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Improved Coffee Management by Farmers in State Forest Plantations in Indonesia: An Experimental Platform

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Abstract: The Indonesian state forest managers have accepted farmer-managed coffee agroforestry in their estates as part of their social forestry program. Access by local farming communities to state-owned plantation forestry supports public motivation to maintain forest cover. However, balancing the expectations and needs of forest managers with those of the local farming communities is not easy. Coffee yields in Indonesia are lower than those of neighboring countries, suggesting that there is scope for improvement. Here we describe an experimental research platform developed through an international collaboration between the Universitas Brawijaya (UB), the UK Centre for Ecology and Hydrology (UKCEH), and smallholder coffee farmers to explore options for improving pine-coffee agroforestry systems within existing regulations. Located in a former state-owned pine production forest on the slopes of the stratovolcano, Mount Arjuna, in the Malang Regency of East Java, the research platform has seven instrumented research plots (40×60 m^2), where agronomic practices can be trialed. The aim of the platform is to support the development of sustainable agronomic practices to improve the profitability of coffee agroforestry and thus the livelihood of low-income rural communities. Current trials are focused on improving coffee yields and include pine canopy trimming, fertilizers, and coffee pruning trials, with links to the development of socio-economic and environmental models. Whilst it is too early to assess the full impacts on yields, a survey of farmers demonstrated a positive attitude to canopy pruning, although with some concern over labor cost. The initial ecosystem modelling has highlighted the benefits of coffee agroforestry in balancing environmental and economic benefits. Here we provide a detailed description of the site, the current trials, and the modelling work, with the hope of highlighting opportunities for future collaboration and innovation.

Keywords: agroforestry; social forestry; coffee; pine; UB Forest; tropical forest management

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1. Introduction

Indonesia has an extensive forestry industry producing timber and a range of other forest products such as eucalyptus oil and oleo pine resin. The forests are an important source of income and are directly or indirectly owned and administered by the state under the Ministry of Environment and Forestry (Kementerian Lingkungan Hidup dan Kehutanan). The value of timber (predominately plywood, pulp, and paper) exports alone in 2019 were estimated between 11 and 19 billion US $, making up just under 7% of

Indonesia's total exports based on value [1,2] despite constituting less than 1% of the total timber production, with the rest being used domestically [1]. In addition to timber exports, raw and processed pine resin (rosin) were valued at around 83 million US $ in 2019 [3].

Indonesia's forest industry is founded on large areas of natural and plantation forests, which still covers 49% of the country despite widespread historic deforestation [4]. Around 10.2 million low-income people live in the areas surrounding these forests [4,5], including many who work within the forests in a mix of formal and semi-formal agreements with forest managers [6,7]. In the past these rural communities had limited rights, and relationships with forest managers have been, at times, confrontational [6,8]. However, in response to both internal and external political pressure, in 1989 the Indonesian government launched its first social forestry program, starting an ongoing process to move to more equitable forest governance systems [9,10].

In state pine plantations, as part of the government's social forestry program, local communities have been encouraged to cultivate shade-tolerant coffee under the pine trees as a source of income [6,9]. This is a significant change, as prior to this program forest authorities have been resistant to forest-edge farmers wishing to expand coffee production into existing forests [6]. However, similar agroforestry techniques (combining cash crops with trees) have been utilized in social forestry programs worldwide as a method to accommodate the needs of multiple actors, improve land-use efficiency, reduce deforestation, provide opportunities for environmentally sensitive management, and potentially improve coffee plant resilience to climate change [11–16]. Encouraging pine-coffee agroforestry systems is expected to provide an income to local communities whilst also preventing the illegal practice of removing or damaging plantation trees to facilitate the growth of agricultural crops [9,17]. Challenges in meeting these expectations, however, are to be expected, having been observed in other social forestry programs where aims to empower local communities have proven difficult to achieve [8,18,19]. Such programs have multiple actors with differing goals, priorities, and power over decision making can make the development of effective programs difficult [8,18,19]. In pine-coffee agroforestry systems, forest managers often prioritize the production of forest products and the maintenance of forest cover, potentially leading to sub-optimal conditions for coffee production, and whilst coffee quality can benefit from being grown under shade, farmers may not have the knowledge or resources needed to optimize coffee production. Combined, these factors can make achieving economic coffee yields within an agroforestry system challenging [9,10].

The key agronomic challenges with coffee agroforestry are divided into those related to the management of the trees, for which achieving the optimal balance between tree density and shade level for coffee production is paramount, and those related to the management of the coffee itself, namely fertilizer practices, weeding, pruning and pest control [20–24]. Management of shade levels requires collaboration between farmers and forest managers. Whilst there is interest within state forests to facilitate such collaboration, research into shade management within plantation forests is limited, and even within more traditional shade coffee systems, there is still uncertainty regarding the relationship between shade and coffee productivity [23]. Therefore, there may be understandable reluctance to alter forestry practices without evidence of the potential benefits and risks. Research on optimizing coffee management within shade systems is also somewhat limited, partly due to the worldwide shift to more intensive systems without shade [21,23]. Recent studies in shade and sun systems do suggest, however, that the optimization of nitrogen applications and coffee canopy management through effective pruning are key factors for both yield and economic performance [9,21–23,25]. Coffee pruning and fertilizer practices within Indonesia's state pine plantations, however, remain suboptimal with a need for both tailored agronomic studies that reflect the conditions faced by smallholder farmers and improved knowledge transfer and dialogue between researchers and the community [6,22,24,26]. Ensuring coffee farming is profitable in terms of returns for the invested labor must be a priority. Forests, however, play a role in wider regional and national economic and environmental objectives [27]; thus it is also important that solutions consider environmental sustainability and cultural context [5,8]. This will support safeguarding the long-term survival of the social forestry program and help to maximize the benefits to the community as a whole.

The aim of the University of Brawijaya–UK Centre for Ecology and Hydrology (UB-UKCEH) research platform is to address these challenges. The research platform is located in "UB Forest", a 543 ha former state-owned plantation forest. The platform was created in collaboration with the local farmers and provides facilities for trialing and demonstrating agronomic approaches that optimize pine-coffee agroforestry practices. The platform aims to demonstrate options that can balance the needs of the farming community and forest managers whilst also considering environmental sustainability. Designed as a long-term experimental platform, it is our hope that this platform will be a resource for the wider research community; thus here we describe the platform and outline the current lines of research with the aim of facilitating this engagement. Further, the platform serves as a demonstrator of agronomic innovation to local communities who co-created the experiments within. Whilst the focus of the platform is agronomic practices, it also acts as a hub for research into the wider social and economic aspects of coffee agroforestry, including forest governance, supply chains, and market access.

2. Site Description—UB Forest

The UB-UKCEH research platform is located within UB Forest, which is located in Karangploso, Malang District, East Java, on the slopes of Mount Arjuna. UB Forest was transferred from state ownership to UB in 2016 as a special purpose forest area. The purpose, in this case, was defined as "education". The forest consists predominantly of planted stands of pine (*Pinus merkusii*), a native tree of northern Sumatra that was introduced to Java in the early 1920′s, which were until recently used for resin production [27]. There is also a smaller area of mahogany (*Swietenia mahagoni*), located on the eastern edge, and linear patches of protection forest bordering the steep-sided seasonal streams that drain the forest (Figure 1) (see [28] for sp. list in a protected forest). Under tenancy agreements with the forest managers, smallholder farmers live in small hamlets within the forest boundary (Figure 1). They practice agroforestry in all areas of the forest apart from the areas designated as protected. Crops include vegetables such as taro and chilies, but coffee is the most widespread. Farms within the forest, as in other areas of Java, are relatively small, with individual farmers managing between 0.25–1 ha of land. The transfer of the forest to UB included the transfer of the farmer's tenancy agreements. As a result, the UB Forest Management team acts as landlords for 195 farmers and 58 households spread across three hamlets within the forest: Sumbersari, Sumberwangi, and Bontoro. UB also has some rights to control building and business activities within the forest hamlets, including the development of eco-tourism such as mountain biking routes, although this is subject to approval by government forest authorities.

Whilst the designation of UB Forest as a special purpose 'education' forest means its ownership model is different to forests run by the state forestry company, Perum Perhutani, UB Forest's biophysical characteristics are typical of a state-owned pine forest [27]. Similar to much of the 900,000 ha of *Pinus merkusii* plantations on Java, UB Forest has been established on fertile volcanic soils (Andosol complex with Latosol) in an upland area with a mean elevation of 1122 m. The average rainfall is 2500 mm $yr^{-1,}$ and the average yearly temperature is 27 °C [27]. Located within the pine forest zone as designated by the government [29], the forest is part of a band of state-managed plantation pine forestry encompassing the surrounding chain of volcanos. The site is also deeply drained with a groundwater depth of more than 200 m leading to limited access to surface water. As in state-owned forests, the UB Forest Management team must adhere to local and national forest regulations. There is, however, some flexibility within these regulations to move away from standard practices, which provided a valuable opportunity to collaborate with the local farmers in the development of a research platform to explore innovative solutions to improve the livelihood of the farmers, which, if successful, also have the potential to be implemented within the wider state forestry.

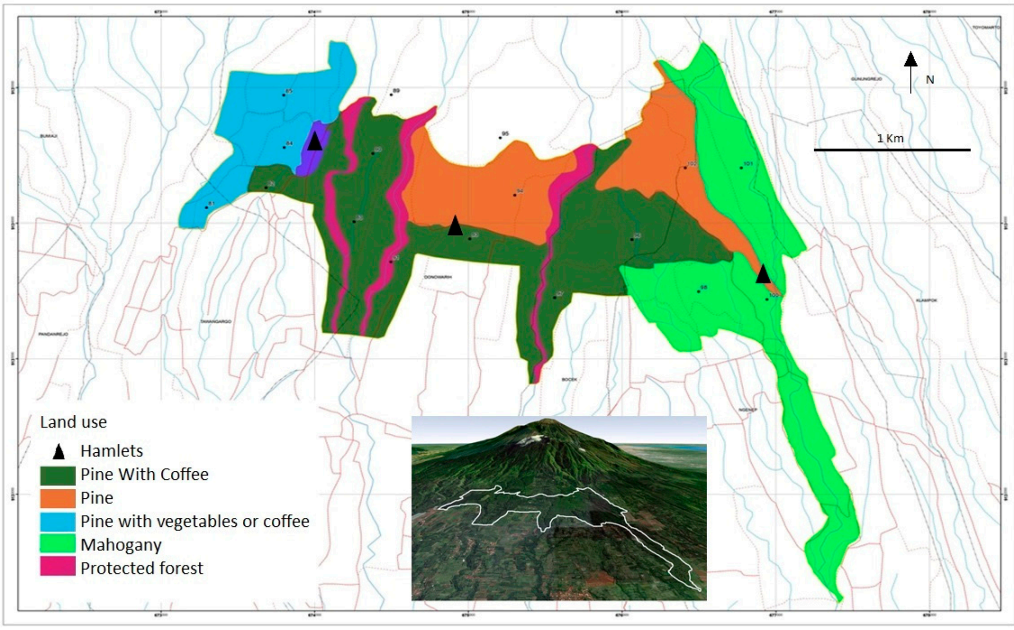

Figure 1. UB Forest area. Map shows the forest types and the location of the hamlets, photo insert shows forest location on the slopes of the volcano Mount Arjuna.

3. The Research Scope

The full scope of the UB-UKCEH collaboration within UB Forest has five work packages encapsulating physical measurements, socio-economics, ecosystem services, and policy dialogue (Figure 2). Here we have focused on presenting our activities around agronomic innovations and the research platform. However, we welcome collaboration on any aspect of the work, and details of the full range of activities can be found on the project website (https://ubforestplatform.ceh.ac.uk/ (accessed on 28 March 2022)).

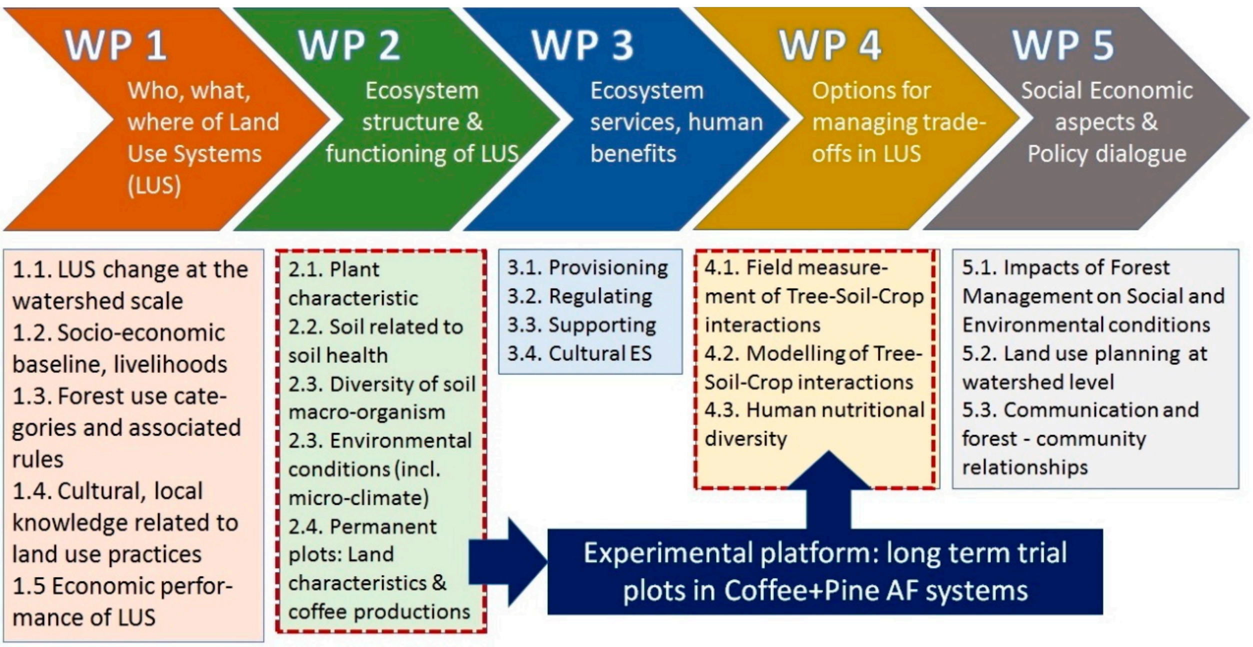

Figure 2. Project overview showing how the physical research platform supports, and is integrated, within the wider UB research on land use systems (LUS) and ecosystem services (ES) and the overall project objective to support sustainable and equitable pine-coffee agroforestry management.

4. The Research Platform Design

In order to enable the testing of agronomic innovation a research platform was created, consisting of a suite of four permanent experimental plots which were established in collaboration with smallholder farmers [30,31]. Locating areas of consistent management was challenging due to the combination of the diversity of farming practices, the small size of individual farms, and the requirement to have relatively large blocks within these plots (40 m × 60 m) to facilitate the scope of planned experiments. Therefore, rather than looking for replicate blocks, plots were selected to span the gradient of coffee management intensity and pine canopy density present within the forest. The plots spread across the western section of the forest between 100 m and >500 m apart. Whilst this does result in the absence of plot-level replication (with only one plot within each management intensity), it does allow agronomic solutions to be tested across a range of conditions, providing insight into the effectiveness of any agronomic innovation under the full scope of conditions expected within commercial forests. In addition, whilst the plots are still within a single forest area, this design avoids aspects of pseudo-replication that would be present with replicated plots with consistent management.

4.1. Management and Shade Intensity

Three of the four permanent experimental plots are located within relatively young 19 year old pine stands and the highest pine canopy density. Thinning of the pine trees is yet to be conducted in these areas with tree spacing of 3 m × 2 m and shade levels 30–40% higher than those considered optimal for shade-grown coffee [21,32]. These plots also span a range of coffee management intensity (low, medium, high). The low management coffee (LC) plot has low-density unpruned coffee, with an absence of fertilization and weeding. The medium management coffee plot (MC) also has no weed control, fertilizer has only been applied at the time of planting, and pruning is restricted to just the initial formation pruning (tree shaping) conducted when the coffee is approximately two years old. The higher management coffee plot (HC) has a higher density of coffee plants, and in addition to the formation pruning at 2 years, minimal maintenance pruning has been conducted with the removal of non-fruiting stems (stems growing upright from the main coffee stem). Fertilizer is applied once a year in the HC plot, and manual weed control is conducted around the coffee plants.

The fourth plot is located in an older 42 year old pine stand, where past thinning of the pine trees has increased the tree spacing to 6 m × 2 m, resulting in conditions more favorable to coffee production. Coffee management intensity is high within this plot, with a high density of coffee plants that are regularly pruned following industry advice, with fertilizers applied twice a year and regular manual weed control. This plot acts as an exemplar, representing the best current combination of growing conditions and management for coffee production in UB Forest. It provides a benchmark to which we can compare the success of management interventions in our more challenging younger stands. Although it is important to note that whilst this plot represents current best management practice (BMP), there is still scope for improvement.

4.2. Canopy Thinning

Shade was identified by the farmers as the primary constraint on coffee yields in the younger denser stands. In order to address this, a trial of pine canopy thinning was incorporated into the design of the platform. The trial consisted of the removal of the lower pine branches to a height of 12 m with the aim of increasing light levels whilst maintaining tree density as required by the forest managers. In order to facilitate this within the design, the plots within the younger stands (LC, MC, and HC) were split into two adjacent blocks, each measuring 60 m × 40 m with a 10 m buffer between the two, with canopy thinning conducted on one randomly selected block of each pair (Figure 3). These blocks are only intended to be used to explore the impact of canopy thinning and interactions with additional agronomic interventions. As such, the blocks within a plot will not be treated as independent replicates, rather they will only be included within mixed random effect modelling or similar procedures where their nesting within the plots can be accounted for. Canopy thinning was not required in the BMP plot. Thus, this plot consisted of a single block measuring 60 m × 40 m (Figure 3).

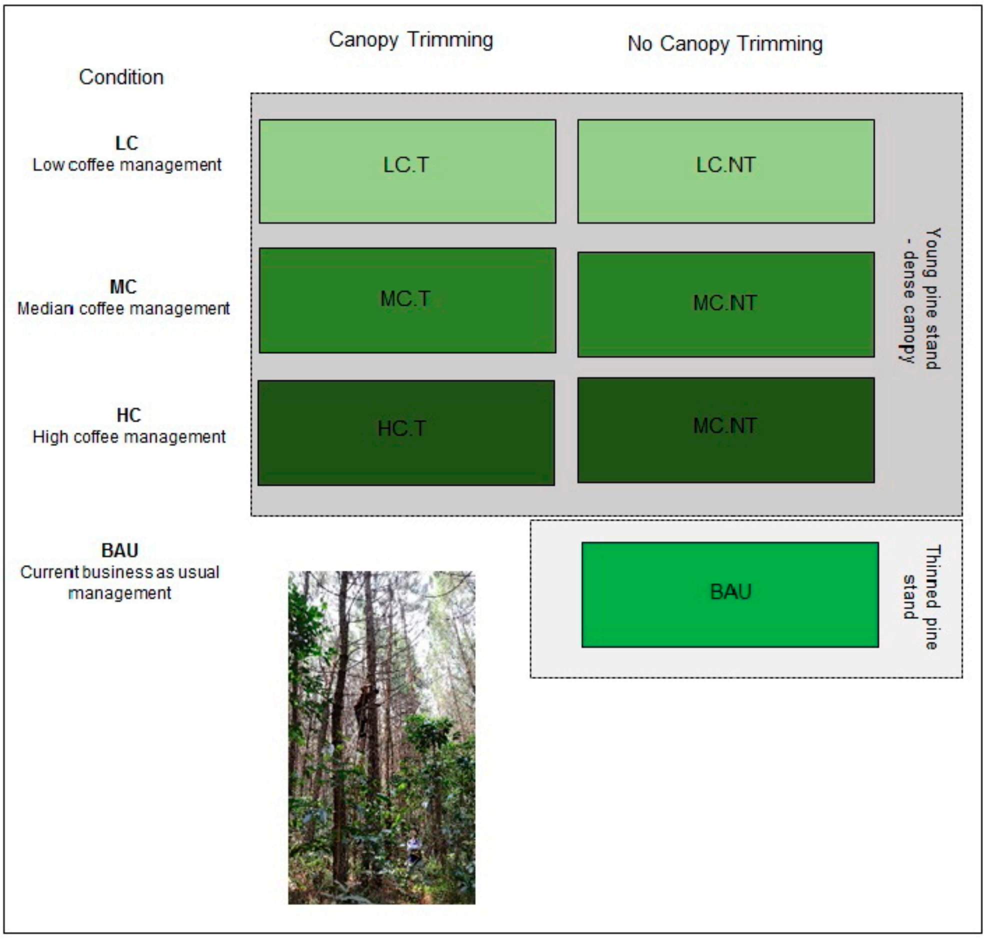

Figure 3. Experimental platform. Consists of four plots spanning the range of coffee management intensities present within the forest (see text for details). The LC, MC and HC are divided into two blocks (with a small 10 m buffer between the two halves) to allow for pairwise comparison of pine tree canopy trimming. Pine tree canopy trimming was started in late February 2019 and completed in May in 2019. Plots are located across the western section of the forest with a minimum of 100 m between each plot.

The large size of the individual blocks allows sufficient area to host nested experiments of additional agronomic interventions, such as fertilizer trials. The longevity of the plots has also been considered, with blocks divided into a 10 m × 10 m grid and activities requiring destructive sampling being restricted to the outer 10 m, leaving a central core area where non-destructive activities are conducted. In all cases, plots were selected and marked out in collaboration with the local farmers.

5. Plot Characterization

By reflecting on the multi-year lifetime of both coffee and pine trees, the platform is designed to facilitate long-term studies, with considerable effort being placed on obtaining baseline data and detailed characterization of the site. Each plot has been divided into 10 × 10 m grid squares; the location, stem diameter (DBH), and condition of every pine tree and coffee plant within the blocks are recorded, and a permanent, unique label is attached. Canopy cover before and after trimming has been recorded using the phone application, CanopyApp (University of New Hampshire), along with measurements of the amount of branch material removed. Soils have been characterized with measurements of bulk density, soil C content, and pH. Measurements of coffee flowering, bean set, and yields have commenced and will be conducted yearly [31]. Litter depth and mass have also been recorded together with understory plant diversity and cover [33].

In order to monitor the impacts of the canopy trimming and provide valuable data to support future experimental and modelling activities, microclimate data loggers, together with a range of measurement protocols, are being used on a discrete and continuous basis to record the condition. Microclimate data loggers consist of (per block); three air temperature and humidity sensors (Lascar EL-USB-2) located with solar shields at the height of 1 m, five light sensors (HOBO MX2202) located both above and below the coffee canopy (at ~2 m and 0.20 m above ground level respectively), five soil temperature sensors (HOBO MX2201) installed at a depth of 5 cm, and three soil moisture sensors installed at an approximately 45 degree angle covering depth range of 5–10 cm (Odyssey Soil Moisture Loggers). These were positioned randomly within the central area of each experimental block and recorded a measurement every hour. Such microclimate loggers have been used successfully in other studies to help understand how shading can influence coffee plant growth structure, yields, and abiotic conditions, and we expect they will enable similar insights within the platform [14,15]. Changes related to carbon cycling and coffee yield are being monitored through measurements of litter fall, quality and turnover (litter bags), root turnover (litter bags and mini-rhizotron), yearly coffee yield, and yield metrics including flowering density, bean set, bean size, and weight [30] (Figure 4). The prevalence of coffee fungal disease, insect pests, and insect damage are being recorded, along with natural predator diversity and abundance. Measurements related to soil health taken during the plot characterization will be repeated (soil C stocks, bulk density, and pH).

Figure 4. Examples of measurements being conducted within UB Forest. (**a**) Solar shield containing a combined temperature and humidity sensor/logger being attached to a pine tree trunk. (**b**) Ground level light sensor being deployed. (**c**) Litter trap, utilised in measuring and modelling of carbon cycling in the forest. (**d**) Litter bag experiment being deployed to explore decomposition rates.

Assessment of Socio-Economic and Environmental Impacts

Socio-economic and environmental factors related to the canopy trimming trial and wider coffee agronomy are being explored. Key drivers for this work are to support the integration of the research findings into policy and to aid the adoption of new practices by smallholders. Policymakers need to understand the environmental implications of land management changes, especially in relation to impacts on watershed management or low carbon growth, where these stakeholders have a regulatory role [27,34,35]. Whilst for smallholders, it is critical that we both correctly identify agronomic challenges and ensure that the solutions derived from the research area can be effectively implemented by individuals. In order to support policy integration, agronomic trials are being used for the parameterization of a suite of models, including WaNuLCAS, CAF2014, and InVEST [36–38]. These models enable the exploration of future management scenarios providing insights on the likely impacts on yield, water, carbon, and nutrient dynamics, thus helping to support decision-making. The output of these models is also being incorporated in an assessment of the net present value (NPV) of the farming system, allowing the economic assessments of options to support decision-making. A survey has also been conducted on farmers' current practices and their willingness to undertake canopy trimming [6]. This work has incorporated studies on ground flora diversity, assessing both the presence of any species of conversation concern and any naturally occurring species with potential commercial or cultural value [33]. Earthworm abundance and diversity are also being assessed, reflecting the ties between the social and environmental aspects of forestry management. This work is not only looking at the impacts of management on earthworm-meditated aspects of soil health but also explores the farmers' understanding of the role of earthworms within the forest ecosystem.

6. Initial Results

6.1. Plot Characteristics

The characterization of the plots in the research platform broadly confirms the pattern expected based on the management gradient. Coffee plant density is highest in the HC and BMP plots, and mean tree density is lowest in the BMP plot reflecting the past thinning (Figure 5, Table 1). The differences in coffee pruning are reflected in the coffee plant mean diameter at breast height (DBH). The MC plot has the highest coffee mean DBH (Figure 5, Table 1). Here, formation pruning was conducted but was not followed with maintenance pruning (removal of additional stems), resulting in a greater number of stems per plant and a higher DBH (DBH is calculated on the sum of all stems per plant). In contrast, regular maintenance pruning in the HC plot has resulted in plants with fewer stems (2–3) per plant and a lower DBH (Table 1). Interestingly the LC plot has a similar DBH to the HC plot, but in this case, the absence of formation pruning has resulted in tall coffee plants with a single dominant stem rather than the industry standard of plants with 2–3 stems.

6.2. Canopy Density and Canopy Thinning

Tree density is higher in the LC plot than in the other plots; this is the result of higher tree density in the block randomly selected not to undergo canopy thinning (Table 1). Although, this higher density did not confer a greater percentage of canopy cover. Interestingly, despite farmers' impression, canopy cover is similar between the BMP and LC plot, possibly because whilst there are fewer trees within the BMP plot, they are, on average, larger (see mean DBH, Table 1). In all plots, however, canopy cover is well above the level of 30% recommended to achieve the best balance between coffee yield and quality [21]. Post-trimming canopy measurements are currently preliminary as they are based on one measurement per grid as opposed to the five taken pre-trimming. These will be completed once COVID-19 restrictions allow. However, these early results suggest that the canopy thinning has made the canopy cover closer to the optimal 30%. It is also clear from the initial measurements of coffee yield, taken before any impact of canopy trimming, that, as expected, yields are lowest in the LC plot and highest in the BMP plot [31].

Table 1. Summary of key plot characteristics measurements and comparison of plot level differences using one way Anova and Tukey post hoc testing of significant main effect. Same superscript letters indicates no significant difference in comparison of plot level values. Means are based on a per grid value (n = 24) and excludes MC trimmed plot grids D1–6 and C6. Post-trimming canopy cover percentage cover values are preliminary as they are based on one measurement per grid in contrast to the 5 measurements per grid taken pre-trimming.

Plot/Blocks	Soil % C		Mean No. Pine Per Grid (100 m^2)	Mean No. Coffee Per Grid (100 m^2)	Mean Pine DBH (cm)	Mean Coffee DBH * (cm)	Canopy Cover %		Mean Coffee Yield Per Plants (g)
	0–20 cm	20–40 cm					Pre-Trimming	Preliminary Post-Trimming	
LC			8.12 ± 2.2^{a}	14.7 ± 4.7^{a}	22.1 ± 2.0^{a}	2.6 ± 0.4^{a}	66.9 ± 4.8^{a}		831.56
LC -NT	6.67	4.41	9.0 ± 2.2	15.9 ± 3.9	21.5 ± 1.3	2.5 ± 0.4	67.0 ± 4.2		
LC-T	6.05	4.41	7.2 ± 1.9	13.6 ± 5.1	22.8 ± 2.5	2.6 ± 0.4	66.8 ± 5.4	47.8 ± 4.1^{a}	
MC			6.9 ± 2.3^{b}	15.1 ± 4.5^{a}	22.4 ± 3.0^{a}	3.5 ± 0.6^{b}	70.2 ± 6.7^{b}		1460.26
MC-NT	7.19	4.72	6.7 ± 2.5	15.7 ± 3.8	22.6 ± 2.4	3.9 ± 0.5	67.0 ± 5.5		
MC -T	6.71	4.05	7.3 ± 2.0	14.3 ± 5.3	22.1 ± 3.6	3.0 ± 0.5	74.6 ± 5.6	41.0 ± 5.93^{b}	
HC			6.6 ± 2.0^{b}	24.6 ± 7.9^{b}	24.1 ± 2.1^{b}	3.0 ± 0.6^{c}	71.6 ± 5.9^{b}		1804.31
HC- NT	6.45	3.97	7.0 ± 2.0	26.7 ± 8.2	23.8 ± 1.7	2.8 ± 0.5	73.7 ± 3.5		
HC- T	6.57	3.95	6.8 ± 1.9	22.5 ± 7.1	24.3 ± 2.4	3.1 ± 0.6	69.6 ± 7.0	40.4 ± 4^{b}	
BMP	6.53	4.24	3.8 ± 2.1^{c}	24.5 ± 6.8^{b}	31.0 ± 3.3^{c}	2.4 ± 0.5^{a}	64.1 ± 5.3^{a}		3473.39
ANOVA Comparison of plots			$F_{3,158} = 21.6$ $p = <0.001$	$F_{3,158} = 33.43$ $p = <0.001$	$F_{3,156} = 73.91$ $p = <0.001$	$F_{3,158} = 33.76$ $p = <0.001$	$F_{3,158} = 11.79$ $p = <0.001$	$F_{3,63} = 16.48$ $p = <0.001$	For details see [18]

* Where individual coffee plants have multiple stems these are cumulative values, calculated by summing the area of all stems and converting to a single DBH value.

6.3. Microclimate

Data from the microclimate loggers have already shown a pattern for higher humidity in the trimmed plot. The cause of this is now being investigated, with consideration being given to potential changes in the coffee evapotranspiration rates and canopy interception by the pine trees (Figures 6 and 7). These data are also being used together with the biophysical data on tree and coffee density and soil metrics as inputs into the modelling activities.

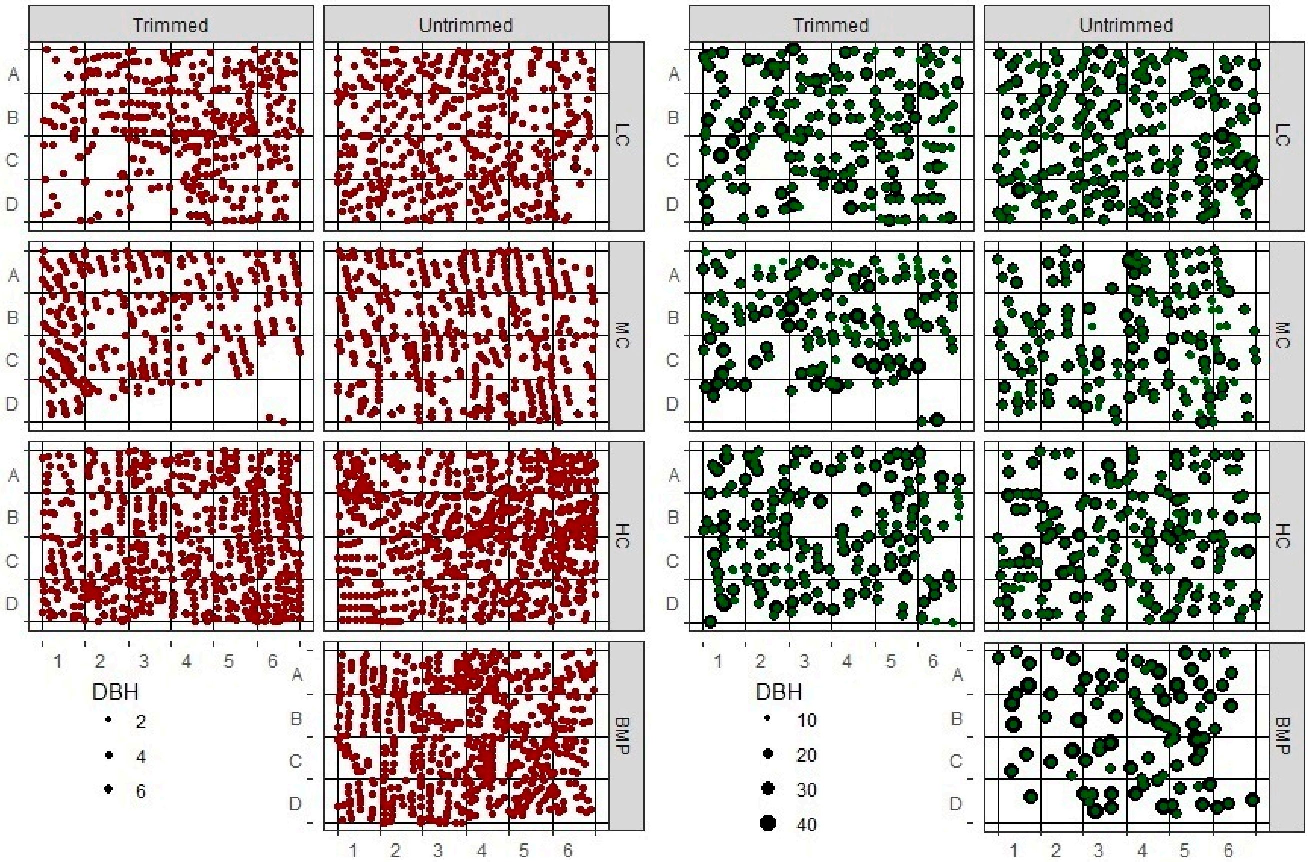

Figure 5. Location and size of all coffee plants and pine trees within the plots. The area of low plant density in MC trimmed plots located in grids D2–D6 and C6 is due to the presence of a small seasonal stream. Whilst this area is still shaded by the surrounding trees it has been excluded from subsequent experiments and statistical analysis of baseline metrics.

6.4. Socio-Economic and Environmental Impacts

Our study of farmers' perceptions of the canopy trimming experiment showed that whilst the farmers were generally positive about the benefits of canopy trimming, they would require support to cover the initial labor costs if they were to undertake this activity [6]. The survey of ground flora diversity identified a number of ferns with ornamental (*Davallia denticulata, Histiopteris incisa, Marattia sambucina*), culinary (edible fern *Diplazium esculentum*), and cultural uses (*Adiantum flabellulatum* L., used in traditional Chinese medicine) which could be explored as additional income streams in future work [33]. NPV modelling work is still ongoing, but parameterization of InVEST models has been completed. These models have been used to explore landscape-scale impacts on ecosystem service delivery [39]. Comparisons were made between a range of alternative land uses (annual root crop, full-sun coffee, coffee-pine agroforestry, pine plantation without crops, and natural forest) and the impacts modelled based on converting the government designated plantation zone across four catchments of the Upper Brantas watershed (encompassing UB Forest and the surrounding state owned forest areas). The modelling showed that pine-coffee agroforestry provides a middle ground, balancing negative impacts on ecosystem services whilst maintaining crop production [39] (Figure 8).

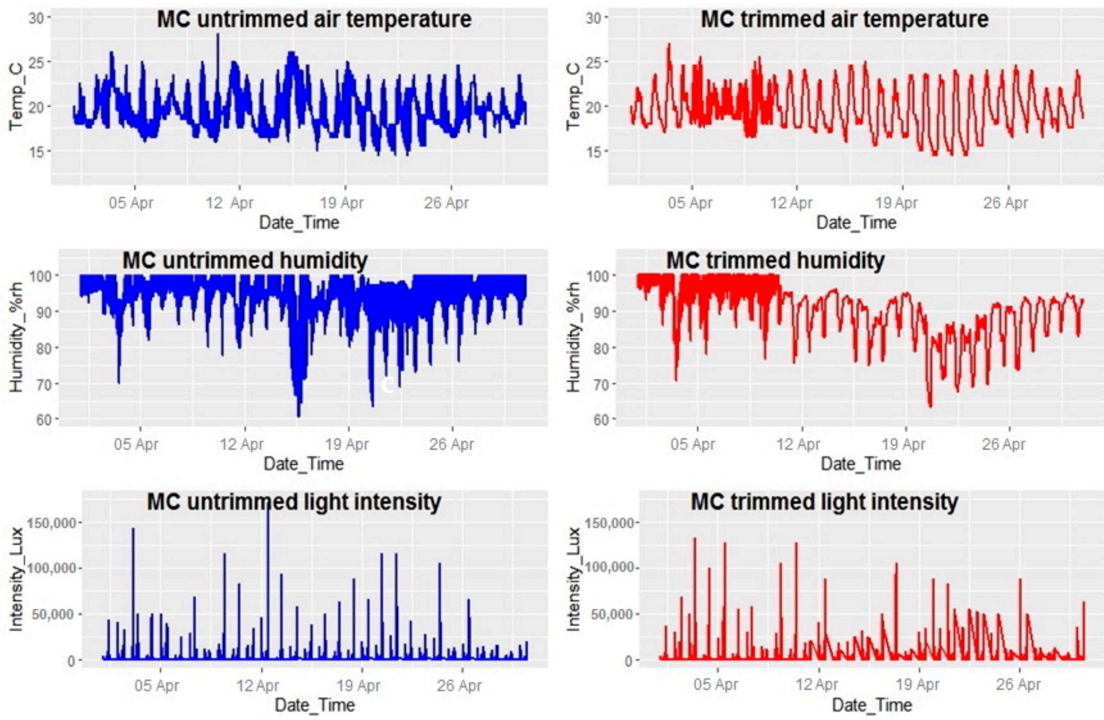

Figure 6. Example datasets collected from air temperature, humidity and light level sensors during April 2021 from the MC trimmed and untrimmed plots, showing daily cycle of all 3 parameters. In each treatment block there are 3 air temperature and humidity sensors, 5 light sensors, 5 soil temperature sensors, and 3 soil moisture sensors positioned randomly within the central area of each plot (excluding the outer 10 m buffer zone). These record a measurement every hour.

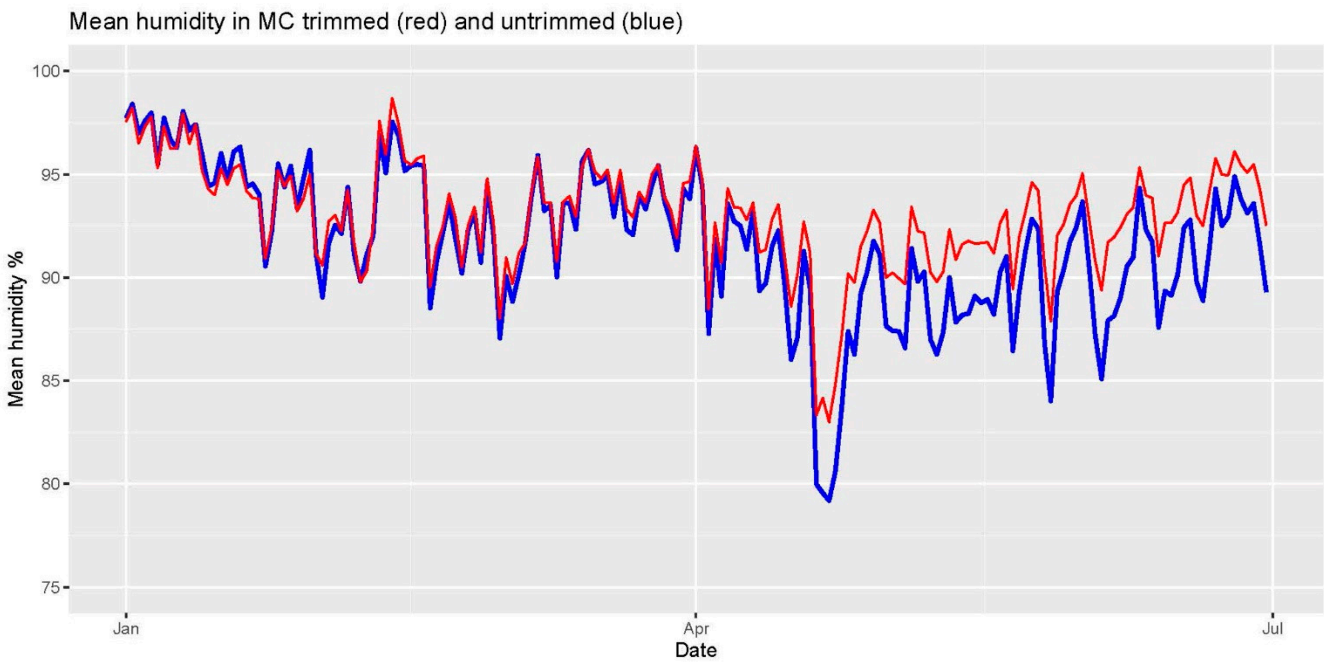

Figure 7. Daily mean humidity levels in trimmed and untrimmed pine plots in MC management plots from January to June 2021, showing a trend for a reduction in humidity as the area transitions from the wet (mid November–late April) to the dry season (late April–mid November).

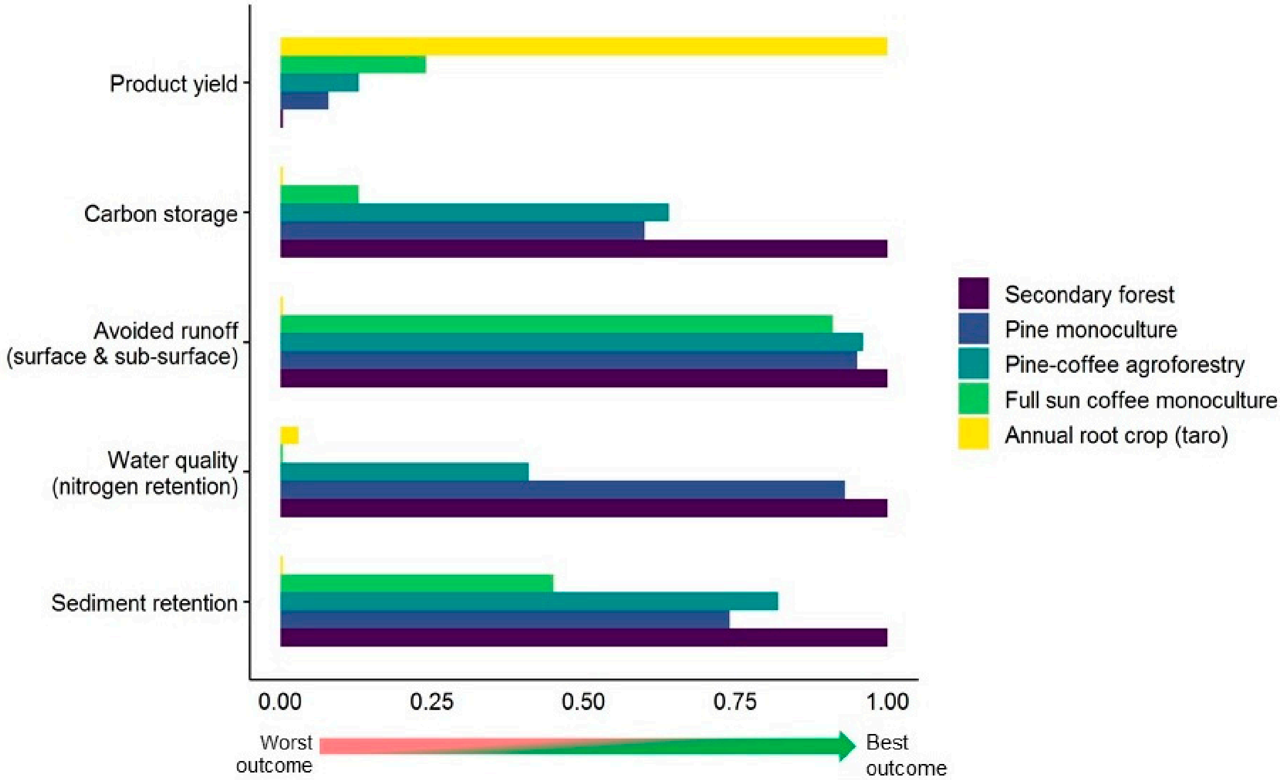

Figure 8. InVEST models of carbon storage, nitrogen retention, sediment retention and water yield were run for five different land use scenarios. Yield of crop or product was calculated separately using locally or regionally sourced data. Timber yield was not considered as a product as smallholders do not benefit from its sale. Results were normalized using minimum-maximum scaling to aid comparison between scenarios; the best performing scenario is scaled to 1 and the worst performing scenario is scaled to 0.

7. Current Agronomic Trials

In addition to the long-term canopy trimming, the platform is designed to be capable of hosting a range of smaller scale agronomic trials; currently, this includes trials on coffee pruning and fertilization. Details of these trials are below as examples of the type of trials that the platform can host.

7.1. Coffee Pruning

The regular pruning of the canopy of coffee trees is a well-accepted essential activity to maximize yields, practiced in all coffee-growing regions [21,24]. However, coffee canopy management is highly variable across the forest, reflecting the limitation in farmers' technical knowledge and their level of motivation to conduct pruning under high shade conditions. This absence of adequate coffee pruning has also been reported in other state managed forests [9] and in the non-shade coffee farms of North Sumatra [21], with lack of knowledge being the primary cause. In UB Forest, the absence of pruning has, in some cases, resulted in very tall coffee plants with a limited number of lateral fruit bearing branches. Therefore, to address this constraint on yield, remedial coffee pruning is being evaluated within the LC and MC plots. In January 2021 coffee plants in both the trimmed and untrimmed treatments had been cut down to a height of 50 cm (Figure 9) above the ground. This approach followed earlier trials of pruning methods and discussions with farmers. However, in two 10 m × 10 m grids per block, the coffee plants have been maintained as untrimmed, allowing exploration and practical demonstration of the individual and combined effects of coffee pruning and canopy trimming on coffee yield.

Figure 9. Photos showing pruning of overgrown coffee plants and measurements being taken of the regrowth following pruning.

Regrowth is now present on the pruned coffee plants (Figure 9). Once branches have elongated, all but the two strongest branches will be removed, with subsequent formation pruning conducted to develop two vertical stems and a high density of lateral fruit bearing branches. This follows well-developed and widely implemented pruning guidelines where selected plagiotropic and orthotropic stems are removed to increase yield [21,24]. The precise method applied in this case is based on that described by Dufour et al., [21]. This formation pruning also reflects the methods conducted within the BMP plot, where a higher level of farmer knowledge has resulted in greater levels of management. The expectation, based on the results reported by Dufour et al., [21], is that the pruning will result in increased yields, and in the long-term, this is something that will be quantified. This pruning method, however, does result in the coffee plants bearing no or very limited fruit for 2 years. This has clear financial implications for the farmers; thus the conditions that would need to be in place for farmers to be willing and able to apply remedial pruning across UB Forest, and more widely within state forests where this is also an issue, is being explored through interviews and discussions with relevant stakeholders. This highlights the purpose of the platform as a demonstrator of innovations that could be adopted by smallholder farmers.

7.2. Fertilizer Trial

Coffee yields are positively associated with fertilizer applications; however, fertilizers are also a major cost for smallholders and a source of potential environmental pollution [18–21]. Fertilizer applications are a key metric controlling the economic performance of coffee production [21,23], yet there is evidence that fertilizer application to pine-coffee systems in Indonesia is sub-optimal and may be excessive [24]. In order to support the optimization of applications, fertilizer trials have been initiated within the UB forest platform to explore variation in both the dose and type (inorganic and organic) of fertilizer. Whilst there is a belief that coffee grown on naturally high carbon Andisol soils, such as in UB Forest and other plantation forests, will not benefit from organic fertilizers, trials of organic fertilizer in non-shade coffee systems have shown a yield increase of 33% [26]. It is theorized that this yield response is due to increased P availability. Research on agricultural soil shows organic fertilizers can increase P availability in Andosol soils, where P is often bounded and immobile, although the mechanism is not clear [40,41].

The UB Forest fertilizer trial aims to optimize fertilization practices in UB Forest, balancing the cost of fertilizers with the relative impact on yields. It will span both canopy trimmed and un-trimmed plots. This multi-year study will explore the cost-yield ratio of using three different fertilizers: inorganic, organic, and a mix, to supply three different rates of nutrient applications. These are the current rates used by the farmers, the industry standard, and a bespoke rate based on measurements of nutrient export (Figure 10). Whilst the primary aim is to optimize fertilization practices in UB Forest, this work will also incorporate measurements of the impacts on soil carbon and nitrogen dynamics, and consider the wider environmental impacts.

Figure 10. Layout of fertilizer trial. The letter gives the fertilizer type, O = organic, I = inorganic, M = 50:50 organic-inorganic mix based on nutrient levels. The number gives the dose rate, 1 = current farmer application rate (157 g of urea, 59 g of SP-36 {Superphosphate fertilizer}, and 42 g of potassium chloride {KCl} per coffee plant per year), 2 = recommended doses from the International Coffee and Cacao Research Institute (300 g urea, 160 g of SP-36, 200 g KCl, and 100 g Kieserite {$MgS0_4$} per coffee plant per year), 3 = dose based on replacing nutrient export through harvesting (140 g urea, 72 g of SP-36, and 157 g of KCl per coffee plant per year). Within each plot (trimmed and untrimmed) there are a total of 36, 5 × 5 m trial plots, with four replicates of each dose and fertilizer combination within 4 20 × 20 m^2 blocks.

8. Discussion

Within the UB Forest research platform we are currently exploring three of the key agronomic challenges for pine-coffee agroforestry within Java plantation forests; shade, fertilizer optimization, and coffee pruning, both in isolation and in combination [6,9,21,23,24,26]. This work is strengthened by the holistic approach with studies on agronomic factors supported by research and modelling work on the socio-economic and environmental implications of pine-coffee agroforestry management.

The trials are long term, and it will take several years until we are able to fully assess the combined impacts of the changes in management on coffee yields and the economic, environmental, and social consequences. The coffee plants will need to recover from pruning, and even unpruned coffee plants will take time to respond to the changes in shade levels and fertilizer applications (with a minimum of 6 months from the formation of new flower buds to harvest). Early outcomes for the work have, however, been published [6,30,31,33,39]. We envision that this work will enable us to provide scientifically robust and practical advice regarding the management of pine-coffee systems, combining work from the trials, modelling, and socio-economic research. In order to facilitate the translation of our results into changes in practice, we are working closely with individual farmers and farmer groups within the forest. This includes holding regular "farmer days" within the forest where researchers and the community come together to share findings and challenges, and to agree jointly on research priorities. Wider engagement is also being achieved through regular contact and hosted forest visits with local to national officials, including the Ministry of Environment and Forestry. A weakness with our current approach is the lack of replication of the forest platform outside of UB Forest. This limits, to a degree, the strength of our statistical approach and our understanding of the potential applicability of our solutions to other areas within Indonesia and internationally. To counter this, we seek collaboration with researchers working within comparable agroforestry systems, especially in areas with contrasting social, economic, and biophysical conditions. As has been proposed for natural forests, whilst challenging, developing a network of long-term sites could provide valuable insights [42].

One area where our work may have more immediate applications to areas outside of UB Forest is modelling. Data from the plot characterization have allowed, for the first time, the WaNuLCAS, CAF2014, and INVEST models to represent pine-coffee agroforestry systems. In the case of WaNuLCAS, this has involved the development of a new pine library (collection of parameters used to drive the modelling process), allowing the model to incorporate pine forestry and improvements to the representation of coffee fruiting through detailed measurement of the position of flowers and fruits on the coffee branches. Similar work on the INVEST and CAF2014models has or will allow the modelling of pine-coffee agroforestry systems for the first time. This lays the groundwork for these models to be utilized in other pine agroforestry systems both within Indonesia and in other regions. Crucially this will, together with our microclimate measurements, support researchers' ability to predict and help mitigate the impact of climate change on smallholder coffee farms, the necessity of which is becoming more urgent with concerns over the intensification of the El Niño-Southern Oscillation [16,43]

Future Opportunities

There is considerable scope to increase the number and complexity of studies within the forest platform and to broaden the work across additional sites. The trials currently being undertaken are the first steps in this, but we fully expect the work to develop. Learning from the initial fertilizer trials is, for example, expected to form the basis of an ongoing process to refine and optimize fertilizer applications within the forest system, helping to support the wider understanding of nutrient cycling with Andosols soils [40,41]. Whilst the coffee pruning work, which already closely matches the approach by Dufour et al., [21], can be linked to the work on pest and disease and microclimate data to provide additional insight into the relative role of pruning and microclimate management on pest and disease occurrence purposed by Dufour et al. [21]. We welcome any collaboration either related to the current trials or requests for new avenues of research related to any aspect of pine-coffee agroforestry.

9. Conclusions

In many countries agroforestry systems provide an attractive option to support rural development, reducing pressure on land by allowing multiple uses in a single area and helping protect natural and plantation forests. Delivering effective agroforestry systems that support wider social forestry programs is, however, not straightforward. The UB Forest research platform seeks to support pine-coffee social agroforestry programs in Indonesia, providing key research on potential agronomic interventions and, through collaboration with stakeholders, an understanding of the wider social, economic, and environmental framework required to deliver a sustainable system that benefits the rural communities. It is the hope of the research team that this paper summarizing the main research activities within UB Forest will introduce the platform and facilitate future collaborations with the wider research community.

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