and black pepper farming systems and livelihoods in the 3 target provinces

3.1. Land use overview

Individual plot sequences over the period 2007-2017 show, for 211 plots of Dak Lak and Dak Nong, how coffee and pepper-based plots are transitioning towards more diverse systems (Figure 3; Burra et al., 2021). Coffee plots keep a stable share of land use in the area surveyed and become more diverse with progressive intercropping with cashew and pepper from 2013, pepper is more and more introduced in tree-based plots. The impact of these changes on soil health and on farmers livelihoods, as well as the relevance of the chances with respect to land suitability and system management were not studied so far.

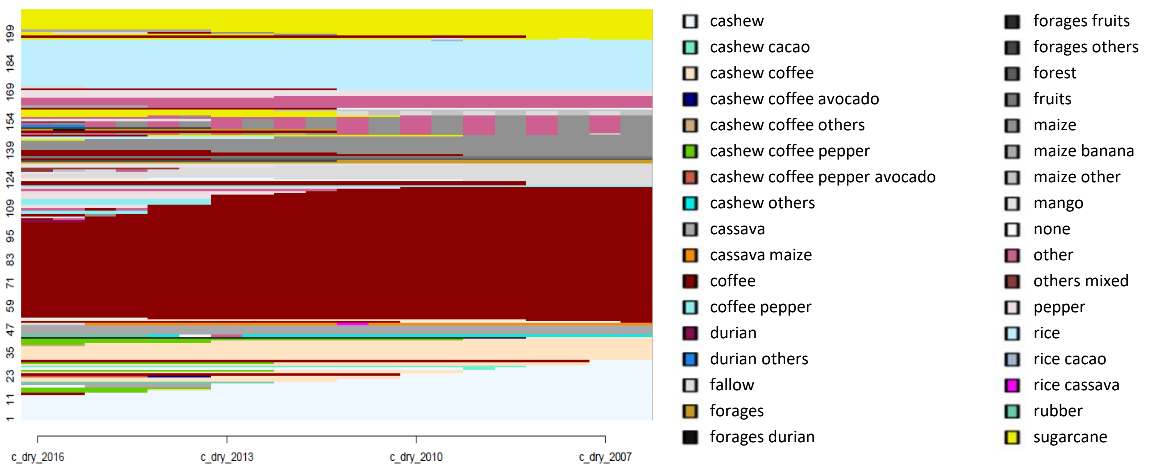


Figure 3. Individual plot sequences for 211 plots of Dak Lak and Dak Nong, Vietnam.

3.2. Coffee-based farming systems (ECOM database)

Based on an analysis of the ECOM data and on literature, the main trends were defined for the 3 target provinces.

1) Most coffee systems have already started transitioning towards intercropping/agroforestry systems, especially in Dak Lak and Dak Nong Provinces. Only in Gia Lai Province does monoculture coffee remain dominant in Ecom's farmer network (55%); it represents less than 11% in Dak Lak and Dak Nong Provinces. Pepper is the crop most commonly found in coffee farms, with 32 to 51% of the farms reporting pepper vines in all 3 provinces. Fruit trees, notably avocado durian and cashew to a lesser extent, are reported in 43 to 47% of the farms in Dak Lak and Dak Nong Provinces, only in 13% of the farms in Gia Lai. This confirms that coffee-based systems are moving towards more diversification.

2) The average household farmers are 50-year-old or above in all 3 provinces. Transitioning towards sustainable farming systems must therefore consider the upcoming issue of

farmers retiring, with its implication in terms of investment capacity/willingness, labor availability as well as attractiveness for younger generations of farmers. This highlights that a complete characterization of livelihoods strategies will be critical for future efforts on coffee systems sustainability.

3) Data available on farm management practices reveals the intensity of management practices and the resulting high yields. The average farmer in Dak Lak and Gia Lai Provinces uses 460 kg.N.ha^{-1}.yr^{-1} for a coffee yield close to 4 t.ha^{-1}.yr^{-1}; while the average farmer in Dak Nong uses 370 kg.N.ha^{-1}.yr^{-1} for a coffee yield of 3.2 t.ha^{-1}.yr^{-1}. The difference between provinces reflects agroecological conditions slightly less favorable to coffee at higher elevations. Furthermore, the discrepancy between farming systems opens up the door to major avenues for improvement in farming practices through a reduction in inputs (Figure 4). Applying more than 600 kg.N.ha^{-1}.yr^{-1} is common, even though yields reach a maximum around 300 kg.N.ha^{-1}.yr^{-1}, and some farmers apply more than 1 t.N.ha^{-1}.yr^{-1}. Yields decline under these high input rates, hinting for soil degradation issues. Data is most accurate for fertilizers; soil remediation techniques (lime and compost inputs) are common but not sufficient to restore soil conditions (Byrareddy et al., 2019); there is a lack of knowledge and characterization of pesticide use, and a lack of accurate data regarding irrigation practices (Byrareddy et al., 2020). There is a need to decrease chemical inputs application in order to reduce environmental damages. Farming practices should be better characterized and adapted to crop needs and soil health status.

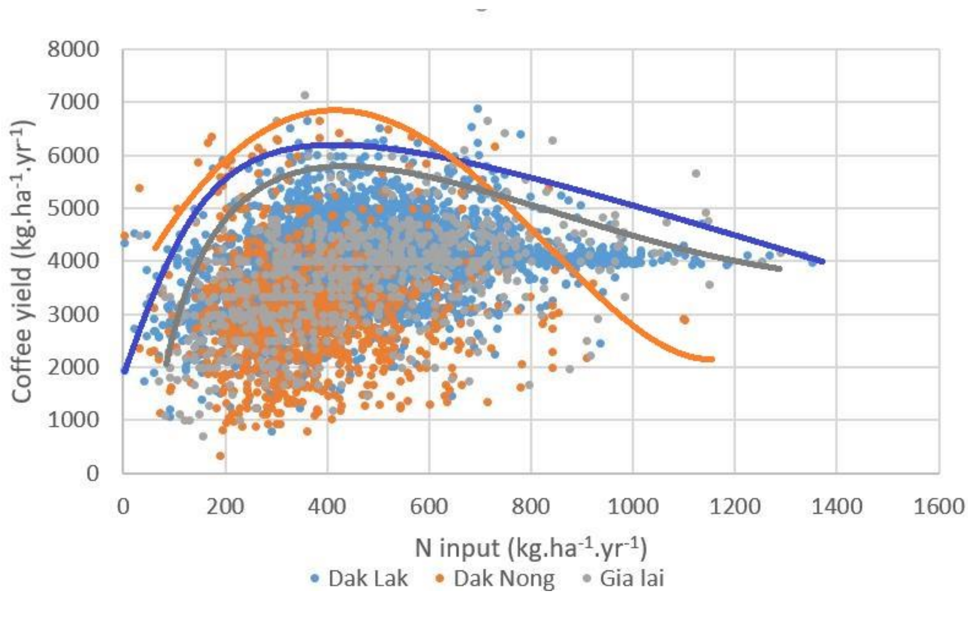


Figure 4. Yield gap analysis for coffee farms from ECOM farmer network. Maximum yield is achieve around 300 kg.N.ha^{-1}.yr^{-1}. Yields decline for inputs higher than 500 kg.N.ha^{-1}.yr^{-1} hinting for issues related to soil degradation.

3.3. Pepper-based farming systems (WASI database)

1) The relatively low fertilizer inputs reported in pepper farms (230 kg.N.ha^{-1}.yr^{-1}) compared to coffee farms could reflect overall better farming practices, or could result from a bias estimate (lead farmers) or inaccuracy in the interview answer. Still, the input rates reflect the fact that Dak Nong and Dak Lak have the highest rates and highest yields, while Gia Lai is slightly less suitable for pepper growing. There is still need to better characterize the pepper farming systems, management practices, and household indicators.

2) Most farms report input rates smaller or within the range optimal for highest yields (200-300 kg.N.ha^{-1}.yr^{-1} from the yield gap analysis). A few farms report inputs higher than 300 kg.N.ha^{-1}.yr^{-1} and justify the potential for reduction input use in pepper farms in order to improve sustainability. A few farms report less than 100 kg.N.ha^{-1}.yr^{-1} in Gia Lai, either questioning the accuracy of data or reflecting a lack of management from and a trend of pepper replacement by other cash crops. In parallel, farmers in Gia Lai Province have the most intense use of agrochemical products (8,400,000 VND.ha^{-1}.yr^{-1}), when farmers in Dak Lak and Dak Nong Provinces spend 4,800,000 to 5,600,000 VND.ha^{-1}.yr^{-1}. This might also reflect the rise of pests and diseases in Gia Lai Province and explain a decline of the pepper sector. Here as well chemical inputs should be reduced to improve sustainability, and farming practices should be adapted to crop needs and soil health status.

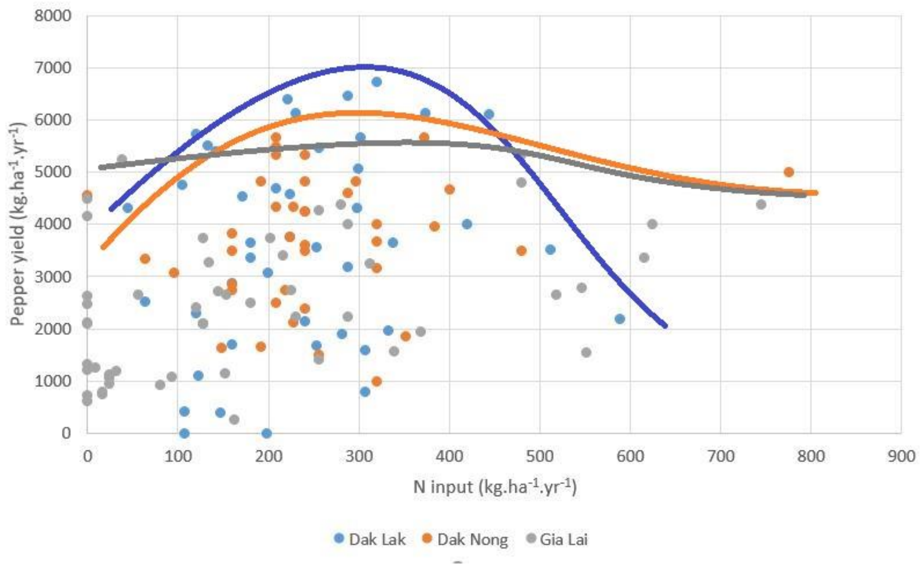


Figure 5. Yield gap analysis for pepper farms from WASI database.

3.4. General system performance and farmers' perceptions (Hands and Minds database)

Based on a household survey conducted in 2016 in Dak Lak and Dak Nong province, 37% of the smallholder households cultivating coffee and pepper were food insecure, mildly to severely (Table 2). Income is low, with in average 3270 USD/year. The average family size was 3.4, for land areas relatively small. Farming systems were diverse, with in average 6 different species of crop cultivated on a single farm, and 2 to 3 livestock species. On each farm, 90% of the production in average was destinated to the market.

Most farmers perceived environmental change negatively (Figure 6), with 83% thinking that weather, water quality and availability, trees quantity, soil fertility and abundance of animals has been decreasing/worsening compared to 5-10 years ago.

Table 2. Characteristics of coffee and pepper-based smallholder systems in Dak Lak and Dak Nong provinces (n=193)

Class	Variable name	Unit	Type	Mean	SD	%	Definition
Household level	Ethnic group	n.a.	categorical			19	Ethnic group of the household head is a minority (Ede, Mnong, Tay or Thai)
	Household size	AME [3]	continuous	3.42	1.31		Number of people in the household
	Education	n.a.	categorical			20	Education level of the household head is not above primary
	Land cultivated	ha	continuous	1.80	1.59		Total area cultivated
	Livestock holdings	TLU	continuous	3.57	5.30		Number of livestock assets
	Crop diversity	n.a.	continuous	6.22	1.33		Number of different crop species cultivated
	Livestock diversity	n.a.	continuous	2.67	1.02		Number of different livestock species cultivated
	Market orientation	%	continuous	89	18		Proportion of farm products sold to the market
Performance	Progress out of Poverty	n.a.	continuous	16.13	23.16		Likelihood of household's total expenditure below the national poverty line [2]
	Total income [3]	$USD.year^{-1}$	continuous	3,270	4,390		Sum of income from agricultural activities
	Food availability	$kcal.AME^{-1}.year^{-1}$	continuous	144,211	561,518		Potential amount of food that can be generated from on and off-farm income [4]
	Food Self-sufficiency	$kcal.AME^{-1}.day^{-1}$	continuous	1,692	2,770		Capacity to fulfill the household energy requirements from food produced on-farm
	Food insecurity	n.a.	categorical			37	Food insecure on the Household Food Insecurity of Access Scale (HFIAS)[5]

[1] Adult male equivalent (adult = 1; child=0.5)
[2] PPI score = Desiere, S., Vellema, W., D'Haese, M., 2015. A validity assessment of the Progress out of Poverty Index(PPI)(TM). Eval. Program Plan. 49, 10-18.
[3] data from Ritzema et al. 2019
[4] Ritzema et al. 2019
[5] HFIAS measures the frequency and severity of hunger (Coastes et al., 2007).

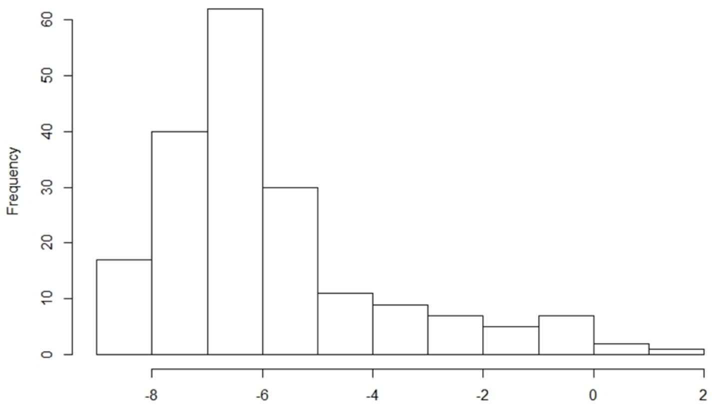


Figure 6. Perception of environmental change by coffee and pepper smallholder farmers in DakLak and DakNong provinces, Vietnam (n=193)

Objective 2

1. Analysis of secondary data

1.1. Farm characterization

In this part we will show some characteristics of the database with a focus on intercropping systems.

Table 3. Number of fields by cropping system

Intercrops	A, P, D	A, D	A, C	A	A, P	C	C, P	Co	D	J	O	P	P, D	R	M
Number of fields	600	138	397	276	848	502	580	6	98	81	15	1976	169	69	823

Avocado: **A**

Avocado / Durian: **A,D**

Avocado / Cashew: **A,C**

Avocado / Pepper: **A,P**

Avocado / Pepper / Durian: **A,P,D**

Cashew: **C**

Cashew / Pepper: **C,P**

Durian: **D**

Rubber: **R**

Monocropping: M

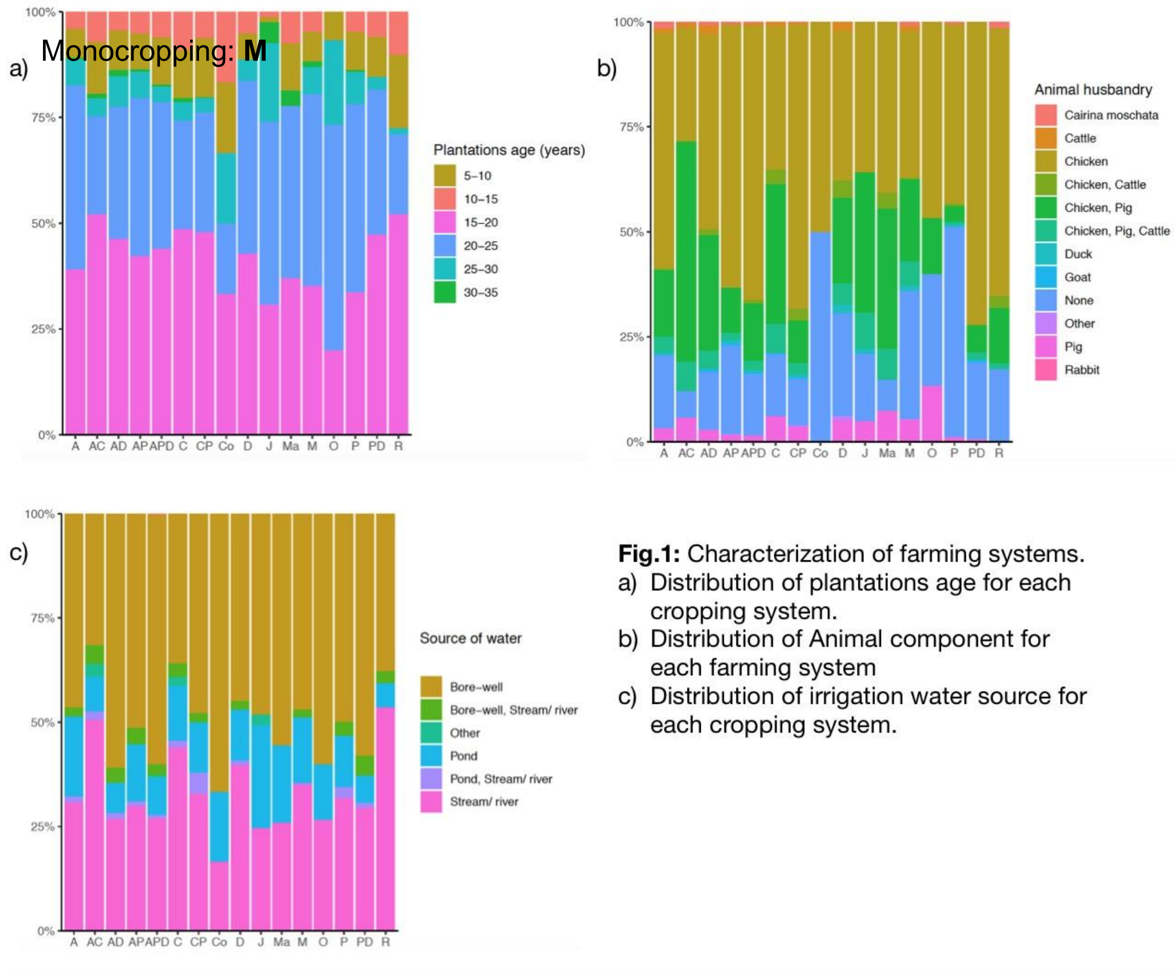


Fig.1: Characterization of farming systems.
a) Distribution of plantations age for each cropping system.
b) Distribution of Animal component for each farming system
c) Distribution of irrigation water source for each cropping system.

Most of plantations are 15 and 25 years old, the animal component of farm is mostly chicken only or chicken and pigs (this could be interesting according to organic fertilizers use). Water used for irrigation comes from bore-well or river and stream and from ponds in a lesser way.

1.2 Intercropping

Table 4. Distribution of the four classes of the nematode incidence (number of fields/class)

	Nematode incidence			
total size	0 %	1-10 %	11 - 25%	26-50%
6605	70	4789	1727	19

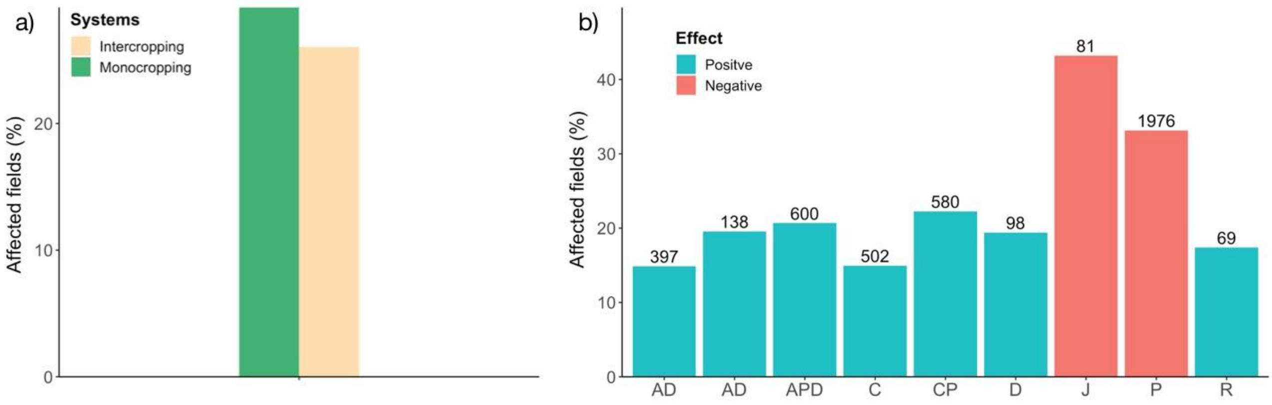


Figure 7. Effect of intercropping on nematode incidence.
a) Percentages of affected fields: monocropping system (N_m = 823) *versus* intercropping system (N_i = 5782). b) Percentages of affected fields for the different intercropping associations (number of fields given at the top of the columns.

Intercropping system in general is significantly effective for reducing the nematode incidence compare with the monocropping system. However, the intercropping with Jackfruit and Pepper is significantly negative and may not be accurate for mitigating nematodes in coffee plantations.

1.3 Fertilization

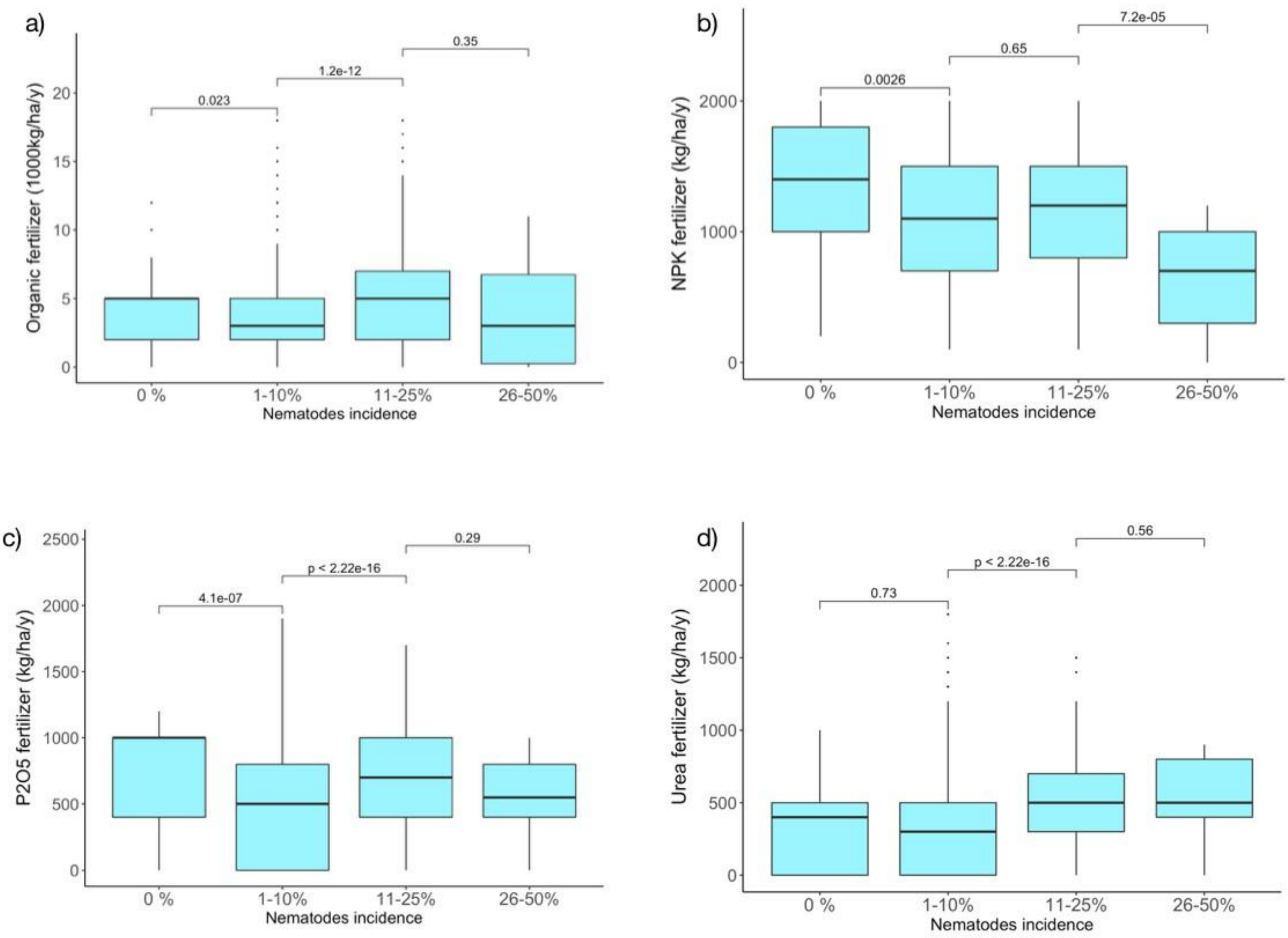


Figure 8. Interaction between the sources of fertilization and the incidence of nematode incidence. P-value is calculated for consecutive classes.

a) Organic fertilizer utilization. b) NPK fertilizer utilization. c) P_2O_5 fertilizer utilization. d) Urea fertilizer utilization

Table 5. Fertilizers effect on disease incidence (previously we just presented results about nematodes but the full analyse was done on Leaf rust, Pseudomonas, Die-back and Berry borer as well).

	Nematodes	Leaf rust	Pseudomonas	Die-back	Berry borer
Organic	+	O	+	O	O
NPK	O	O	-	+	O
P2O5	+	+	+	+	+
Urea	+	+	+	+	+

+: Fertilizer amount is higher in class 11-25% than 1-10%.

o: No differences between 1-10% and 11-25% classes

-: Fertilizer amount is lower in class 11-25% than 1-10%.

1.4 Fertilization and Intercropping

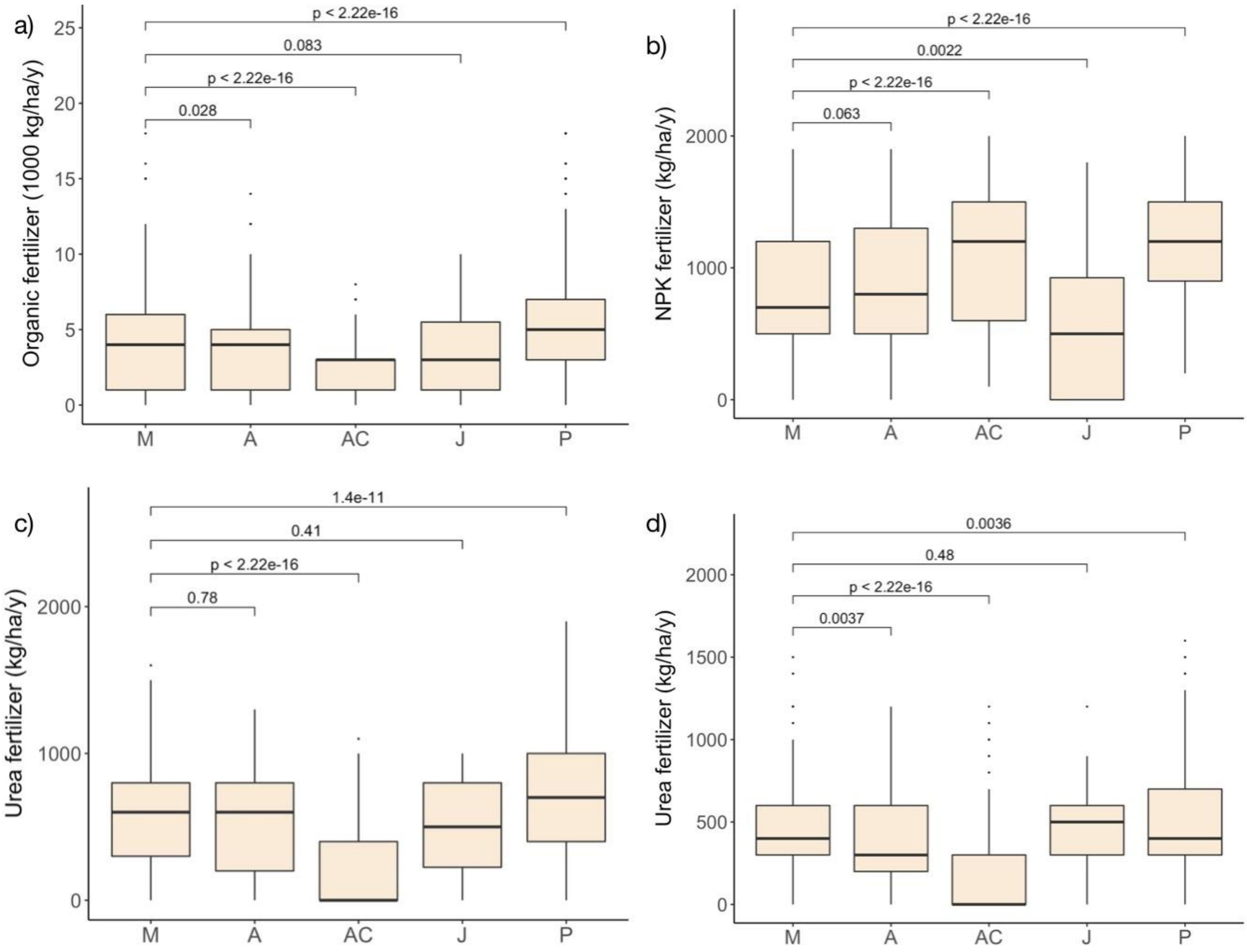


Figure 9. Fertilizers use for 5 cropping systems. The p-value is calculated for consecutive classes. a) Utilisation of organic fertilization. b) Utilisation of NPK fertilizer. c) Utilisation of P_2O_5 fertilizer. d) Utilisation of Urea fertilizer.

According to the effect of fertilizers on diseases and the differential use between intercropping systems, we assessed the correlation between input practices and diseases incidence for the 5 intercropping systems highlighted previously.

Table 6. Correlation Fertilizers use and intercropping effect

	Fertilizer use				Affected fields proportion				
Systems	**Organic**	**NPK**	**P_2O_5**	**Urea**	**Nematodes**	**Leaf rust**	**Pseudomonas**	**Die-back**	**Berry borer**
A	-	o	o	-	o	o	o	o	+
AC	-	+	-	-	-	-	o	-	o
J	o	-	o	o	+	+	o	o	+
P	+	+	+	o	+	o	+	+	+

+ more than monocropping; o no differences with monocropping; - less than monocropping

Yellow cells mean that the results for affected fields may be explained by the differential use of fertilizers.

The gap between affected fields proportion in monocropping and systems « Avocado, Cashew » and « Pepper » may be explained by differential uses of fertilizers. However, several factors can have combined effects which leads to differences in proportions (nature of organic fertilizers, source of irrigation, age of plantations, etc…).

2. **Presence of SBPD in the seedlings at the nursery: case study in Gai Lai Province**

Table 7. Soil characteristics for each type of seedlings per nursery.

	pH	**Organic C (%)**	**Total N (%)**	**P_2O_5 available (mg/100g soil)**
Tinh, pepper *Sri Lanka* (TSR)	4,69	1,57	0,10	0,54
Tinh, pepper *Vinh Linh* (TVL)	4,60	1,65	0,10	0,41
Tinh, coffee (TCF)	3,90	1,80	0,10	1,27
Duc, pepper *Vinh Linh* (DVL)	4,33	1,44	0,08	9,72

Duc, coffee (DCF)	4,34	1,18	0,07	9,64
Thuy Duong, pepper *Sri Lanka* TDSR	4,46	3,07	0,11	2,54
Thuy Duong, coffee (TDCF)	4,99	2,99	0,12	6,96

Most of these soils are very acidic (from 3,90 to 4,99). Indeed, the total N content and the P_2O_5 available are not low but we were in nurseries and farmers are used to apply fertilizers. This may explain the variability we observed between the nurseries. Even the organic C content is high for the 3 nurseries.

2.1 Presence of nematodes in coffee seedlings

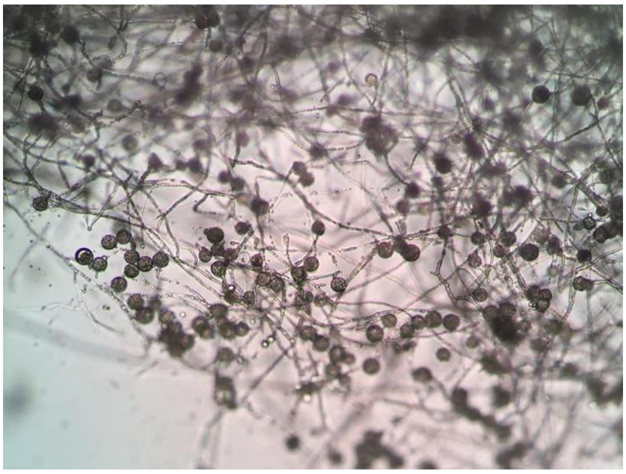
Table 8. Average number of nematodes found in coffee seedlings for each of the nurseries.

Nursery references	Rate of *Meloidogyne* *(number of nematodes/g of fresh roots)*	Rate of *Pratylenchus* *(number of nematodes/g of fresh roots)*
TCF	1,4	0
DCF	1	0
TDCF	0,3	0

The population of nematodes found in the coffee seedlings is very limited for the 3 nurseries and it clearly shows that there are healthy. These seedlings cannot be responsible of spreading nematodes in the field after plantation.

2.2 Presence of *Phytophthora* in black pepper seedlings

Our investigations did not detect the presence of any *Phytophthora* in the seedlings. On the other hand, we came up with some strains of *Pythium/Phytopythium* (see the photo below)



These *Pythium* were inoculated to the plant (leaves) to determine if there were pathogenic or saprophytic. Our results showed the absence of symptoms suggesting these isolates are only saprophytic (see the photo below: positive control on the left and inoculation test on the right).

As for the nematodes for the coffee seedlings, we can conclude than all the seedlings of black pepper produced in the 3 nurseries of Gai Lai are healthy and deprived of any SBPD agents.

3. Preliminary investigations on SBPD affecting black pepper in the 3 regions (Dak Nong, Dak Lak and Gai Lai)

We found isolates of *Pythium* and *Phytopythium* in infected black pepper plantations of the 3 provinces (12). This identification was done based on the morphology of the fungus in Petri plates. Meanwhile, we managed to find some *Phytophthora* isolates in highly infected black pepper plantations in Dak Nong (6). This first assessment remains preliminary but confirms an ongoing work carried out by PPRI in June/July 2020 showing that most of the pathogenic fungus affecting black pepper plantations in the 3 provinces are *Pythium* and

Phytopythium instead of *Phytophthora*. All our isolates will be sequenced during the full Aciar project which has started this year.

4. **Literature review entitled "Manage pepper and coffee soil pests and diseases in the Central Highlands in Vietnam by using microbial agents and increasing soil health"**

A complete document has been prepared on such topic and will be used for writing up a review paper to submit for publication in an International journal with impact factor.

Manage pepper and coffee soil pests and diseases in the Central Highland in Vietnam by using microbial agents and increasing soil health

Abstract

Vietnam is the world's 2nd largest exporter of coffee and its pepper production is increasing sharply. However, due to land management, the production of these crops is affected by pests and soil diseases : 300,000 ha of coffee are more than 25 years old and must be renewed, but all attempts to replant have failed. Pepper plantations have exceeded the Vietnamese government's plan and according to the latter, pepper plants have been dying for 2 years. This paper reviews and synthesizes two possible countermeasures that are present in the scientific literature. While many examples exist to limit the impact of pepper and coffee diseases and other crops, research has highlighted poor quality products, a lack of an evaluation method that makes the different soil restoration techniques comparable. It would seem that these approaches cannot be standardized and that solutions must be considered in relation to the territory. Finally, a new line of work is proposed by the company Pheronym, which markets nematode pheromones, thus limiting their damage.

As we can read below, we have gathered scientific information related to the potential of bio-control strategies for controlling nematodes affecting coffee plantations and/or pathogenic fungus damaging black pepper plantations. Meanwhile we have developed the concept of soil health and came up with options for enhancing soil health and mitigating the population of SBPD. We cited some examples where both strategies (biocontrol – direct action and improvement of soil health – indirect action) were successfully combined with promising results in the field.

5. Preliminary investigations on the commercial bio-inoculants available in Vietnam to control SBPD such as nematodes and pathogenic fungi.

From our interviews, we came up with a list of 15 commercial bio-inoculants available on the market in Vietnam described as effective for controlling the population of pathogenic fungus and nematodes.

The list is presented below:

No	Commercial name	Microbial content	*SBPD*
1	AT Padave	- *Paecilomyces spp: 1 x 10^8 cfu/ml* - *Bacillus subtilis: 1 x 10^8 cfu/ml* - *Actinomycetes: 1 x 10^8 cfu/ml* - *Saccharomyces cerevisiae: 1 x 10^8 cfu/ml*	*Nematodes*
2	BioBac 50WP	- *Bacillus subtilis: 50%w/w*	*Phythopthora spp.*
3	NEMA – Dien Trang	- *Trichoderma spp.: 10^8cfu/g* - *Paecilomyces spp.: 10^8 cfu/g*	*Nematodes* *Phytophthora spp.* *Fusarium spp.* *Root growth*
4	Tricho Gold – Dien Trang	*Trichoderma spp.: 10^8 cfu/g* *Bacillus subtilis: 10^8 cfu/g*	*Nematodes* *Phytophthora spp.* *Fusarium spp.*

5	Điền Trang Tricho 5B	*Bacillus subtilis: 1 x 10^8 cfu/g* *Trichoderma spp.: 1 x 10^8 cfu/g*	*Colletotrichum spp* *Fusarium spp* *Phytophthora spp* *Neoscytalidium spp*
6	META – Dien Trang	*Metarhizium anisopliac: 1 x 10^8 cfu/g* *Bacillus thuringiensis: 1 x 10^8 cfu/g*	*Cicadidae* *Nematodes* *Phytophthora spp.* *Fusarium spp.*
7	BT – META – Đien Trang	*Bacillus thuringiensis (Bt): 1 x 10^8 cfu/g* *Metarhizium anisopliac: 1 x 10^8 cfu/g*	*Pyricularia oryzae,* *Pyricularia grisea,* *Rhizoctonia solani,* *Fusarium spp.,* *Phytophthora spp*
8	Trichoderma AGI	*Organic: 15%* *Trichoderma sp: 1 x 10^8 cfu/g*	*Rhizoctonia solani,* *Fusarium spp.,* *Phytophthora spp*
9	Phân bón TKS - NEMA	*Bacillus* sp.: *10^9 cfu/g* *Arthrobotrys oligospora: 10^9 cfu/g* *Verticillum* sp.: *10^9 cfu/g* *Paecilomyces* sp.: *10^9 cfu/g* *Paenibacillus chitinolyticus: 10^9 cfu/g*	*Nematodes*
10	TKS – Trichoderma	*Trichoderma hazianum* *Trichoderma hamatum* *Trichoderma viride* *Trichoderma koningii* *Trichoderma reesei*	*Phytopthora,* *Fusarium,* *Palmivora…*
11	PHYTO-M of the Plant Protection Research Institute	*S.misionensis 1 × 10^8 cfu/g* *B. methylotrophicus 1 × 10^8cfu/g* *Trichoderma harzianum: 3,2 × 10^9cfu/g* *Azotobacter sp.* *Burkholderia sp.*	*Phytophthora* *Fusarium,* *Palmivora…*
12	Tricho - VTN	*Trichoderma spp.: 10^6cfu/g*	*Phytophthora* *Fusarium,* *Palmivora…*

13	Tricho DHCT	*Trichoderma spp.* 10^8 *cfu/g*	*Fusarium,* *Rhizoctonia,* *Phytophthora,* *Pythium…*
14	Bio-inoculant of Tay Nguyen University	+ *Trichoderma sp.* 10^8 *cfu/g* + *Metarzhium sp.* 10^8 *cfu/g* + *Pseudomonas sp.* 10^8 *cfu/g* + *Bacilus sp* 10^8 *cfu/g*	*Nematodes* *Rhizoctonia,* *Phytophthora,* *Pythium…*
15	Soil Activator	*Bacillus subtilis* 2,48 x 10^8 cfu / g *Bacillus amyloliquefaciens* 5x 10^6 cfu /g *Pseudomonas monteilii* 1x 10^6 cfu /g	*Fusarium,* *Rhizoctonia,* *Phytophthora,* *Pythium…*

Among these 15 products, we have started some microbial investigations on 5 of them.

No	Commercial name	Expected strains	Isolates found
2	BioBac 50WP	*Bacillus subtilis*	**Only one bacterial strain** found. The aspect of the colonies suggests a *Bacillus* strain
4	Tricho Gold – Dien Trang	*Trichoderma spp.* & *Bacillus subtilis*	Instead of 1, a **total of 7 bacterial** strains were isolated and the counting of the fungus has not been done yet
5	Điền Trang Tricho 5B	*Trichoderma spp.* & *Bacillus subtilis*	Instead of 1, a **total of 6 bacterial** strains were isolated and instead of 1, **5 fungal isolates** were isolated
7	BT – META – Đien Trang	*Bacillus thuringiensis &* *Metarhizium anisopliac*	Instead of 1, a **total of 4 bacterial** strains were isolated and instead of 1, 3 **fungal isolates** were isolated

15	Soil Activator	*Bacillus subtilis &* *Bacillus amyloliquefaciens &* *Pseudomonas monteilii*	Instead of 3, a **total of 6 bacterial** strains were isolated (all *Bacillus*, no *Pseudomonas*) and the counting of the fungus has not been done yet

Indeed, this ongoing investigation remains preliminary and all the isolates must be sequenced for molecular identification. However, we can see that 4 or the 5 tested commercial products contained significantly more bacterial strains and those which had been tested more fungal isolates than what was expected according to the information provided by the manufacturer. There is an obvious risk of getting products with microbial contaminants. This investigation will be continued during the ACIAR full project and all these products will be tested after inoculation to both coffee and black pepper planted in infected soils.

Objective 3

1. Pilot land cover classification using remote sensing

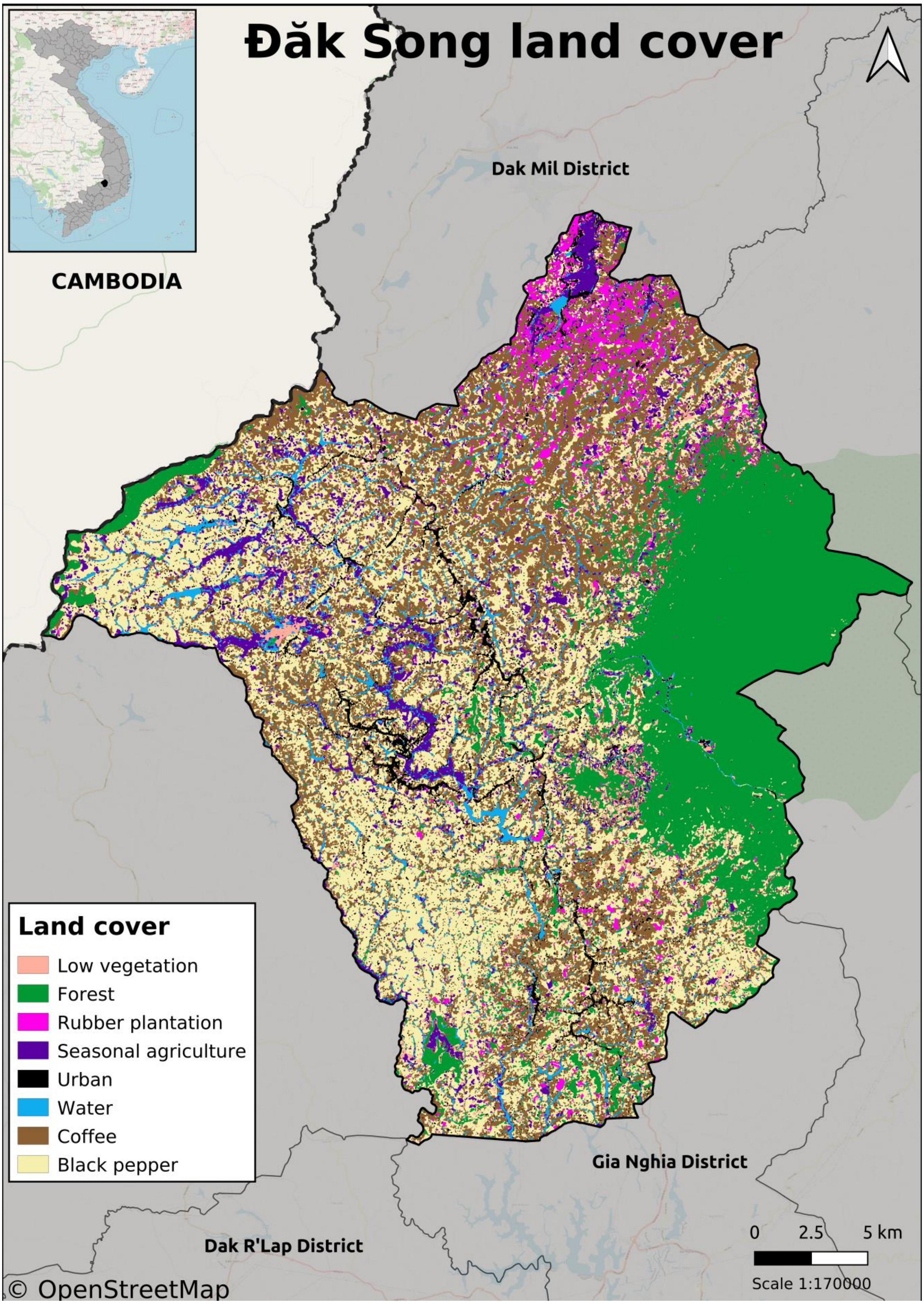
The first important outcome of this work is the creation of the GPS points database. Modern land cover classification method like convolutional neural network needs many samples to be trained on. This dataset will be a key asset to improve black pepper and coffee mapping in the future. While most of the categories are simple to discriminate from, the biggest challenge is to separate coffee from black pepper. The main reason is that at the resolution of the available image, full sun coffee and black pepper look similar from above. This can be partially mitigated, when images of blooming coffee are available, allowing for easier discrimination of coffee plantations. The other challenge we met, are the presence of field where coffee and black pepper trees are grown together. The presence of shade trees or black pepper grown on tree further complicate the task. In case of plot mixed with coffee, the coffee label was chosen in order to avoid misclassification from the interpreter in the training sample. The third challenge is the recognition of early-stage coffee or black pepper from the available image as the young systems might look very similar to bareland. More mature coffee and pepper systems at 4-5 year are most recognizable thank to their patterns. The second outcome is the classifier and the land cover map. The classifier has been chosen by splitting the training sample in 80% of the point used for training and 20% for validation. The best performing neural network on the validation sample has been used and has the following confusion matrix:

Reference\Map	1	2	3	4	5	6	7	8
1 Low veg.	40	3	0	2	0	0	3	0
2 Native veg.	1	629	0	0	0	1	3	0
3 Rubber	0	0	252	1	0	0	1	1
4 Seasonal agri.	0	0	3	475	1	0	10	5

5 Urban	0	0	0	0	106	2	2	6
6 Water	0	0	0	3	1	101	0	0
7 Coffee	1	3	0	15	2	3	855	12
8 Pepper	0	1	1	4	2	1	15	377

The overall metric is as follows:
Overall Accuracy: 0.9625, Precision: 0.9566, Recall: 0.9430, F1 Score: 0.9492

It should be noted that those numbers are crude approximation and overestimate the final map accuracy, as the sample are biased toward what the image interpreter was able to recognise and is also not taking into account the percentage area of each class in the final map. In order to properly validate the map, it is recommended to use the method by P. Olofsson et al. (2014), where stratified random sampling is used. While ideally this should be accomplished with people on the ground, it can also be done using high resolution satellite imagery. However, in this pilot, image resolution was limiting the possibility to distinguish between random coffee and black pepper points as explained previously. This mean that proper map validation, will need some groundwork or higher resolution imagery (for example, using drone).
A visual assessment of the map quality shows a good power to discriminate coffee and black pepper from other land cover. However, while hard to quantify without ground assessment, confusion between coffee and black pepper is expected. This could be partially solved by iteratively taking new training points in the confusion area and training new model to generate maps. Another issue worth noting is the tendency of the model to miss-classify pixel at boundary between area respectively growing one and shrinking the other. This is a direct drawback of the method used, as the convolutional neural network receive spatial information and needs to understand that it needs to classify the central pixel. This can be solved by taking many samples on the border of the different area. In the other hand, this drawback is counterbalanced by the advantage of the extra spatial information, which allow the classifier to have context on surrounding pixel and canopy structure allowing them to resolve shaded system.


Đăk Song land cover
Dak Mil District
CAMBODIA
Land cover
Low vegetation
Forest
Rubber plantation
Seasonal agriculture
Urban
Water
Coffee
Black pepper
Gia Nghia District
Dak R'Lap District
0 2.5 5 km
Scale 1:170000
© OpenStreetMap

2. Weather sensitivity of coffee yield

The sensitivities of yield anomalies to weather varied substantially between provinces and districts. In Dak Lak and some districts of Lam Dong, weather explained 25% of the variation in Robusta coffee yield anomalies, while low sensitivities were identified at districts in Dak Nong and Gia Lai. Precipitation and temperature were the most influential weather variables, while solar radiation and water deficit were highly correlated with temperature and precipitation, respectively. The used yield and weather data suggest that Robusta coffee in Vietnam is most sensitive to two key moments: 1) a prolonged rainy season of the previous year favours vegetative growth and increases the potential yield, ii) while low rainfall during bean formation decreases yield (Figure 1). As expected, the model has higher predictive value at higher spatial resolution, i.e. at district level rather than provincial level. Interestingly, coffee yield has become more stable and weather-independent in the last ten years, probably due to management improvements. However, this does not mean that climate change will not have an impact on coffee in the Central Highlands of Vietnam. However, the results need to be interpreted with caution, as the quality of the yield data would need to be further evaluated to make sure that they are useful for informing crop-climate relationships. A more mechanistic understanding of crop x environment x management interactions is required to better understand how coffee is affected by climate and to what degree management can adapt coffee to adverse climatic conditions.

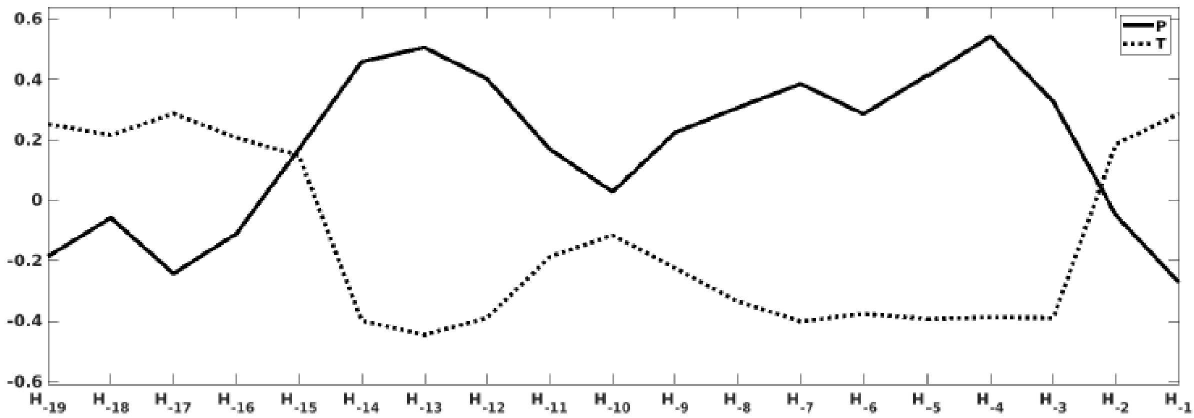


Figure 10. Correlation between the yield anomalies and weather variables (i.e., precipitation (P) and temperature (T)) for Dak Lak province. The x-axis refers to the months before harvest (i.e. H_{-1} being one month before harvest)

3. Agroecological zones

According to the land use map of NIAPP, the areas where coffee and pepper are grown overlap. Therefore, the climatic conditions are similar. Based on the cluster analysis of the climate data extracted from the coffee growing areas of the three provinces (Gia Lai, Dak Lak and Dak Nong), six different ACZ were identified (Figures 2,3). In Gia Lai two zones can be distinguished, both have high annual precipitation and a strong dry season; however, they differ in elevation and therefore temperature. In Dak Lak there are also two zones that mainly differ in elevation and therefore temperature. However, both have low annual precipitation with relatively dry wet and dry season. In Dak Nong, there are three zones, one of which is the same as the one in Dak Lak. They are all at higher elevation with low rainfall during wet season and high rainfall during dry season (except the zone also present in Dak Lak).

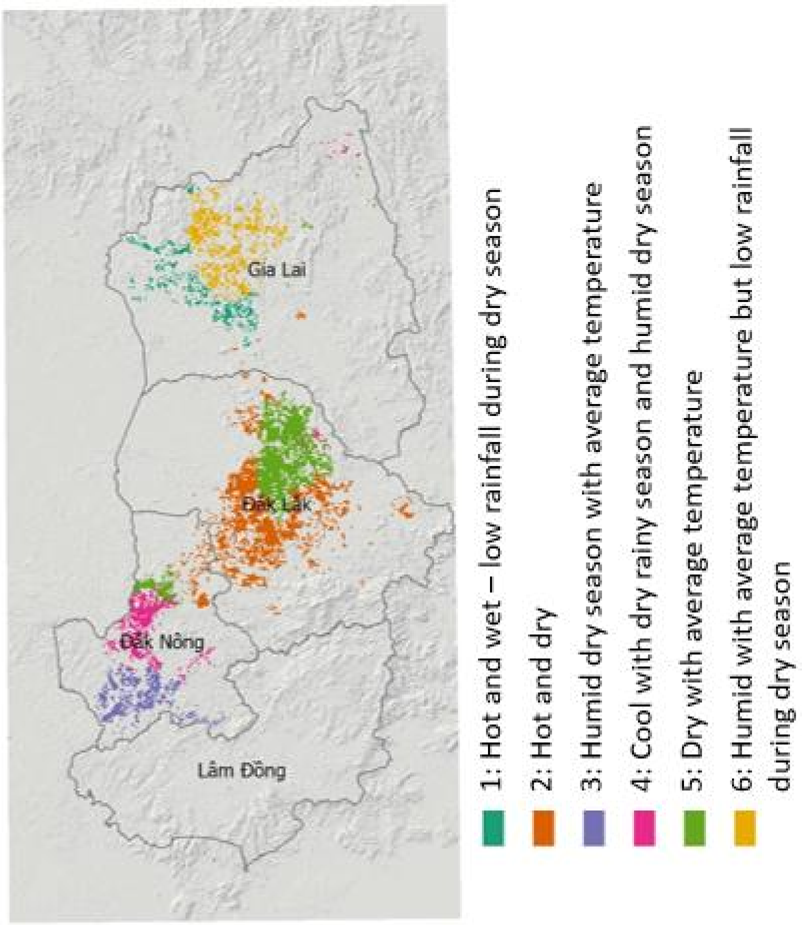


Figure 11. Agroclimatic zones of coffee growing areas in Gia Lai, Dak Lak and Dak Nong.

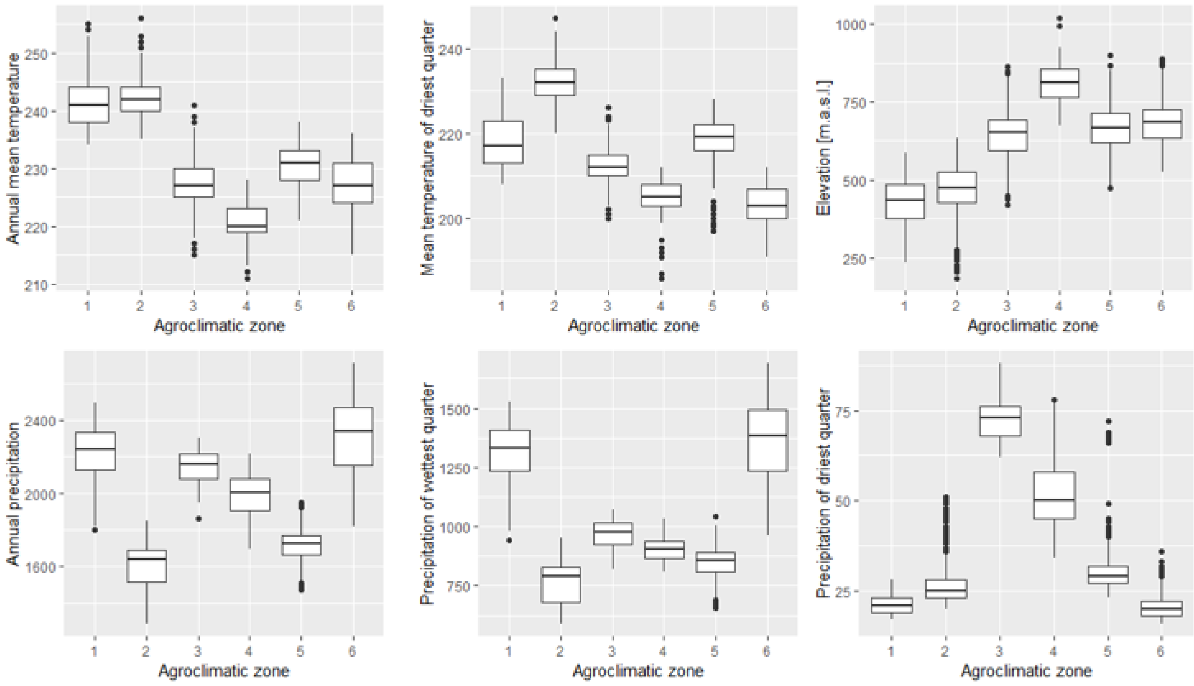


Figure 12. Main differences between agroclimatic zones of coffee growing areas in Gia Lai, Dak Lak and Dak Nong

The big majority of coffee and pepper is grown on Rhodic Ferralsols. Therefore, with this broad scale classification the soil type maps are not very informative with regard to how they influence coffee and pepper production. More detailed information on soil physical, chemical and biological aspects are required in combination with detailed information on management practices.

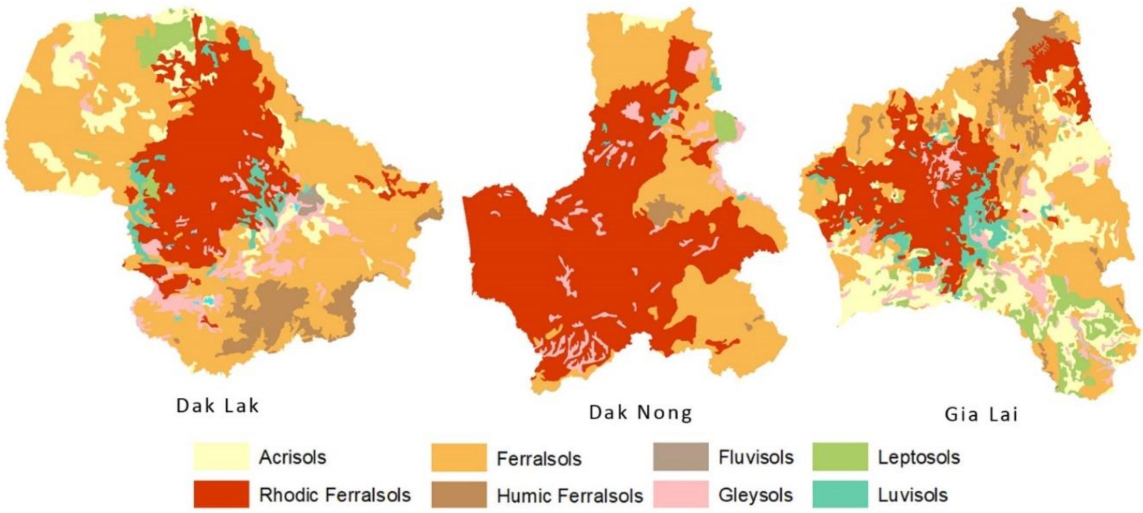


Figure 13. Soil types in the three provinces

3. Nematode incidence

Most coffee farms of the ECOM database have a low incidence of nematodes (0-10%) and are located in the hot and dry area of Dak Lak (Figure 5). No observations are available for ACZ 1 and only few for ACZ 4. Over 50% of the farms in ACZ 6 (High annual precipitation with strong dry season) have no incidence of nematode, while 37% of farms in ACZ 5 (Dry with average temperature), have a nematode incidence of 11-25%.

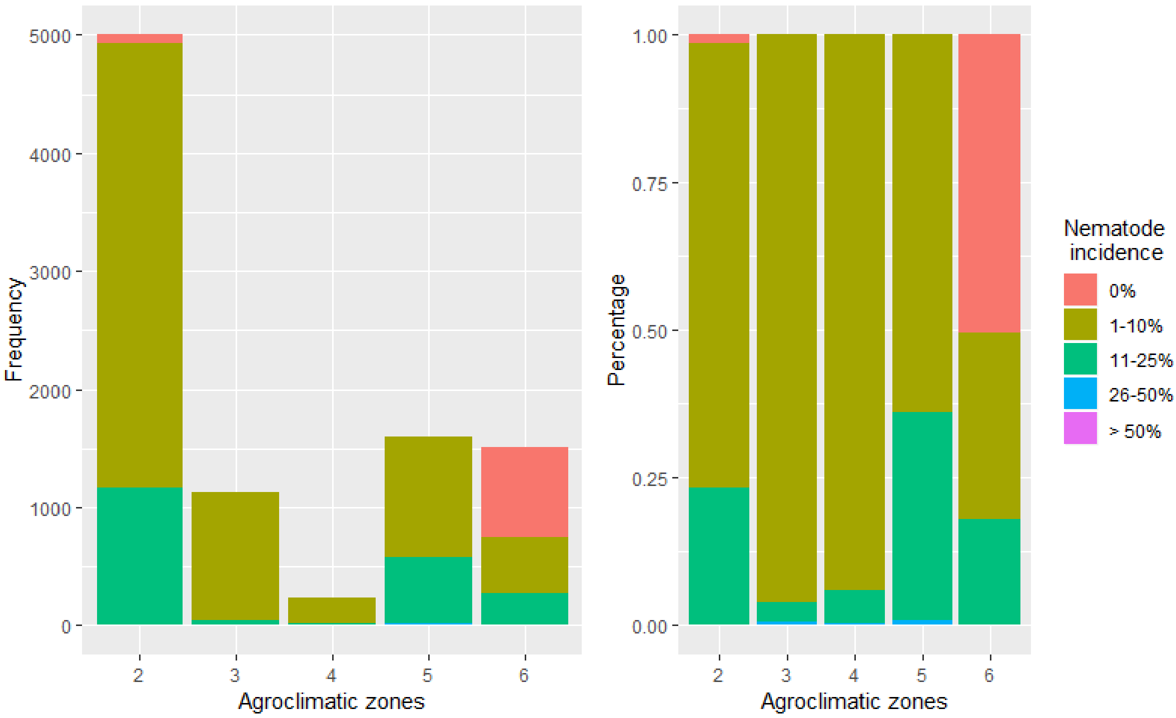


Figure 14. Incidence of nematodes in coffee farms according to agroclimatic zones

There is little available data on the relationship between pests and diseases, soil health, environmental conditions and agronomic management practices. This knowledge and data gap add to the knowledge gaps of other production factors related to Robusta coffee and pepper ecophysiology. Carefully designed research experiments in combination with mechanistic modelling will be needed to improve required knowledge for a more sustainable production of coffee and pepper in the Central Highlands of Vietnam.

7 Impacts

7.1 Scientific impacts – now and in 5 years

Objective 1.

- Coffee plots keep a stable share of land use in the area surveyed and become more diverse with progressive intercropping with cashew and pepper from 2013, pepper is more and more introduced in tree-based plots.
- Pepper is the crop most found in coffee farms, with 32 to 51% of the farms reporting pepper vines in all 3 provinces.
- The relatively low fertilizer inputs reported in pepper farms (230 kg N ha^{-1} yr^{-1}) compared to coffee farms could reflect overall better farming practices. Still, the input rates reflect the fact that Dak Nong and Dak Lak have the highest rates and highest yields, while Gia Lai is slightly less suitable for pepper growing.
- Most farmers perceived environmental change negatively, with 83% thinking that weather, water quality and availability, trees quantity, soil fertility and abundance of animals has been decreasing/worsening compared to 5-10 years ago.

Objective 2.

- A literature review describing what is happening with SBPD affecting black pepper and coffee in Vietnam and how to sort the problem out (directly by bio-control approaches & indirectly through a significant enhancement of soil health). One review paper is under work for a submission to Agriculture, Ecosystems and Environment.
- If black pepper is getting serious problems with *Phytophthora*, there are other pathogenic fungus responsible of damages in the field in Central Highlands such as *Pythium* and *Phytopythium*. This needs to be considered for any further development of strategies for controlling the SBPD affecting black pepper in the future.
- The current market is full of commercial bio-inoculants dedicated to the control of SBPD such as nematodes and pathogenic fungus. However, their effectiveness has not been scientifically proved and our preliminary results show that we may have some serious quality issues with them according to the number of contaminants found in the tested products. For any bio-control strategy based on the utilization of bio-inoculants, it will be important to identify very effective products is there occur and otherwise to develop a good one in collaboration with the private sector considering all the biotechnology requirements for reaching a satisfying quality.

Objective 3.

- The labelled set of GPS coordinates database collected for the land cover mapping will be used to develop future more powerful land cover mapping tools or for other projects needing them. CNN is a novel approach when it comes to land cover mapping. The model developed in this project is already used in other projects and will be documented in scientific publication.

- One research paper was submitted to Agricultural and Forest Meteorology on statistical analysis of the weather impact on Robusta coffee yield in Vietnam.

7.2 Capacity impacts – now and in 5 years

As it is a very short-term project, it is difficult to assess and materialize all these impacts.

7.3 Community impacts – now and in 5 years

7.3.1 Economic impacts

7.3.2 Social impacts

7.3.3 Environmental impacts

7.4 Communication and dissemination activities

8 Conclusions and recommendations

8.1 Conclusions

For Objective 1.

The data collected allowed realizing the importance of inputs reduction to improve sustainability. A more thorough understanding of current management practices for coffee and pepper is still needed to adapt inputs to crop needs and soil health status. This is especially the case for pepper farming systems, where management practices have been much less documented than coffee. In terms of livelihood indicators, information is lacking for both coffee and pepper production systems. Although both systems tend to be more diverse than ten years ago, data does not allow to assess how sustainable this evolution is. More information could be obtained from the private sector, as partnership and trust are building up in the view of long-term potential collaborations. For example, a non-disclosure agreement was signed between McCormick and ICRAF to open up the access of the supplier databases which will allow to better characterize the pepper sector.

Another key aspect is the lack of information at landscape level: production should be targeted to locations that are best suitable. Pepper seems declining in Gia Lai, and the reasons for this should be better understood, to take appropriate action. This involves a need for a better understanding of environmental drivers and issues from the research side. As farmers seem mostly aware of these issues, the grounds are set for a constructive dialogue on sustainability measures.

For Objective 2.

Our analysis of secondary data about coffee plantations in Dak Lak was too preliminary for coming up with strong conclusions as the private sector did not agree to share with us what they have. It could be relevant to collect our own data to ensure about their quality even if this is costly and time consuming. However, our results suggest that the association coffee – black pepper is not accurate because too favourable for nematodes and meanwhile, the intensive management with chemical inputs is also a way to promote SBPD such as nematodes.

Through our investigations in Gai Lai province, it seems that the seedlings of both coffee and black pepper are totally healthy and totally deprived of any SBPD. Indeed, this shall be confirmed by further investigations in nurseries of Dak Lak and Dak Nong Provinces, but it suggests that in most cases, the SBPD are already in the fields and the seedlings do not play any role in spreading the diseases.

Surprisingly, regarding black pepper, it seems that *Phytophthora* is not the main pathogenic fungi damaging the plantations. Obviously, *Pythium* and *Phytopythium* already described in the literature as SBPD of other crops are a serious problem in the black pepper plantations in Central Highlands. It is important to take this into consideration for further developments of any strategies to control the main SBPD affecting the black pepper production in Vietnam.

For Objective 3.

There are already good geospatial data available from NIAPP on land use (including coffee and pepper), soil types and coffee and pepper suitability. However, improvements in terms of accuracy and frequency of map production can be achieved at relatively low cost. The land cover classification method using Sentinel satellite imagery showed a good potential to discriminate between coffee/black pepper from other land use classes. However, to measure the ability and potential to recognise coffee from pepper, more ground and/or higher resolution imagery are needed. In order to show its full potential, the classifier needs to be refined by collecting more ground trothing points using ground survey or higher resolution imagery. This will enable to improve and measure the capacity to separate coffee from black pepper.

Based on the coffee and pepper land use map by NIAPP, we identified 6 agroclimatic zones that are differentiated by climatic variables and elevation. Further research is required to better understand how these agroclimatic zones affect coffee and pepper growth and development. Climate change is increasingly affecting Robusta and pepper production in the Central Highlands. This requires a mechanistic understanding of crop response to long-term climate trends such as increasing temperature and changing precipitation patterns but also climate variability with increasing extremes (e.g. drought). A detailed analysis of how the agroclimatic zones will change based on future climate scenarios and mechanistic crop models can benefit such an analysis and also contribute to identifying relevant plant traits for breeding, agronomic management for adaptation and land use planning for reconciling plot and landscape level sustainability.

8.2 Recommendations

For Objective 1.

Future work on coffee and pepper farming systems improvement in the Central Highlands will need to be based on a solid primary data collection to cover all dimensions of sustainable intensification (productivity, economic, environment, human condition and social domains), which will then allow identifying the relevant techniques and system targeting to ensure positive impact. This is now planned as one of the activities of the large ACIAR Coffee and Pepper proposal.

For Objective 2.

Future investigations on seedlings produced in nurseries shall be undertaken especially in Dak Lak and Dak Nong to confirm or not those we have got in Gai Lai. A certification

Currently on the market, there are commercial bio-inoculants available targeting *Phytophthora* or nematodes. We listed most of them. Our preliminary investigations on their microbial quality suggests the presence of contaminants in most of them. Indeed, their effectiveness for controlling SBPD shall be assessed as well to complete the screening of these bio-inoculants but the quality seems to be an issue.

For Objective 3.

There is little available data on the relationship between pests and diseases, soil health, environmental conditions and agronomic management practices. This knowledge and data gap add to the knowledge gaps of other production factors related to Robusta coffee and pepper ecophysiology. Carefully designed research experiments in combination with mechanistic modelling will be needed to improve required knowledge for a more sustainable production of coffee and pepper in the Central Highlands of Vietnam.

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9.2 List of publications produced by project

Enter text

10 Appendixes

10.1 Appendix 1:

General list of indicators

Scale	Component	Variable
Farm	**Household**	Composition
		Age of hh head
		Education level
		Gender of hh head
		Main activity of hh head
		Ethnicity
		Land ownership status
	Productive assets	Tractor
		Water pump
	Soil	Soil chemics (OM, N,P,K,..)
		SBPD
		Soil physics
		Soil fertility perception
		SWC measures
		Landscape position
	System and Performance	Total income
		Income from coffee
		Income from pepper
		Food security
		Diet diversity
		Land productivity
		Poverty
		Off-farm income
		Agric diversity (number of commodities present on the farm)
		Market orientation (%production sold vs total production at farm level)
		Consumption expenditures (food and non food)
		Savings and loans
	Crops	Area
		Age plantation
		Yields
		Intercropping information
		Variety
		Seed origin and seed system
		Fate
		Nurseries information
		Chemical inputs
		Organic inputs
		Pests and diseases
		Irrigation
		Associate trees management
		Use of residues
		Labour
		GIS information
	Livestock	Herd size
		Production levels
		Breeds
		Fate of the production
		Feed sources
		Labour
		Water use
		Pests and diseases
Community		Communal resources
		Farmer networks
		Trainings, extension, Knowledge sharing/pathways
Value chain	**Market information**	Highest and lowest products prices
		Inputs prices
	Post harvest processing	Quantities
		Labour
		Energy use
		External services
	Actors	Type of actors and numbers
		Contracts
		Quality control
		Standards and grades
		Transport
		Certification
		Services

District targeting

Province/district	Population	GDP per capita (USD)	Poverty index (2018) (% of total households)	EM population (% of population)	Main ethnic groups	Total natural area (ha)	Coffee area (ha) (GSO 2018)	Coffee production (ton) (GSO 2018)	Pepper area (ha) (GSO 2018)	Pepper production (ton) (GSO 2018)	Soil types
Dak Lak	**1,872,574**	**1,779**	**9.1**	**33**	**Ede (52%), Mnong (8%) are the main local indiginous group. Nung (12%), Tay (9%) are the main migrated minority groups.**	**1,303,049**	**203,063**	**478,083**	**37,601**	**77,498**	
*Krong Nang**	*126,562*	*n/a*	*n/a*	*n/a*	*n/a*	*61,460*	*24,419*	*66,786*	*5,313*	*14,344*	***Ferralsols: 16,472 ha*** *Acrisols: 4,898 ha* *Humic Ferralsols: 1,265 ha* *Gleysols: 1,237 ha* *Leptosols: 178 ha* *Luvisols: 119 ha*
Cu Kuin	*101,404*	*n/a*	*n/a*	*n/a*	*Ede is the local indiginous group, 19 migrated ethnic groups. Ethnic minorities accounts for 32% of total population*	*28,830*	*12,744*	*29,696*	*4,873*	*11,746*	***Rhodic Ferralsols: 17,962 ha*** ***Ferralsols: 6,982 ha*** *Gleysols: 3,354* *Luvisols: 620*
Dak Nong	**652,754**	**1,995**	**10.52**	**31**	**Mnong (25%) and Ede (4%) are the main local indiginous groups. Nung (17%), H'mong (16%) and Tay (14%) are the main migrated minority groups**	**650,930**	**129,546**	**280,974**	**34,552**	**19,758**	
*Dak Song**	*80,726*	*n/a*	*n/a*	*n/a*	*n/a*	*80,650*	*23,402*	*54,630*	*15,216*	*8,616*	***Rhodic Ferralsols: 70,363 ha*** ***Ferralsols: 4,391 ha*** *Gleysols: 3,703 ha* *Humic Ferralsols: 2,270 ha*
Gia Lai	**1,520,155**	**2,105**	**10.4**	**46**	**Jarai (65%), Bana (27%) are the main local indiginous groups. Tay (2%) and Nung (2%) are main migrated minority groups.**	**1,551,098**	**89,315**	**222,700**	**16,278**	**51,498**	
*Ia Grai**	*106,090*	*n/a*	*n/a*	*49*	*Jarai (96%) is the main group of ethnic minorities*	*111,959*	*Productive area: 15,812*	*52,915*	*Productive area: 572*	*2,002*	***Rhodic Ferrasols: 61,700 ha*** ***Ferrasols: 40,697 ha*** *Acrisols: 4,425 ha* *Luvisols: 3,177 ha* *Humic Ferralsols: 1,447 ha* *Gleysols: 1,160 ha*
Dak Doa	*123,908*	*n/a*	*n/a*	*58*	*Bana (65%) and Jarai (34%) are the main groups of ethnic minorities*	*98,530*	*Productive area: 19,905*	*45,857*	*Productive area: 2,650*	*10,112*	***Rhodic Ferrasols: 42,226 ha*** ***Ferrasols: 28,509 ha*** *Acrisols: 7,653 ha* *Gleysols: 7,674 ha* *Luvisols: 4,801 ha*

** Currenly targeted*
***Soil types in bold: Most suitable for coffee and pepper*