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Article

Valorisation of Natural Resources and the Need for Economic and Sustainability Assessment: The Case of Cocoa Pod Husk in Indonesia

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Abstract: The uptake of innovative technologies and practices in agriculture aimed at the valorisation of natural resources can be scant in Low and Middle Income Countries (LMICs). Integration of financial viability assessments with farmers and environmental evaluations can help to understand some aspects of low uptakes of innovations. Using the case study of Cocoa Pod Husk (CPH) valorisation in Indonesia, we provide insights on: (i) a choice modelling method to assess the economic viability of CPH valorisation and (ii) an agronomic trial assessing the consequences on soil quality of diverting CPH from its role as a natural fertilizer. The economic viability assessment suggested that farmers require higher levels of compensation than might be expected to collect or process CPH (a small proportion of farmers would undertake all processing activities for 117 GBP/t CPH). The agronomic trial concluded that CPH plays only a minor role in the maintenance of soil phosphorus, calcium and magnesium, but an important role for crop potassium. CPH removal would reduce the partial balances for carbon and nitrogen by 15.6 and 19.6%, respectively. Diversion of CPH from current practices should consider the long-term effects on soil quality, especially since it might create increased reliance on mineral fertilizers.

Keywords: cocoa pod husk (CPH), valorisation; choice experiment; soil quality; soil carbon; soil nutrients

1. Introduction

Rural households in Low and Middle Income Countries (LMICs) engage in a diverse set of income-generating activities in an attempt to diversify their income base, accumulate wealth, buffer the effects of shocks or break cycles of poverty [1–4]. However, income generation strategies are often hindered by environmental threats and socio-economic factors that pose complex challenges associated with poverty and food security [5]. Innovative technologies and processes that are directed to the valorisation of raw and by-product or low-value materials can represent an opportunity to create environmentally sustainable opportunities for new income streams directed to poorer rural households and to create new markets [6,7].

Nonetheless, the uptake of technologies and alternative practices linked to innovative processes can be disappointingly low [8]. To prevent the costly implementation of unsuccessful valorisation projects due to poor uptake, there needs to be a prior assessment of the economic and environmental viability of these initiatives. In this paper we provide an example of choice modelling methods to assess the economic viability from the farmers' viewpoint of diverting what is generally considered a low value by-product (cocoa pod husks (CPH)) to sale for income generation, alongside assessment of the implications for soil quality that result from diverting CPHs from their original return to the soil of cocoa farms. Timely financial viability assessments and environmental impact evaluations can help to understand some of the aspects of low uptake of improved technologies and could feed into a broader cost benefit analysis. For example, the discrete choice experiment addresses farmers' willingness to accept innovative production processes and additional costs to modify their established practices linked to cocoa farming. Additionally, assessing the environmental impacts of by-product material valorisation examines unintended environmental damages and medium- and long-term threats to soil quality and farm productivity.

CPH, generated when the cocoa beans are removed from the cocoa pods, is the main by-product of the cocoa harvest with the CPH constituting about 75% of the mass of whole cocoa pod fruit. As reviewed in Fei et al. (2018), after harvest, CPH is commonly recycled to soil on farm as fertilizer, although it is frequently removed to reduce the spread of diseases. It may be used for other relatively low value applications such as animal feed, starting material for soaps and preparation of activated carbon. However, alternative processing and valorisation of CPH may represent an unexplored income stream for cocoa producing farmers. CPH is rich in minerals (particularly K), fibre including lignin, cellulose, hemicellulose and pectin and antioxidants such as phenolic acids. There are interesting agrochemical valorisation potentials for CPH and its fractions that include their incorporation in food production. Such innovative applications to CPH allow the addition of fibre-rich husk fractions into different food products (bakery, dairy, chocolate-based confectionary products) and can be potentially used to reduce sugar and fat content and increase fibre content of a large range of food products [9].

However, to supply CPH for new uses, farmers may need to modify part of their cocoa production processes and integrate alternative harvesting practices. These may generate extra costs, and modification in the allocation of labour and farm space that could compete with more valuable production of cocoa beans or other crops. Hence, farmers may demand compensation to adopt alternative practices directed to CPH valorisation. Understanding the type of practices that need to be introduced and assessing the adequate compensation levels are central to improve the technology uptake and its long-term financial viability [10].

At the same time, the large internal cycle of organic matter and nutrients within the field via decomposing crop residues and litter from both cocoa and shade trees [11,12] is a major influence on the maintenance of soil fertility for cocoa production. The retention of crop residues is a key in promoting physical, chemical, and biological attributes of soil health in agricultural systems for developing countries [13] and soil organic carbon (SOC) is a key indicator of soil quality and sustainability because it measures soil organic matter (SOM), which provides beneficial soil physical properties (e.g., aggregate stability, soil water retention) and the provision of plant-available nutrients. Most of the variability of nutrient content of the cocoa harvest can be attributed to differences in the nutrient content of the CPH rather than that of the beans [12]. Therefore, the diversion of CPH to other uses could result in significant depletion of the crop's nutrient supply and soil quality. Hence, assessing the balance between nutrient inputs and outputs is crucial to inform the long-term sustainability of cocoa and the need for fertilizer. Published data on the nutrient element composition of CPH are mostly from Africa and Latin America and quantitative information on the contribution of CPH to the internal and external nutrient balances is scarce. Fontes et al. [14] found that Brazilian cocoa agroforestry systems varied greatly in nutrient cycling and internal balance, concluding that CPH was particularly relevant for P and K, and that further research is needed to develop nutritional balance systems integrating litter, fruits, and nutrient pathways. Our work addresses this need in the Indonesian situation and furthermore links the biophysical nutrient balance information with socioeconomic aspects of CPH management.

Drawing on data collected in Indonesia we set out to empirically assess: (i) the financial feasibility of innovative processes directed to CPH by employing a discrete choice experiment and; (ii) the potential environmental impacts of the off-farm removal of CPH on soil properties and soil nutrient cycling. Our innovative approach speaks to the literatures contributing to an integrated and innovative "technology translation" paradigm [10] using an approach that bridges biophysical science and economics.

2. Materials and Methods

2.1. Economic Viability Assessment

The financial feasibility of CPH valorisation and farmers' willingness to adopt the proposed practices is explored by using Discrete Choice Experiment (DCE) and followed three stages:

- Exploratory survey, designed and administered to a small sample of the farmers to provide an initial understanding of CPH practices in Sulawesi and informs the design of the DCE;
- Focus Group Discussions to identify compensation levels to process CPH;
- Design and deployment of DCE survey.

2.1.1. Exploratory Survey

The exploratory survey consisted of three sections: (i) farmer's and farm characteristics; (ii) cocoa production practices; (iii) CPH practices.[1] The island of Sulawesi (circled in **Error! Reference source not found.**) represents the main area of Indonesia where cocoa is produced, mainly by smallholder farmers (about 90% of total production) (Johnston et al. 2004). Given the centrality of Sulawesi in the cocoa production, the pilot study and subsequently the DCE were deployed in this area. Sample selection and the identification of 56 respondents were supported by the International Coffee and Cocoa Research Institute (ICCRI), and interviews were conducted in four districts covering the four main areas of the island: Luwu (South Sulawesi) 15 farmers; Mamuju (West Sulawesi) 16 participants; Parigi Moutong (Central Sulawesi) 11; and Kolaka (Southeast Sulawesi) 10 farmers.

57% of farmers reported that CPH went unused, 34% dispose of CPH mainly as fertilizer and 8% as animal feed and fertilizer combined (8%). However, it was not clear if farmers that did not use CPH were leaving it on the field. Only 4% of farmers sold a proportion of CPH in the preceding year. When used as animal feed, CPH processing is minimal (sometimes involving chopping and drying). When used as compost or mulch, the processing includes "rough" chopping, and CPH is left in the fields to decay and recycle nutrients into the soil.

The survey indicates that the main processes that farmers would have to undertake in order to modify their current practices with regards to CPH and supply material for new uses, include collecting, chopping, drying and transporting. These four processing stages are used as attributes in the DCE. Farmers indicated their willingness to adopt alternative practices for the disposal of husks. Finally, while farmers are responsive to price incentives, considerations about obstacles to transport CPH and additional labour requirement were identified as main challenges in modifying current practices around CPH.

2.1.2. Focus Group Discussions (FGD)

[1] Field-work and data collection for the pilot study was executed by ICCRI staff in May 2018 and interviewed 52 farmers in the island of Sulawesi. Before deploying the survey, ICCRI tested the questionnaire on five farmers in East Java (in the area of Blitar). This exercise provided the platform to develop and finalize the pilot questionnaire.

The focus group discussion aimed at benchmarking the compensation levels that would be appropriate to use in the choice modelling method to assess the economic viability of CPH valorisation. The FGD consisted of two stages. The first stage was undertaken with five farmers in the area of Blitar (East Java) and five farmers in Lowu (South Sulawesi). The second stage involved interviews with experts at ICCRI, local partners in the project. Respondents were asked to individually provide both the lowest and highest levels of compensation they believed were necessary for them and other farmers in their village to collect, chop, dry and transport CPH.[2] At the end of the FGD with the farmers, enumerators conducted a group exercise to reach a consensus on the lower and upper bound compensation level for each of the processing stage (**Error! Reference source not found.**).

Table 1. Median lower and upper limit of the compensation demanded to collect, chop, dry and transport dry CPH (GBP/t).

	Collect	Chop	Dry	Transport
	GBP/t			
Median Lower Limit	36.4	25.5	52.4	52.0
Median Upper Limit	59.7	26.0	78.0	70.2

Exchange rate used: GBP 1 (Great Britain Pound) = IDR 19231 (Indonesian Rupiah). Source: (https://www1.oanda.com).

We report median values due to substantial variations in reported compensation levels. Drying is associated with the highest compensation level followed by transport and collection of CPH. Chopping is the activity that appears to require the lowest compensation. These trends are consistent for both upper and lower limits.

2.1.3. Design and Deployment of DCE

Field work was conducted in South and South East Sulawesi, Lampung (South Sumatra) and West Sumatra. 156 small and medium size cocoa farmers across four districts were interviewed (**Error! Reference source not found.**).[3]

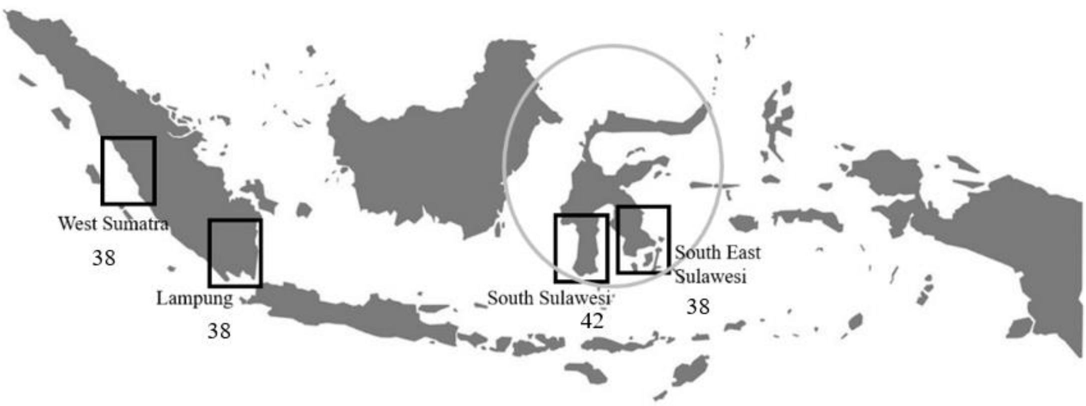

Figure 1. Locations of the districts of the Discrete Choice Experiment in Sulawesi and Sumatra (Indonesia) with numbers of participating farmers indicated for each district.

The pilot survey and discussion with ICCRI experts helped determine the list of attributes for the DCE. The information collected during the focus group discussion was used to define the prices attached to the attributes in each set of cards. The cards were used to assess the compensation needed

[2] Farmers were asked to identify the transportation cost required to transport CPH for 15 km. Compensation levels were asked per kg of wet CPH or wet-equivalent CPH.
[3] The project followed the ethical procedure detailed by the partner institution (ICCRI). All eligible farmers were informed of the purpose of the study and their right to refuse participation. Interviews were performed after receipt of written consent from the participants. At the end of the interview respondents were remunerated with a small amount of cash to thank them for their time.

to accept new/additional processing practices connected with supplying CPH for new uses. We identified six options that include one or more identified attributes:

a) Collect
b) Collect and Transport
c) Collect and Chop
d) Collect, Chop and Transport
e) Collect, Chop and Dry
f) Collect, Chop, Dry and Transport

Compensation levels are expressed in wet-equivalent CPH, using the conversion factor of 0.22.[4] The attributes and prices generated 192 alternatives. Each participant was presented with 32 choice cards, each showing six options of CPH combination of attributes and their compensation level. An opt-out question was included. Details on the design of the econometric estimation are provided in Appendix A. After being informed of the purpose of the exercise, farmers were asked to select one preferred compensation level attributed to one option on each card. Each choice option was accompanied by a standardized script, which was read by the interviewer. Sample DCE cards are shown in S1 and **Error! Reference source not found.** in the Supplementary Material.

We conducted a short survey following the DCE module, asking farmers' information of farm characteristics, cocoa production, labour availability (family and employed), CPH current practices (fertilizer and feed), and household demographics. The survey and consent forms were developed in English and translated to Bahasa Indonesia. The surveys were piloted, revised, and administered by a team of five experienced interviewers. Interviews lasted 30–40 min and were conducted using electronic tablets (Lenovo Tab4 8) with SurveyCTO software (Dobility, Inc., Boston, United States of America).[5]

2.2. Soil Quality Assessment

2.2.1. Field Trial Design and Assessment Methods

In order to evaluate the role of CPH in soil fertility maintenance, a programme of additional sampling and analysis was conducted over 15 months in one treatment of an established on-station trial of the Cocoa Research Station of MARS Inc, Tarengge, Sulawesi, Indonesia (l2°33′ S; 120°47′ E ; altitude ~12 m ASL). The trial was planted in February 2014 and aimed to be realistic of local on-farm conditions by including banana (*Musa paradisiaca*) and gliricidia (*Gliricidia sepium*) companion trees. Nearby trees, in particular two mature durian (*Durio zibethinus)* trees (thought to be >40 years old), that contributed to litter fall also remained undisturbed to maintain a realistic situation. The treatment monitored provided mineral fertilizers at the current local "best practice" annual rates of 82, 92, 155, 330 and 115 kg/ha of N, P, K, Ca and Mg respectively, based on the suppliers' analyses. There were three replicate plots and cocoa seedlings of MARS clone MCC02 were planted at a density of 1111 plants/ha.

2.2.2. Harvesting and Sample Collection

Cocoa pods are produced throughout the year and all ripe pods were harvested from all trees in each plot at intervals of two weeks and the number recorded. During the peak production seasons of June–July 2018 and October–December, 2017 and 2018, a sample of 12 pods was taken per plot and split into beans and the remainder (CPH), the latter being chopped into small (<2cm) pieces. Beans and CPH were air dried and weighed. The biomass production at the other harvests was estimated from the number of pods harvested and the ratio of bean weight to CPH weight as established for

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[4] The conversion factor was derived at ICCRI and described in Appendix B.
[5] Training on digital data collection and DCE surveys deployment was conducted between 28th and 30th of November 2018 at ICCRI headquarter (Jember, Indonesia), followed by a pilot survey collection in Blitar between 3-7 of December 2018. Data were collected over a period of 8 weeks (11th December 2018 to 31st January 2019), after the completion of the main cocoa harvest season.

the measured harvests. Trees were pruned in April, July and November 2018. Leaves and woody parts were collected separately, weights recorded and the woody parts were chopped into smaller pieces. Samples of each were air-dried for analysis and the rest returned to the plot. Falling leaf litter in each plot was collected in three square traps (each 0.5m^2) per plot, which were shifted to different random positions every three months. Litter was collected every seven to 10 days, air-dried and combined into batches each representing one month finishing on the 14th of each month from November 2017 to December 2018. Samples collected in the June to October period were sorted by hand into that of cocoa origin and the rest, the latter mostly originating from the shade trees.

2.2.3. Assessment of C and Nutrient Cycling in Soil

Subsamples of each of the above materials were analysed for total C, N, P, K, Ca and Mg at University of Reading laboratories according to standard methods (Appendix C). A partial balance of external inputs and offtakes of the plots for each of these elements was calculated using elemental concentrations and dry matter yields, for a period of one year, from December 2017 to November 2018. Data for losses via drainage water and gaseous emissions (e.g., CO_2, CH_4, NH_3, N_2O, NO_x) and inputs via atmospheric deposition and biological nitrogen fixation were not available for this location. The offtakes were the sum of results for beans and CPH (when appropriate). Nutrient inputs via litter, prunings and CPH (when appropriate) were considered to be internally cycled. Therefore external nutrient inputs were fertilizer and the C inputs were litter, prunings and CPH (when appropriate), since C is derived from photosynthesis by crop and accompanying trees.

3. Results

3.1. Economic Viability Assessment

Responses were elicited from 156 farmers using face-to-face interviews technique. Demographic characteristics of the respondents are summarized in **Error! Reference source not found.**. The mean age was 49 years and 61% of interviewed farmers were men. The household size was on average 4.45 (with 3.36 adults and 1.09 children). The average landholding was 1.67 ha with 1.07 ha allocated to cocoa farming, and during the previous agricultural year, farmers had produced on average 336.5 kg of (dried) cocoa. Households are located almost 8 km away from the nearest product markets. 50% of farmers use CPH as fertilizers and only 16% use it for animal feed.

Table 2. Descriptive Statistics of households and farms.

	Mean	**SD**
Age of respondents (years)	48.8	(11.87)
Household size	4.45	(1.59)
Number of adults (>15 years old)	3.36	(1.34)
Number of children (<=15 years old)	1.09	(1.07)
Total land holding (ha)	1.67	(1.67)
Total size of cocoa farm (ha)	1.07	(0.96)
Age of cocoa trees (years)	12.91	(7.63)
Distance from nearest market (km)	7.63	(8.74)
Cocoa beans produced last year (dry, kg)	366.28	(472.72)

Percentage of:	
Male respondents	61%
Farmers using CPH as fertilizer	50%
Farmers using CPH as animal feed	16%
Number of households	156

Error! Reference source not found. reports the distribution of farmers' Willingness To Accept (WTA) compensation in order to perform the six sequences of activities required to supplying CPH for new uses. The options did not prompt farmers to think about soil nutrient losses (especially potassium) and to quantify additional compensation needed to replace them with fertilizer. Hence, we are not able to differentiate the compensation needed to purchase fertilizers from the attributes presented in the choice cards. Prices are reported in GBP/t of dry-equivalent CPH. Figure 2. Cocoa farmers Willingness-To-Accept alternative practices with CPH (GBP/t).

reports the mean, standard error of the mean, standard deviation and median of the compensations by for each individual activity. These figures illustrate that chopping requires on average the lowest compensation level, followed by collecting, transporting, and drying husks.

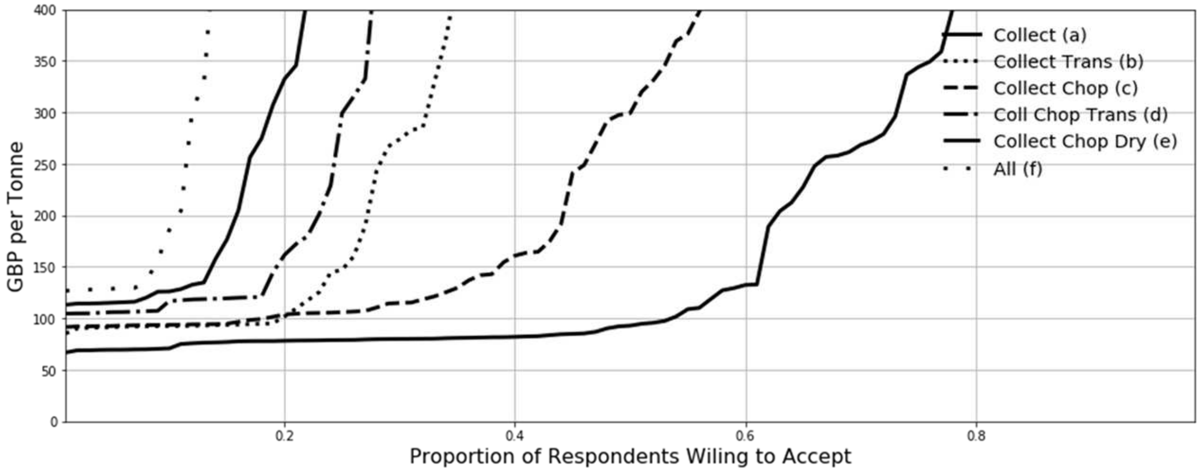

Figure 2. Cocoa farmers Willingness-To-Accept alternative practices with CPH (GBP/t).

Table 3. Willingness to accept compensation break-down (GBP/t).

	Collect	**Chop**	**Dry**	**Transport**
Mean	235.2	162.6	354.0	316.1
SEM	7.1	7.5	9.6	10.1
SD	88.9	93.8	120.3	125.7
Median	103.9	50.3	553.5	268.3

In general, a substantial proportion of farmers signalled a willingness to engage in activities such as collecting through to transporting CPH. However, only approximately 5% of farmers appear to be prepared to perform all the activities (collecting, chopping, drying and transporting) for a compensation level between 140–150 GBP/t of dry CPH, and most require a relatively higher compensation level. Almost 50% of farmers are willing to undertake collection only of CPH for approximately 75–100 GBP/t of dry CPH. Collecting and transporting and collecting, chopping and transporting exhibit very similar compensation distributions, and 20% of farmers are willing to undertake these activities for approximately 100 GBP/t of dry CPH.

While some farmers were willing to undertake activities for relatively smaller compensation levels, they were also the ones that tended to require substantial amounts for the same activities earlier in the sequence. This is indicative of the fact that once farmers decide there are only a set of activities they will engage with, they appear to exhibit considerable levels of inertia and low levels of responsiveness to monetary incentives to deviate from that decision. Farmers are likely to be inclined to prioritise cocoa bean production and exhibit a certain level of resistance to allocate resources (i.e., labour and farm space) to CPH management.

In terms of types of farmers who were prepared to undertake these activities, there was very little explanatory power using revenue from CPH (closely related to size and level of production), labour and distance from the market as explanatory variables. Around 7% of variation in the WTA for collection and drying activities could be explained by these factors whereas for chopping only around 1.5% could be explained and 3% for transporting. In terms of statistical significance only revenue was significant for collection and transporting and distance for drying at a 10% level of significance.

Indonesia is among the biggest cocoa producers (593,832 t in 2018; [15]) and provides the main source of income for over 1,400,000 smallholder farmers [16]. Because lower levels of compensation are demanded by 5% of interviewed farmers, CPH valorisation could potentially benefit about 70,000 Indonesian cocoa farmers and their families willing to engage with all processing activities. Over time and with the development of infrastructures and processing systems that better integrate the valorisation of CPH into existing processes and value chains, the cost of processing CPH could gradually decrease. This could enable a larger share of farmers to take advantage of CPH sale and diversify their incomes.

3.2. Soil Quality Assessment

3.2.1. Crop Performance

Pod, bean and CPH production varied greatly during the experimental period, in accordance with the two normal main cocoa harvest peaks in Sulawesi, around July and November (**Error! Reference source not found.**). The annual bean yield of 1292 kg/ha was high compared with typical current Indonesian yields of around 500–700 kg/ha [16], and approach the best yields (~2000 kg/ha) obtained in a recent on-farm trial in another area of south Sulawesi [17]. The annual dry biomass input to the soil was 8323 kg/ha, provided by CPH (1328 kg/ha), litter (4526 kg/ha) and prunings (2469 kg/ha). The variation in litter fall over the year suggested a tendency to increase over the duration of the experiment (Figure 3), although low litter fall in the May to July period may be associated with wetter weather at this time since cocoa litterfall is highest in dry weather.

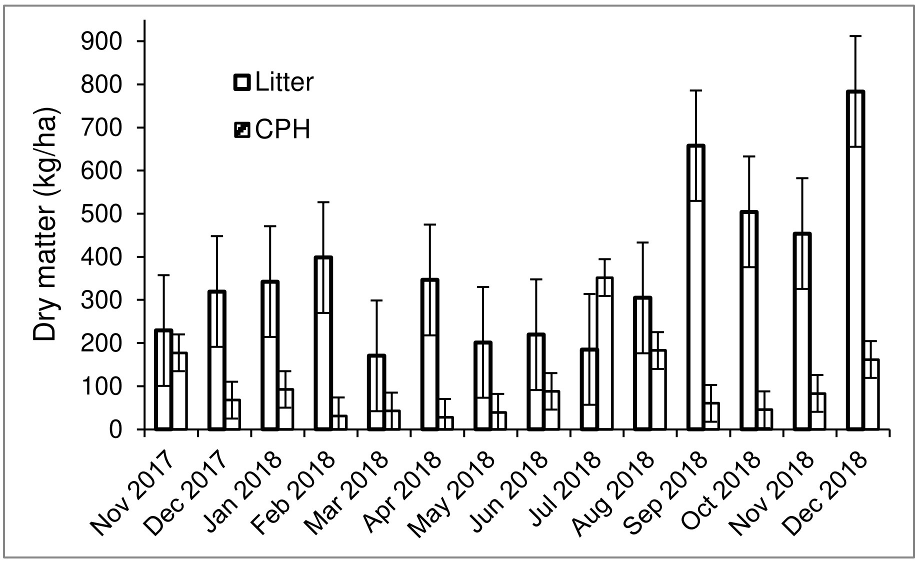

Figure 3. Monthly CPH production (hatched column) and litter fall (open column) in the year November 2017 to December 2018, for periods ending on 14th of each month with error bars denoting ± (SD).

The annual C and nutrient contents for CPH were 504, 11, 1, 46, 7 and 4 kg/ha for C, N, P, K, Ca and Mg respectively (**Error! Reference source not found.**). Similar values are reported by Wood and Lass [18] for a bean yield of 1000 kg/ha. They amount to 15.6% (C), 6.2% (N), 1.1% (P), 18.0% (K), 1.5% (Ca) and 2.7% (Mg) of the above-ground inputs to the soil from external (i.e., photosynthate-C, biologically fixed-N, and fertilizer N, P, K, Ca and Mg) and internally recycled (N, P, K, Ca and Mg) sources, suggesting that CPH played an important role in the C and K cycles, but a lesser part in the cycles of the other nutrients.

This trial was young (the study took place in its fourth year) compared to the mean tree age of 12.9 years at the farms investigated (**Error! Reference source not found.**) and the typical lifespan for hybrid cocoa is 15–20 years [12]. However, for the purpose of nutrient balance assessment., it is concluded from the crop performance results that it is reasonably representative of a high-yielding cocoa crop in Sulawesi.

Table 4. Partial annual plot-level balances (kg/ha) of C, N, P, K, Ca and Mg under the alternatives: Scenario 1 (CPH retained); Scenario 2 (CPH removed); and Scenario 3 (CPH removed and no fertilizer), with standard deviations for each element in the scenarios.

Element	Nutrient Cycle Component					Scenario			
	Litter	Prunings	Fertilizer	CPH	Bean	1	2	3	(SD)
C	1791	935	0	504	n/a	3230	2726	2726	369
N	58	26	82	11	27	56	45	–38	3.2
P	4	3	92	1	6	86	85	–8	0.3
K	21	35	155	46	14	141	94	–61	5.0
Ca	75	27	330	7	1	328	322	–8	1.0
Mg	18	10	115	4	4	111	107	–8	0.4

3.2.2. Nutrient Cycling and Sustainability

Shade trees play a significant role in nutrient cycling in addition to their agronomic value and in the period from May to October, 67, 63, 62, 43 and 44% of the N, P, K, Ca and Mg respectively in the litter came from the shade trees (Appendix C), showing their value for maintaining soil fertility. Given the presence of leguminous shade trees (i.e., *Gliricidia sepium*), a proportion of the shade litter input of N was probably derived from biological fixation from the atmosphere and therefore represents an external (as opposed to internally-recycled) input to the system.

The net balance of inputs minus offtakes provides an indicator of sustainability because continuous depletion of nutrients in the soil is not sustainable in the long term. Three scenarios were quantified: (1) CPH retained on the plot, as actually carried out, (2) CPH removed and (3) CPH removed and fertilizer application discontinued. Scenario 1 showed a surplus of C and nutrients (**Error! Reference source not found.**). Under scenario 2, the C and nutrient balances were reduced significantly ($P<0.05$) showing that CPH made a significant contribution to maintaining soil quality. Under scenario 3 the balances for the nutrients would be reduced highly significantly ($P<0.001$), becoming negative.

The maintenance, turnover and potential accumulation of soil organic carbon is a function of the long-term balance between plant carbon inputs and losses, mainly via microbial respiration. CPH provided about 16% of the above-ground C input to soil, representing a reduced annual input of ~500 kg/ha (equivalent to 50 g/m^2) under the CPH removal scenarios (**Error! Reference source not found.**). The magnitude of the CPH-associated C input should be considered not only alongside the above ground inputs from litter and prunings but also alongside the likely significant C inputs to SOC from fine root turnover below-ground, which were not measured here but have been estimated to be ~140 g/m^2 and ~180 g/m^2 annually in 10 year old cocoa systems in Central Sulawesi under natural or planted shade trees, respectively [19]. Whilst current evidence suggests that below-ground plant-derived inputs might be most influential for building SOC [20], there is considerable uncertainty regarding the consequences of variation in both quantity and quality of above ground plant-derived inputs to soil for below-ground processes, as a result of the complexity of governing mechanisms and factors involved. However, a meta-analysis [21] has indicated that (sub-) tropical forest systems may be most sensitive to increases or decreases in above-ground inputs, with substantial alterations in the turnover and accumulation of SOC over relatively short time scales possible. Indeed, a study in primary tropical forest (Costa Rica) has shown that only two years after annual C inputs were reduced by 450 g/m^2 by leaf litter removal, SOC concentrations were reduced by 26% [22]. In our CPH removal scenario, how the comparatively modest reduction (50 g/m^2) in C input would affect SOC dynamics over the short and longer term requires further investigation. Data of Dawoe at al. [23] and Tondoh et al. [24] in West Africa emphasize that the initial conversion of forest to cocoa causes a decline in SOC due to perturbations in the balance between C input and output. If CPH was sold off-site, the further perturbation caused by lost C input could be mitigated by addition of an alternative source of organic matter to prevent further decline in SOC and requires further investigation.

CPH provided 6% of the N input to soil and the external balance showed a surplus in scenario 1, the current practice (**Error! Reference source not found.**). There are several uncertainties in this N balance. Substantial losses of N from soil via leaching in drainage water are possible in humid climates and not accounted for here. However, the deeper roots of many shade trees provide a "safety net" to capture soluble nutrients and recycle them to the soil via plant uptake and litter, so Hartemink [11] concluded that leaching under cocoa might be between "very small" and 22 kg/ha annually, based on measurements in Latin America. Based on other research in cocoa agroforestry in Central Sulawasi [25], relatively small N losses via gaseous emissions (e.g., ≈ 3 kg N as N_2O/ha annually) are also likely. Based on estimates from cocoa systems in Malaysia, Central & South America and Africa, annual deposition of N in rainfall may add a further 5 to 12 kg/ha [11], although some records suggest that specific N deposition rates in Sulawesi maybe be lower at 1.4 to 2.7 kg/ha [26]. As already mentioned, we also did not quantify the contribution of biologically fixed N as an external input to the system. However, based on our partial N budget, results overall suggest that offtake of N via CPH would not cause a major shortfall in the N supply if fertilization is maintained at current levels. But without fertilizer, CPH would be an important N source because of the negative balance.

Leaching losses also affect K and might be up to 17 kg/ha (Hartemink 2005) per year. CPH was the largest single non-fertilizer source of K (**Error! Reference source not found.**). If CPH was removed from the land, the K supply to soil would be reduced by 18%. Without CPH and mineral fertilizer, there would be a substantial deficit in K, further increased by leaching losses: CPH plays a significant role in the maintenance of K fertility. The impact of CPH removal on nutrient balances would be quite small for P, Ca and Mg, accounting for 1.1, 1.5 and 2.7% respectively of the internal nutrient cycles.

4. Discussion and Conclusions

Valorisation of farm by-products or (seemingly) non-utilized agricultural material is often viewed an attractive option to diversify income or generate revenue among poorer farmers in LMICs. However, failing to consider the economic viability from the smallholders' viewpoint and assess the environmental effects of such strategies, represents a considerable obstacle for the overall uptake and long-term sustainability of such interventions. In addition, unintended (or ill planned) impacts on soil quality can hinder agricultural productivity, damage the main resource for livelihood (the soil) of poorer farmers and reverse the original positive intent of the intervention.

In this paper the assessment of residue material valorisation was undertaken with regards to alternative uses of CPH directed to the agri-food industry. The paper provides insights into the evaluation process on two fronts: (i) choice modelling methods to assess the economic viability of supplying CPH for new uses; and (ii) impacts on soil quality caused by diverting CPH from its role of organic fertilizer.

The economic viability assessment concludes that farmers require higher than expected levels of compensation to supply CPH for new uses. Such prices are comparatively high for a material that could be considered low value or unused. Based on the findings from the exploratory survey, this can signal that to adapt current practices, farmers require additional resources to adjust labour constraints and compensate farm space originally allocated to cocoa bean production. We assessed that approximately 5% of farmers are in the position to supply CPH for new uses at a starting compensation level of 150 GBP/t. Given the large population of smallholder cocoa producers in Indonesia, a significant number of farmers could take part to the CPH valorisation process and supply husks for new uses. Over time these numbers can grow further. Adoption and diffusion of agricultural technologies comprehend a certain degree of complexity in the decisions taken by small-scale farmers. To a certain extent, the complexity lies in the lack of certainty with relation to the benefits of such technologies before they are adopted [27]. Improvements in infrastructures and integration of processes directed to CPH alternative uses in existing food value chains can address such uncertainties, maximise farmers' financial benefits. Additional labour costs barriers could be addressed thanks to better integrated production systems and more competitive compensations.

Reviews of cocoa fertilization show that recommended nutrient application rates vary more than 10-fold [12]. The amounts of fertilizer used here were high in relation to the crop requirement since there appears to be a surplus of most nutrients. The partial nutrient balances indicated large surpluses of OM and macronutrient accumulation (**Error! Reference source not found.**), so diversion of CPH to alternative uses is not expected to cause nutrient deficiencies in the short term. CPH played only a minor role in the maintenance of soil P, Ca and Mg, but CPH diversion would reduce the plot-level partial balances for C, N and K by 15.6, 19.6 and 32.6% respectively. These significant losses could be important if continued for several years. K is the nutrient most susceptible to deficiency and complete replacement of the 46 kg/ha from CPH (**Error! Reference source not found.**) by KCl fertilizer would cost IDR 578,080 (GBP 30) per year at the current price.

C input from diverted CPH could be replaced, if there was an appropriate alternative organic amendment available. In our Sulawesi setting, there is a locally available commercial organic fertiliser, 'Petroganik'. Direct replacement of 504 kg/ha of CPH-derived C (calculated from **Error! Reference source not found.**) would require the application of 3359 kg/ha Petroganik (taking into account the C content of the organic fertiliser) costing IDR 9,238,184 (GBP 480). This would also provide 34 kg N and 27 kg K, adding 309% of the N and 59% of the K lost in diverted CPH. Hence, any decision to divert CPH from its conventional use should take into account the long term effects on soil quality, since it may create increased reliance on purchased inputs. However, it may be acceptable to reduce the currently recommended fertilizer application rates in the light of the apparent balance surpluses and possible consequent environmental pollution by excess nutrients in drainage waters.

The nutrient cycling study suggested possible further environmental constraints on the economics of CPH valorisation as experienced by farmers. CPH production varied widely across the year (Figure 3). Despite the willingness of some farmers to process CPH for sale, the seasonality of the work could impose labour constraints on its practicality. The subsidiary investigation of the role of nutrient cycling via shade and companion trees (Appendix C) showed that shade trees (including in this case deposition from nearby large trees) have a significant role in nutrient cycling in cocoa production. In addition to these beneficial effects on soil fertility, accompanying trees in cocoa systems normally provide significant economic benefits in terms of fruit and other products. Farmers' locations and choice of accompanying trees may have location-specific influences on the recycling of CPH for valorisation.

Considerations of the financial viability and environmental impact are central to address the low uptake of improved technology. Challenges to adopt innovation by end-users (such as unrecognised problems for farmers) may be linked to the strategies adopted in the process of technology development, where top-down "solutions" are implemented without a comprehensive involvement of all actors or without performing economic and environmental assessments [28–30]. Holistic approaches to technological development that focus on integrating different actors and consider national resources, and that evolve within broader agricultural development strategies, are in a better position to address the complex and unbounded sustainability issues facing agriculture today [31]. The results of our study indicate that technological interventions, and by-product material valorisation in particular, can benefit from the involvement of multi-disciplinary teams and engagement with farmers from the onset of the development of innovative farming approaches. This allows to assess whether the technologies or innovative approaches meet existing needs and preferences of the end-users as well as assessing environmental impacts and effects on soil quality. Such integrated, participatory, and interdisciplinary practices have the potential to enhance adoption, ensure the sustainability of these innovative technologies and ultimately result in alternative income streams for rural households.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Figure S1: DCE card – English, Figure S2: DCE card – Indonesian.

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Appendix A

The design for this experiment contained the same options (a. Collect, b. Collect and Transport, c. Collect and Chop, d. Collect, Chop and Transport, e. Collect, Chop and Dry, f. Collect, Chop, Dry and Transport) with only variation in price across these options. The price levels were constructed from the initial open ended survey of farmers and experts ranging from 1/3 of the median "entry level" price (the price these respondents felt that some farmers would accept) expressed by these respondents to three times the "majority level" price (the price these respondents expressed the most farmers would accept). The construction of the 32 choice options was then made using a D-optimal design (which should maximise the efficiency of the estimates) under weak prior assumptions about the disutility of the farmer tasks and positive utility for payment.

For estimation we employed a "Mixed Logit" specification. This assumes that each person has a utility function that can be expressed as a linear function of the attributes of delivered to respondents (the farmers) where the attributes are the services performed by farmers along with the payment for performing that service.

Formally, we assume that a person j (j=1....,J) obtains utility U_{ijs} from choice i from a set of alternatives (i=1.....,I) within task set s (s=1,....,S). The utility function is then specified as:

$$U_{ijs} = \gamma_j\left(p_{ijs} - \beta_j' x_{ijs}\right) + \varepsilon_{ijs} = V_{ijs} + \varepsilon_{ijs} \quad \text{(A1)}$$

where εijs is the unobserved random error which is assumed to be extreme value (Gumbel) distributed, $xijs$ is a vector of observed variables (the choice attributes) given to farmers, and p_{ijs} is the payment offered to each farmer to compensate them for delivering these services. Under this specification the probability of respondent j choosing the ith option within set s is:

$$\text{Prob}(i|j, s) = \exp(Vijs) / \textstyle\sum i \exp(Vijs) \quad \text{(A2)}$$

The likelihood function for estimation is then expressed as the product of these probabilities over all choices and individuals. Given this specification βj represents the vector of "willingness-to-accept" for each individual farmer and is assumed vary within the population with density $f(\gamma_j,\beta j|\theta)$ where θ are the parameters that govern the distribution for the population. This form (equation 1) is known as a "willingness-to-accept space" representation because the parameters within βj represent a ratio of the marginal disutility for performing a given service over the marginal utility of the payment, and these are estimated directly rather than being recovered ex-post from a linear in parameters specification. The value for each γ_j and βj were recovered using a Bayesian approach to estimation which places prior distributions of the parameters by specifying the nature of $f(\gamma_j,\beta j|\theta)$ along with the a priori distribution for θ. The distributions for γ_j and βj were specified as normal distributions truncated at zero so that all values were positive. The priors for the means of these variables were normal and the variances were gamma. These priors were set so as to allow relatively diffuse estimates and estimated using Hamiltonian MCMC using the program STAN. The documentation for STAN can be found https://mc-stan.org/ which also contains further detail about Hamiltonian MCMC. We experimented with a variety of priors. The estimates produced in the paper were for relatively conservative priors in terms of producing conservative (i.e., lower) estimates willingness-to-accept. Thus, more diffuse priors lead to slightly larger levels of willingness-to-accept estimates than those produced in the paper.

Appendix B

To determine the wet-dry conversion factor that is needed for economic viability assessment, CPH (1kg) was dried on a cement base in sunshine over a period of seven days at ICCRI Jember in October 2018. The factors for consecutive days were 0.656 (Day 2), 0.499 (Day 3), 0.343 (Day 4), 0.314 (Day 5), 0.225 (Day 6) and 0.212 (Day 7). Comparable factors for clone MCC02 at MARS Tarengge were 0.168, 0.161, 0.169 for harvests in November 2017, June 2018 and November 2018 respectively. It is recognised that the value will vary according to the condition of the crop at harvest, the cocoa variety used and the conditions of the drying process: a conversion factor of 0.22 was used in the economic viability assessment

Appendix C

Nutrient Cycling Materials and Methods

At the Tarengge site, the mean annual rainfall from 2012 to 2018 was 2798 mm, normally well distributed over the year. In the year November 2017 to October 2018 it was 3051mm, with a peak in June 2017 (424mm). The soil is a silt loam classified as Typic Dystrandept with pH (water) 5.02, 4.09%

SOM (loss on ignition), 1.53% total C, 0.169% total N and 13 mg/kg of extractable P (Mehlich III method) averaged over all plots and sampled at October 2017. The mineral fertilizers were applied in four portions per year, using a local phosphate rock, dolomite, "Nitrabor" (calcium nitrate with additional B) and KCl. The annual applications per tree were: Rock phosphate (680g), $CaNO_3$ (480g as "Nitrabor"), KCl (280g) and dolomitic lime (680g).

Cocoa pods were harvested every two weeks and to simplify assessment of yields, this is done routinely by counts of the number of pods. For this work, the harvested pods were also weighed for three consecutive harvesting occasions during the peak production seasons of June–July 2018 and October–December, 2017 and 2018. A sample of 12 pods was taken, split into beans and the remainder (CPH), and CPH chopped into small (<2cm) pieces. All plant samples were air-dried at Tarengge under freely circulating air at ambient temperature until touch-dry. To estimate the bean and CPH production for the other harvests, the pods count was used in conjunction with the weight of dry bean and CPH per pod for the sampled pods. The proportion of the annual dry matter total harvest (from December 2017 to November 2018) accounted for by the actual measurements made in sampling periods was 48% and 59% for beans and CPH respectively. Litter and prunings samples were collected as described in Methods of the main section. There were few significant differences between months in nutrient concentrations, so appropriate mean values were used to estimate nutrients in litter, when necessary.

The air dried samples were analysed at the University of Reading, where most were further dried at 70 °C for 48 h and milled to pass 0.5 mm. Because of their high fat content, raw beans cannot be reduced to a powder by conventional mills, so they were first broken by hand in a ceramic pestle and mortar to pass 4mm sieve, then further reduced in a blender (Waring 8010EB, with 250 mL container). Total C and N were determined by a combustion analyser (Thermo Flash 2000). The total concentrations of Ca, K, Mg and P were determined by dissolution in nitric acid followed by inductively-coupled plasma atomic emission spectroscopy (Perkin-Elmer PE7300).

The peak of pod production in the October–November harvest season was later in 2018 than 2017 (Fig 3.) and this means that any period of exactly 12 months might underestimate the typical total harvest. Data recording and sampling met with difficulties regarding quality at the start of the 2017 sampling season. Therefore, to construct annual nutrient balances, the estimates of production were based on the year 29 November 2017 to 28 November 2018. This is a little different from November 2017 to November 2018 used for litter, but the annual litter fall was not greatly altered by the particular 12 month period assessed.

Litter Contributions by Cocoa and Shade Trees

Litter fall varied by a factor of up to three between months (Figure 3), although not in any clear association with weather variations. Cocoa litter is shed more in dry seasons, eg. in Ghana where several months each year experience <50mm rainfall (Dawoe et al., 2010). However, in our experimental period, no calendar month received <110mm and 12 of the 16 received >220mm, and no period without rain lasted over 13 days, so water was never deficient.

The total annual litter dry matter (3.9 t/ha) is low relative to typical litter fall in shaded cocoa, usually between 5 and 10 t/ha (Dawoe et al., 2010; Fontes et al., 2014; Hartemink 2005). It was noted that there appears to be an upward trend over the 14 months period of measurement (Figure 3). The increase in litter fall suggests that litter production was still limited by the young age of this trial and might become even more important in a more mature plantation.

Table C1. C and nutrients (kg/ha) added to soil via CPH and litter from cocoa and shade trees, between mid-May and mid-October 2018.

	C	N	P	K	Ca	Mg
Cocoa litter	332	9.60	0.78	3.88	18.28	4.27
Shade litter	505	19.88	1.33	6.35	13.80	3.42
CPH	301	6.71	0.69	28.46	4.09	2.46
(SD)	160	5.6	0.32	3.55	4.67	1.17

Much cocoa is grown with shade trees. Their litter adds to the internal nutrient cycle and the annual dry matter contribution may be around 2–3 t/ha (Aranguren et al., 1982; Fontes et al., 2014), constituting 13 to 60% of the total litter. Here, shade trees provided 58% of the total dry litter mass in the five months from mid-May to mid-October 2018. 60, 67, 63, 62, 43 and 45% of the C, N, P, K, Ca and Mg respectively in the litter came from the shade trees (

), showing their value for maintaining soil fertility. The contributions of cocoa and shade litter were approximately equal, being not significantly different for any nutrient. Over the whole year, CPH provided the majority of the recycled K, but significantly less Ca than either litter. The mean N concentration of litter was significantly (P<0.001) higher for shade (1.83%) compared to cocoa (1.19%). The former will in part be because N-fixing trees (*Glyricidia*) were the majority of the planted shade trees. The role of shade trees in the nutrient cycling of cocoa production deserves further investigation.

References

1. Babulo, B.; Muys, B.; Nega, F.; Tollens, E.; Nyssen, J.; Deckers, J.; Mathijs, E. Household livelihood strategies and forest dependence in the highlands of Tigray, Northern Ethiopiao. *Agric. Syst.* **2008**, *98*, 147–155.
2. Cavendish, W. Empirical regularities in the poverty–environment relationship of rural households: Evidence from Zimbabwe. *World Dev.* **2000**, *28*, 1979–2003.
3. Davis, B.; Winters, P.; Carletto, G.; Covarrubias, K.; Quin˜ones, E.J.; Zezza, A.; Digiuseppe, S. A cross-country comparison of rural income generating activities. World Development, 38, 48–63. *World Dev.* **2010**, *38*, 48–63.
4. Ellis, F. Household strategies and rural livelihood diversification. *J. Dev. Stud.* **1998**, *35*, 1–38.
5. de Sherbinin, A.; VanWey, L.K.; McSweeney, K.; Aggarwal, R.; Barbieri, A.; Henry, S.; Hunter, L.M.; Twine, W.; Walker, R. Rural household demographics, livelihoods and the environment. *Glob. Environ. Chang.* **2008**, *18*, 38–53, doi:10.1016/j.gloenvcha.2007.05.005.
6. Garcia-Garcia, G.; Stone, J.; Rahimifard, S. Opportunities for waste valorisation in the food industry – A case study with four UK food manufacturers. *J. Clean. Prod.* **2019**, *211*, 1339–1356, doi:10.1016/J.JCLEPRO.2018.11.269.
7. IES Feeding the nine billion; 2017.
8. Nasirumbi Sanya, L.; Birungi Kyazze, F.; Sseguya, H.; Kibwika, P.; Baguma, Y. Complexity of agricultural technology development processes: Implications for uptake of new hybrid banana varieties in Central Uganda. *Cogent Food Agric.* **2017**, *3*, 1–18, doi:10.1080/23311932.2017.1419789.
9. Fei, L.; Rodriguez-Garcia, Julia Van Damme, I.; Westwood Nicholas J., Shaw, L.; Robinson, James S. Warren, G.; Chatzifragkou, Afroditi McQueen Mason, S.; Gomez, L.; Faas, L.; Balcombe, K.; Srinivasan, C.; Picchioni, F.; et al. Valorisation strategies for cocoa pod husk and its fractions. *Green Sustain. Chem.* **2018**, *14*, 80–88, doi:10.1016/j.cogsc.2018.07.007.
10. Garb, Y.; Friedlander, L. From transfer to translation: Using systemic understandings of technology to understand drip irrigation uptake. *Agric. Syst.* **2014**, *128*, 13–24, doi:10.1016/j.agsy.2014.04.003.
11. Hartemink, A.E. Nutrient Stocks, Nutrient Cycling, and Soil Changes in Cocoa Ecosystems: A Review. *Adv. Agron.* **2005**, *86*, 227–253.
12. van Vliet, J.A.; Giller, K.E. Mineral Nutrition of Cocoa: A Review. *Adv. Agron.* **2017**, *141*, 185–270, doi:10.1016/BS.AGRON.2016.10.017.
13. Turmel, M.S.; Speratti, A.; Baudron, F.; Verhulst, N.; Govaerts, B. Crop residue management and soil health: A systems analysis. *Agric. Syst.* **2015**, *134*, 6–16, doi:10.1016/j.agsy.2014.05.009.
14. Fontes, A.G.; Gama-Rodrigues, A.C.; Gama-Rodrigues, E.F.; Sales, M.V.S.; Costa, M.G.; Machado, R.C.R. Nutrient stocks in litterfall and litter in cocoa agroforests in Brazil. *Plant. Soil* **2014**, *383*, 313–335, doi:10.1007/s11104-014-2175-9.
15. FAO Cocoa production statistics Available online: http://www.fao.org/faostat/en/#home (accessed on Apr 21, 2019).
16. Witjaksono, J. Cocoa Farming System in Indonesia and Its Sustainability Under Climate Change. *Agric. For. Fish.* **2016**, *5*, 170, doi:10.11648/j.aff.20160505.15.

17. Hoffmann, M.P.; Cock, J.; Samson, M.; Janetski, N.; Janetski, K.; Rötter, R.P.; Fisher, M.; Oberthür, T. Fertilizer management in smallholder cocoa farms of Indonesia under variable climate and market prices. *Agric. Syst.* **2020**, *178*, 102759, doi:10.1016/j.agsy.2019.102759.
18. Wood, G.A..; Lass, R.A. *Cocoa*; 4th Editio.; Longman: London, 1986;.
19. Hertel, D.; Harteveld, M.A.; Leuschner, C. Conversion of a tropical forest into agroforest alters the fine root-related carbon flux to the soil. *Soil Biol. Biochem.* **2009**, *41*, 481–490, doi:10.1016/j.soilbio.2008.11.020.
20. Sokol, N.W.; Kuebbing, S.E.; Karlsen-Ayala, E.; Bradford, M.A. Evidence for the primacy of living root inputs, not root or shoot litter, in forming soil organic carbon. *New Phytol.* **2019**, *221*, 233–246, doi:10.1111/nph.15361.
21. Xu, S.; Liu, L.L.; Sayer, E.J. Variability of above-ground litter inputs alters soil physicochemical and biological processes: A meta-analysis of litterfall-manipulation experiments. *Biogeosciences* **2013**, *10*, 7423–7433, doi:10.5194/bg-10-7423-2013.
22. Leff, J.W.; Wieder, W.R.; Taylor, P.G.; Townsend, A.R.; Nemergut, D.R.; Grandy, A.S.; Cleveland, C.C. Experimental litterfall manipulation drives large and rapid changes in soil carbon cycling in a wet tropical forest. *Glob. Chang. Biol.* **2012**, *18*, 2969–2979, doi:10.1111/j.1365-2486.2012.02749.x.
23. Dawoe, E.K.; Isaac, M.E.; Quashie-Sam, J. Litterfall and litter nutrient dynamics under cocoa ecosystems in lowland humid Ghana. *Palnt Soil* **2010**, *330*, 55–64, doi:10.1007/s11104-009-0173-0.
24. Tondoh, J.E.; Kouamé, F.N. guessa.; Martinez Guéi, A.; Sey, B.; Wowo Koné, A.; Gnessougou, N. Ecological changes induced by full-sun cocoa farming in CÔte d'Ivoire. *Glob. Ecol. Conserv.* **2015**, *3*, 575–595, doi:10.1016/j.gecco.2015.02.007.
25. Veldkamp, E.; Purbopuspito, J.; Corre, M.D.; Brumme, R.; and Murdiyarso, D. Land use change effects on trace gas fluxes in the forest margins of Central Sulawesi, Indonesia. *J. Geophys. Res.* **2008**, *113*.
26. Köhler, S.; Jungkunst, H.F.; Gutzler, C.; Herrera, R.; Gerold, G. Atmospheric ionic deposition in tropical sites of central sulawesi determined by ion exchange resin collectors and bulk water collector. *Water. Air. Soil Pollut.* **2012**, *223*, 4485–4494, doi:10.1007/s11270-012-1211-8.
27. Petry, J.F.; Sebastião, S.A.; Martins, E.G.; Barros, P.B. de A. Innovation and the Diffusion of Technology in Agriculture in Floodplains in the State of Amazonas. *RAC - Rev. Adm. Contemp. (Journal Contemp. Adm.* **2019**, *23*, 619–635.
28. Hall, A.; Bockett, G.; Taylor, S.; Sivamohan, M.V..; Clark, N. Why Research Partnerships Really Matter: Innovation Theory, Institutional Arrangements and Implications for Developing New Technology for the Poor. *World Dev.* **2001**, *29*, 783–797, doi:10.1016/S0305-750X(01)00004-3.
29. Klerkx, L.; Leeuwis, C. Establishment and embedding of innovation brokers at different innovation system levels: Insights from the Dutch agricultural sector. *Technol. Forecast. Soc. Change* **2009**, *76*, 849–860, doi:10.1016/J.TECHFORE.2008.10.001.
30. van Mierlo, B.; Leeuwis, C.; Smits, R.; Woolthuis, R.K. Learning towards system innovation: Evaluating a systemic instrument. *Technol. Forecast. Soc. Change* **2010**, *77*, 318–334, doi:10.1016/j.techfore.2009.08.004.
31. Pigford, A.A.E.; Hickey, G.M.; Klerkx, L. Beyond agricultural innovation systems? Exploring an agricultural innovation ecosystems approach for niche design and development in sustainability transitions. *Agric. Syst.* **2018**, *164*, 116–121, doi:10.1016/j.agsy.2018.04.007.