Insight, part of a Special Feature on Seeking sustainable pathways for land use in Latin America

Transformation of traditional shifting cultivation into permanent cropping systems: a case study in Sarayaku, Ecuador

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ABSTRACT. Slash-and-burn shifting cultivation is common in indigenous societies in the Amazon basin. The large land use of this farming practice is of increasing concern because most indigenous communities are faced with population growth and territory losses. Our study aims to evaluate the feasibility of transforming shifting cultivation into a permanent cropping system by application of Terra Preta practice. For this purpose, an overview of the nutrient cycles of the agroecosystem of an indigenous family in Sarayaku, located in the eastern lowlands of the Ecuadorian Amazon, is provided. Household nutrient input and output data were collected and complemented with information from literature. The balances of nitrogen, phosphorus, and potassium were calculated in five different scenarios: (I) recycling of household waste; (II) recycling of household waste and urine; (III) recycling of household waste, urine, and feces. Whereas the first three scenarios include an external wood source, IV and V additionally integrate a tree plantation. In scenario IV the tree plantation is fertilized only with feces, while in V also with household waste. Even after consideration of nutrient losses, scenarios II to V show potential to accumulate nutrients at the farmland. These results indicate the feasibility of closing nutrient cycles with the purpose to generate permanent farmland by combining knowledge of Terra Preta practice and the way of life of indigenous communities. In a described step by step manner this new agricultural system could be implemented and improve greatly resilience and sustainability of land use in the Amazon.

Key Words: *ecological sanitation; Ecuadorian Amazonia; resilience; sustainable agriculture; Terra Preta practice*

INTRODUCTION

While the global population is rising, arable land is running short. Especially in the tropics, the increasing demand for land leads to deforestation and degradation of the soils (Steiner et al. 2007). With 300 to 500 million practitioners, shifting cultivation, combined with slash-and-burn techniques, is still the most common form of land use worldwide (Giardina et al. 2000, Steiner et al. 2007), as it is in our study area.

Intact tropical rain forests are characterized by closed nutrient cycles through tight links between litter fall and immediate root-uptake of the nutrients from rapidly decomposed organic material (Vitousek and Sanford 1986). In slash-and-burn cultivation, the nutrients of the combusted biomass become easily available for crops, but the nutrient cycle is interrupted (Giardina et al. 2000). The predominant highly weathered soils of the lowland humid tropics have a small nutrient retention capacity and thus loose nutrients rapidly. This leads to short periods of only up to three years of productive agriculture after burning (Tiessen et al. 1994). Replenishment of nutrients happens mostly by deposition and nitrogen (N) fixation through leguminous plants. Active fertilization or recycling of nutrients are unusual. To recover the nutrient status, a fallow period of up to 20 years is needed (Kleinman et al. 1996). As a result of population growth, which marks a current trend in many indigenous communities inhabiting tropical forests, fallow periods are often reduced, leading to severe soil degradation, resulting in low food production and hunger (Steiner et al. 2007). Therefore, efficient alternative agricultural production systems must be found in order to achieve food security.

There is a growing scientific interest in terra preta (TP; Portuguese for "black soil"). Terra preta refers to a soil created by pre-Columbian settlements in the Amazonian rain forest (Glaser

2006). These anthropogenic soils contain three times more organic carbon (C) in average, are richer in mineral nutrients, especially phosphorus (P), and are characterized by a larger nutrient retention capacity of TP than surrounding natural soils (Novotny et al. 2009, Glaser and Birk 2012). The crop production potential is usually much larger than in adjacent soils (Lehmann et al. 2003a). It was mostly discovered on nonfloodable land near pre-Columbian settlements (Denevan 1996, Glaser and Birk 2012). Comprehensive studies on the reason and origin of the high content of nutrients in TP have been conducted by Glaser (2006) and Glaser and Birk (2012). Human excreta and bone material, mostly from mammals and fishes, have been found in TP and could explain the high contents especially of P and calcium (Ca; Glaser and Birk 2012). Also, ash and charcoal (referred to as biochar) have been found in the TP. At present, its ancient production process is not completely unraveled, but it is clear that nutrients were recycled leading to an enhanced agricultural productivity that facilitated permanent cropping (Glaser and Birk 2012). Recent studies emphasize terra preta practices (TPP) as an alternative to slash-and-burn techniques (e.g., Glaser and Birk 2012, De Gisi et al. 2014).

A worldwide common method to recycle nutrients is to compost organic residue. It is used to treat household residue that can be reused as soil conditioner. In this process, organic material is decomposed by bacteria, fungi, and insects into humus after a period of months. At the simplest level, it requires only a heap of wet organic matter. The decomposition process can be supported by shredding the organic material, adding water, and ensuring proper aeration (Haug 2015).

Biochar, which has been found in TP, could play a major role to improve nutrient retention in the highly weathered soils of the Amazon (Batista et al. 2018). It creates a stable stock of organic

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matter in the soil, is considered to be the main factor for the persistence of TP, and might have been added purposely to ancient compost procedures (Glaser and Birk 2012). Many studies emphasize the positive effect of biochar on soil fertility and crop yield (Lehmann et al. 2003*b*, Steiner et al. 2007, Verheijen et al. 2010, Agegnehu et al. 2015). Nutrient retention by biochar has been reported, especially for nitrate and phosphate (Lehmann et al. 2003*b*, Dempster et al. 2012).

Another amendment to improve nutrient retention and nutrient status might also be clayey river sediment, while its ancient role by creation of TP remains unclear (Herrera et al. 1992, Guyot et al. 2007). Although its historical role remains unclear, mixing clayey river sediment with soil can also improve nutrient retention (Guyot et al. 2007, Beusch et al. 2019) and nutrient status (Herrera et al. 1992). Furthermore, addition of clay to compost leads to enhanced nutrient retention (Nguyen and Marschner 2013).

Recent studies working on TPP combine cycling of nutrients with new sanitation systems and biochar (De Gisi et al. 2014, Krause et al. 2015). Part of these scenarios include the separation of urine, feces, and greywater for further processing. According to the WHO (2006), untreated or briefly stored urine is safe to be used as a fertilizer. In contrast, feces contain various pathogens (bacteria, viruses, and worm eggs) and require appropriate processing (WHO 2006).

To our knowledge there is no research on the present diet and nutrient fluxes involved in the indigenous way of life and the opportunities achieved by TPP for indigenous agriculture. Thus, the overall aim of this study is to assess the feasibility of achieving permanent cropping by the closing of nutrient cycles and application of TPP in the form of a holistic study. We hypothesize that the combination of the traditional, indigenous way of life with TPP will improve nutrient status of the soils leading to extended cropping periods up to permanent cropping systems.

METHODS

Study site
The methodical approach of this study combined a field survey, laboratory analyses, and a literature review. Nutrient balances of N, P, and potassium (K) were calculated in five different scenarios, based on nutrient data collected from one household in the indigenous community of Sarayaku, Ecuador.

The study was conducted in Sarayaku (400 m a. s. l., 1°44′S, 77° 29′W), an indigenous village in the eastern lowlands of Ecuador (Fig. 1). The closest city, Puyo, is about 65 km away. As part of the Pastaza province, Sarayaku is located east of the Andes in the Amazon basin on the banks of the river Bobonaza. The settlements of Sarayaku are situated in the humid rain forest. Annual rainfall varies between 3000 and 3500 mm and the mean temperature is 23°C (Sirén 2004). Geologically, the area is characterized by fluvial deposits that were uplifted by Pliocene Andean tectonism (Räsänen et al. 1990), followed by heavy erosion resulting in a rugged landscape with ridges and small valleys (Sirén 2014). The water level of the river varies extensively. Periodically it carries new sediments and leaves patches of clayey and sandy sediments at the river banks and flood plains.

Fig. 1. Location of Sarayaku in the eastern lowlands of Ecuador (adapted from Zapata-Ríos 2001).
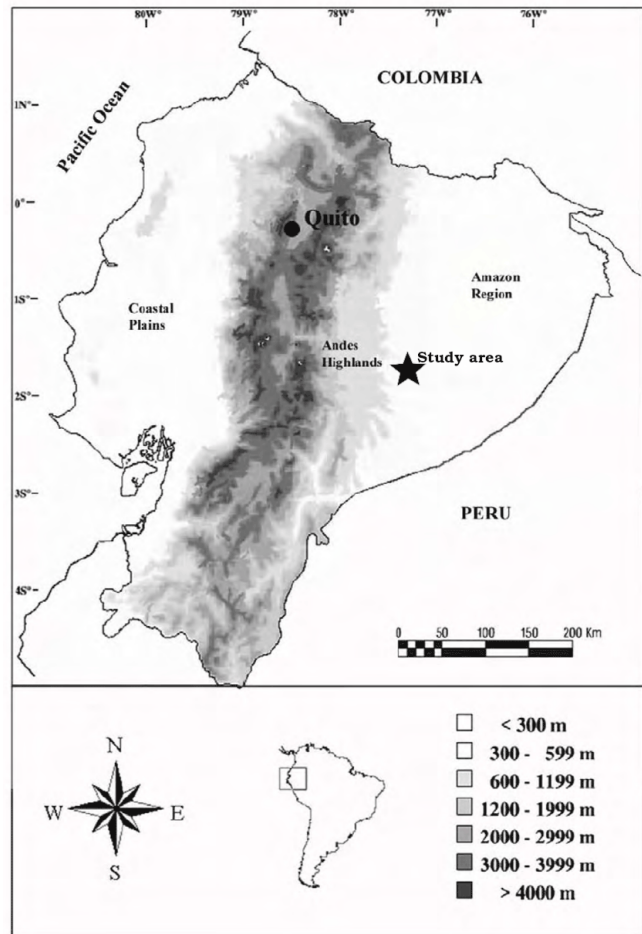
Sarayaku has about 1000 inhabitants in five different hamlets. The population grew annually by about 1.6% in the last decades (Sirén 2007). The community currently claims an area of approximately 1400 km² as its territory (Sirén 2014). For decades, Sarayaku has been known for its resistance against oil extraction. The resources driven invasion of companies and farmers has led to ongoing, and to some extent violent, territory conflicts (see also Figueroa 2006). Sarayaku is only loosely connected to the market economy. The subsistence economy is based on shifting cultivation, fishing, and hunting. The community is organized democratically with elected leaders of different sectors, e.g., a leader of women and a leader of the community. The households are mostly organized in family units. There are different houses for different purposes, e.g., gathering, cooking, sleeping, and a toilet. The families cook with wood collected downstream of the river. Because people in Sarayaku process wood quite frequently, e.g., while slashing new farmland, creating new buildings, or collecting wood, sawdust is a frequent byproduct of the Sarayaku lifestyle. Also, rotten wood is usually available in the forest with a structure similar to sawdust.

Both men and women work the farmland. After slashing, drying, and burning the above-ground biomass, farmers plant directly between the stumps. The burning residue leaves patches of ash, coal, and litter. In general, cultivation works without any further soil treatment or fertilizer addition. The main agricultural tools are machete and ax. Cultivation between two and three years is a common practice, depending on the soil fertility. To ensure soil recovery, cultivated land is usually followed by a fallow period of 20 years. Usually each household has three fields, with an average of 0.2 ha (Sirén and Machoa 2008): one in seedbed preparing or already in seeding status, one in growing status, and one in harvesting status. The heterogeneous landscape leads to farmlands on different expositions and soil types. As a consequence, it is common to have at least a second farm uphill (as flood insurance) if the farmers cultivate in the flood plain. The sandy sediments are especially used for cultivation in the flood plains. Furthermore, the cultivated crop species vary depending on soil and exposition. The most important crops are cassava (*Manihot esculenta*), plantain (*Musa* sp.), and maize (*Zea mays*). Only roots and fruits with peel are harvested, while leaves and all other plant residue is left at the farmland. Within a radius of up to five kilometers to the villages, almost all arable land is in use (Sirén and Machoa 2008). Thus, population growth demands longer distances to farmlands, a shorter fallow period, or other sources of cash income. The annual increase of cultivated area is still modest at 0.4% because of new income through governmental salaries, tourism, migratory labor, and trading that enables village inhabitants to buy their food resources elsewhere (Sirén 2007). Even so, increasing poultry, cattle, and fish ponds constitute a minor complementary food source. Population growth has led to a serious decrease in wildlife in the territory of Sarayaku (Sirén 2012). According to the local people, fish resources are declining as well, especially regarding migratory fishes (Sirén and Machoa 2008). Hunting and fishing might thus become an insecure food source.

Research strategy
One family was accompanied over 10 days at the end of October 2014. With respect to local culture, the study was based on only one participating family, because being inquisitive about food procurement and consumption is considered impolite in Sarayaku (see also Sirén and Machoa 2008). Following discussions with the family member Antonia Aranda, the family had standard habits concerning their lifestyle as subsistence farmers, the size of thier cultivated farmland, their family structure, and their general lifestyle compared to other families. The family relies only to a small extent on external food supplementation (cf. Sirén 2004).

The weights of all inputs and outputs to the household were determined every day for six days from 24 to 29 October 2014. Samples were taken for the analyzing procedure. Food supply bought from the local store could not be quantified, but interviews conducted with family member Antonio Aranda gave an approximation of this input. In order to calculate the scenarios, the wood type that is usually used for cooking was also collected.

Soil samples were taken from farmland close to the village to a depth of 0-20 cm and 20-40 cm and from the clayey and sandy patches of the river sediments. For each area, five samples were collected and mixed internally. Bulk density of the soil was obtained by sampling rings (113 cm³); two samples on five plots were taken at depths of 8-12 and 28-32 cm. Soil texture was

analyzed in the field according to AG-Boden (2006). All samples were first air-dried and then oven-dried at 40° C for at least 24 hours at Universidad Estatal Amazónica. After transport, the samples were oven dried at 105° C for 24 hours. Munktell 132 filters were used for filtration, and for determination of plant available P and K, Munktell 131 filters were used.

Soil samples were sieved (< 2 mm). Soil pH and pH of the sediments was measured in 0.01 M $CaCl_2$. Plant available P and K were determined by using a citric-lactate-acetate-extraction and measured with ICP-OES (Thermo ICAP 6000 Series) and partly with AAS in the case of K (AnalyticJena novAA 400; K = 769.8 nm). Effective cation exchange capacity (CEC_{eff}) was determined in 0.5 M ammonium chloride. Cation concentrations of the extracts were measured using ICP-OES, except for sodium (Na), which was measured with the AAS (Na = 589.5 nm). The base saturation was calculated by the sum of the cations K, magnesium (Mg), Na, and Ca divided by the CEC_{eff} times 100.

For further chemical analysis, the soil samples were ground with a ball mill. Total organic C, N, and sulfur (S) concentrations were determined using a CNS-Analyzer (Elementar Vario EL III). To obtain total concentrations of P, K, Ca, and Mg, 0.5 g solid matter was dissolved in 10 mL aqua regia and heated for 8 hours at 185° C in a closed teflon pot. After filtration, the elements were determined by ICP-OES. Household waste samples and all plant samples were ground with a planetary mill. Nitrogen concentrations were determined with the CNS-Analyzer. To determine the concentrations of P, K, Mg, and Ca, 250 mg of plant material were added to 5 mL nitric acid, and 100 mg of ash to 10 mL, respectively, in the case of the ash. The solution was heated for 8 hours at 185° C in a closed teflon pot and then filtrated. Measurement was done with ICP-OES.

To obtain a total overview of the household's nutrient fluxes, all missing data was complemented by means of literature-derived data and explicitly stated (see Tables 1 and 2). So as to respect the local family, feces and urine were not sampled. The total nutrient amount of feces, urine, and greywater was assumed to be similar to ingestion and was therefore approximated by the consumption of food (Table 2). Nitrogen concentration was derived by multiplying protein concentrations times food specific factors proposed by Mariotti et al. (2008).

Calculations of nutrient fluxes
Parameters describing nutrient dynamics, like leaching and erosion of the study field soil, were taken from literature, if literature data was available and could be compared. Soil erosion was estimated by comparing erosion signs at the farmland with data of erosion in shifting cultivation systems in tropical agroforestry collected by Wiersum (1984). It was finally multiplied times the nutrient difference between the upper layer and the soil below. Leaching of P was approximated with data of a fertilized sandy clay loam in Brazil (Blum et al. 2013). In the case of K, leaching was calculated by an equation developed by FAO (2003) including plant available K of the first 20 cm and a factor F depending on precipitation (PRC) and clay concentration:

$$K_{leaching} = K_{available} * F(PRC, clay\ concentration)$$

According to Blum et al. (2013), N leaching can be estimated by considering the total N input by fertilizers (here zero) and the rainfall. Based on that, N leaching was estimated by comparison

Table 1. Total nutrient concentrations of substances used and produced in the household. Part of the values were derived by own analysis (n = 2), the other values were taken from literature. All moisture data was taken from literature, indicated by references and superscripts below.

	Moisture %	N_{tot} mg/kg	K_{tot} mg/kg	P_{tot} mg/kg	References
Food supply, edible portion					
Cassava	60	3644	6775	675	USDA 2015*a*
Fish	80	146774	17900	10450	USDA 2015*b*
Plantain	65	6633	14257	971	USDA 2015*c*
Lentils	8.26	48114	7380	3063	USDA 2015*d*
Rice	12.89	14210	987	1240	USDA 2015*e*
Eggs	76.15	92716	5786	8302	USDA 2015*f*
Nonedible food portion					
Plantain peel	82.9[1]	14162 ±236	66372 ±1670	2424 ±22	own analysis
Cassava peel	72.1[2]	9786	2912	1671	Akpabio et al. 2012
Residue of *asua*	0.9[3]	4791 ±16	10023 ±81	916 ±33	own analysis
Fish meal	6[4]	130357	6051	44374	Dale 2001
Egg shells	0.1[5]	3750	416	993	Hincke et al. 2012
Wood and wood residues					
Firewood	53[6]	1436 ±47	156 ±11	59 ±3	own analysis
Ash		294 ±22	111405 ±316	8697 ±46	own analysis
Coal		2562 ±803	5455 ±148	1600 ±40	own analysis
Sawdust	53[6]	1436 ±47	156 ±11	59 ±3	own analysis
Waste water					
Urin[†]		87	54	50	Jönsson et al. 2004
Feces[†]		10	12	40	Jönsson et al. 2004

[1]Izonfuo and Omuaru 1988; [2]Akpabio et al. 2012; [3]own assumption; [4]Dale 2001; [5]Nys et al. 2011; [6]Suzuki 1999.
[†] = % of total nutrient value of the household waste water.

with a long-term study conducted in a comparable climate zone, the subtropics in China (Long et al. 2015):

$$N_{leaching} = N_{leaching,China} / PRC_{China} * PRC_{Sarayaku}$$

Data for deposition of nutrients was taken from a study conducted in the south of Ecuador as an example for the deposition of nutrients in the eastern Andes (Boy et al. 2008). Rates of N-fixation were taken from data sampled by FAO (2003), as well as denitrification depending on precipitation. Run-off data was taken from a study of cassava crop fields conducted in the Andean region of Colombia (R. H. Howeler 2001, unpublished manuscript, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.424.7558&rep=rep1&type=pdf).

Although some recycled nutrients would not be plant available in the first year, we argue that it makes sense to calculate with total nutrient concentrations, given the importance of long-term orientation. For the nutrient balance of all scenarios, a hypothetic soil amendment share of 50 vol% biochar and 5 vol% clayey sediment of the compost was calculated, as performed by Schulz and Glaser (2012) and by Bölttcher et al. (2013), respectively. The density of the compost was approximated as 700 kg m^{-3} by comparing with the results of Krause et al. (2015). To calculate the nutrient demand for the tree plantation, we analyzed the required amount of wood for cooking and biochar production and multiplied that with the nutrient concentrations of the analyzed sawdust.

By means of simplification, any child was calculated as a half adult. All calculations related to farmland, field, or soil refer to one farm of the participating family, which is located near the hamlet and covers 0.42 ha. The balance at the farmland is given by the equation:

Farmland = input − output ± Δ soil [g / capita * a]

where input is the sum of compost, clay, coal, and human excreta, output is harvest, and Δ soil refers to the soil dynamic parameters (Fig. 2). All calculations of the scenarios were calculated per person, which means that the field of 0.42 ha was split into 5.5 portions (the number of persons of the participating family), leading to an area of 764 m^2 for each person. If not explicitly stated, all data is related to dry matter.

Fig. 2. Soil nutrient dynamics [kg/ha a^{-1}] of the investigated farmland without human activities, like harvesting or fertilization. Their calculation is based on data taken from the following literature: [1]Boy et al. 2008; [2]FAO 2003; [3]estimated according to Wiersum 1984; [4]Long et al. 2015; [5]Blum et al. 2013; [6]Howeler 2001.
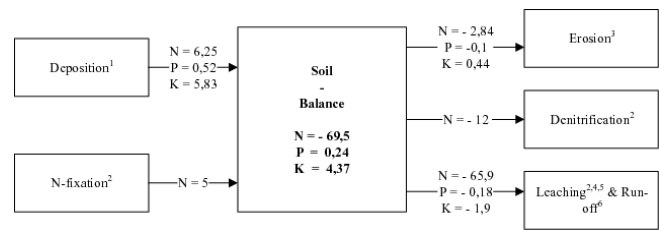
Model and scenarios
Five different scenarios of nutrient cycles were established and balanced based on extrapolation of the results of the field survey, laboratory analyses, and information from literature (Table 3). The first three scenarios were based on the present condition in Sarayaku, in which wood is easily available, which is presumed to

Table 2. Household nutrient fluxes and the amount of food consumption, human excreta, and household waste. Own analysis was complemented by literature, indicated by the superscripts below.

		Dry matter g/capita day[-1]	N g/capita a[-1]	P g/capita a[-1]	K g/capita a[-1]
Consumption					
	Cassava	372[1]	921	92	1028
	Fish	58[1]	3100	221	378
	Plantain	174[1]	508	87	1092
	Lentils	35[1]	617	39	95
	Rice	35[1]	182	16	13
	Eggs	60[1]	2268	203	142
	Total	734	7597	658	2747
Human excreta					
	Urine[†]		6609	355	1374
	Feces[†]		760	79	1099
Compost					
	Plantain peel	91[2]	468	80	2194
	Cassava peel[‡]	43[3]	155	26	46
	Residue of *asua*	114 (90%)[4]	199	38	416
	Ash	15 (0%)[4]	2	46	593
	Fish bones and meat[‡]	25[1,5]	1171	398	54
	Eggshells[‡]	7 (0%)[4]	9	2	1
	Total	293	2003	592	3304

Daily dry matter of the substances is given by the results of the survey about input and output to the household corrected with their moisture given by literature: [1]USDA 2015; [2]Izonfuo and Omuaru 1988; [3]Akpabio et al. 2012; [4]own assumptions; [5]Dale 2001.
[†] Total waste water nutrient amount was derived by comparing to the food consumption. The proportion of each share was given by Jönsson et al. 2004.
[‡] The amount of cassava peels, fish residue, and eggshells were calculated as a certain percentage of the consumed food. In the case of cassava peel it was derived from studies of subsistence, hand-peeled cassava, and was 22.5 wt% of the consumed cassava (Sangodoyin and Amori 2013). Based on our own observations, eggshells were assumed to be 10 wt% of the consumed eggs and fish residues 10 wt% of the consumed fish, in the form of half bones and half meat.

Table 3. Scenarios considered in this study: The first scenario recycles all household wastes without human excreta. Scenario II additionally includes urine, and scenario III, both urine and feces. Scenarios IV and V differ from the third in the way of producing the wood in form of a tree plantation. Scenario IV also recycles the feces, but only to fertilize the tree plantation, rather than in the cropping system, the main aim of which is to avoid hygienic risks. Scenario V includes feces at the tree plantation and at the farmland, by integrating feces in the compost.

	Household waste	Urine	Feces	Tree plantation
Scenario 1	X			
Scenario 2	X	X		
Scenario 3	X	X	X	
Scenario 4	X	X	(X)	X
Scenario 5	X	X	X	X

be similar in most indigenous communities of the Amazonian rain forest. They vary in the integration of human excreta and show consequently the different nutrient recycling potential (Fig. 3). The other two scenarios integrate the production of wood and therefore do not depend on external wood sources (Fig. 4). Firewood, fishery, and purchase of external food are referred to as external input in the scenarios I to III. Nutrient amount of the tree plantation is given by the demand for firewood and coal. The required nutrients come from the feces (scenario IV) or the compost (scenario V).

Fig. 3. Scenarios I, II, and III: As input to the household are shown the nutrients from the farmland and the external input of nutrients to the household by the forest, the fishery, and the purchase of external food (given by neighbors or bought as groceries). All household waste with the exception of human excreta are proposed to be composted with coal and river clay. Part of these scenarios is the input of wood for cooking and coal production with external wood, as is customary in Sarayaku. Although in scenario I no human excreta is recycled, scenario II involves human urine (dotted line) and scenario III, both human urine and feces (dashed and dotted line).
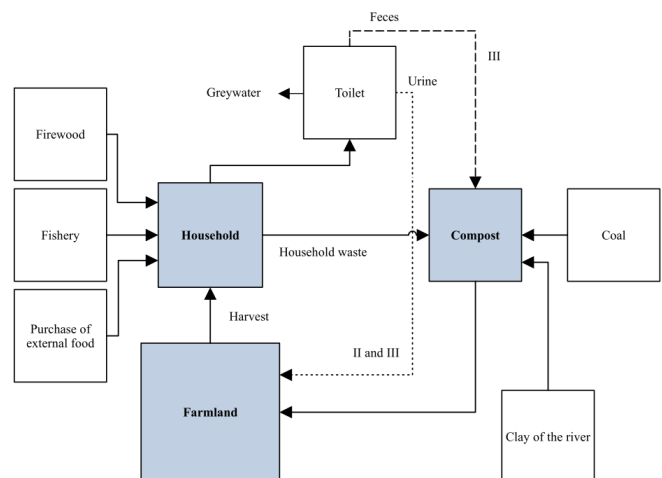
Fig. 4. Scenario IV and V: In these scenarios a tree plantation is integrated in order to produce firewood and coal, which allow independence from external wood resources. Therefore, only the fishery and purchase of external food integrate external nutrients into the system. In scenario IV, feces are used as nutrient input for the tree plantation (dashed line). In constrast, scenario V includes feces only in the compost, and the tree plantation is fertilized by a certain portion of it (dotted line).
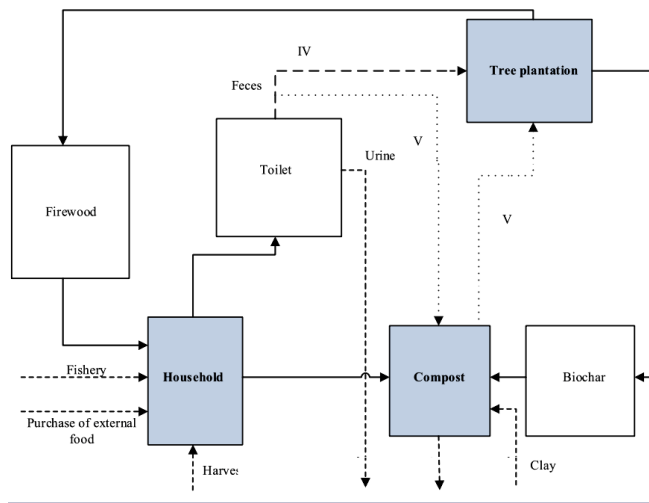
RESULTS

Main features of the case study

The participating family has four adult members and three children. One of the adults earns a small amount of extra cash income by working for the community on the reforestation of palms for rooftop construction and special trees. They usually buy small amounts of food in a little shop in the village or from neighbors, including lentils, rice, eggs, oil, meat, and fish as is custom in Sarayaku (see also Sirén and Machoa 2008). In the morning, family members usually only drink the fermented beverage *asua*, made of cassava, and later on the day they cook. *Asua* is one of the major food sources, especially when other food is rare. As is common for the investigated region, the residue of the food is not composted but thrown out of the kitchen and partly eaten by poultry and dogs of the neighbors. The family cultivates currently two farms of 0.42 and 0.105 ha. A small pathway uphill passes by the bigger farm, which is located on the hillside about one km away from the village, and it was cleared and burned in August 2014. The smaller one is about 3 km away from the hamlet, on top of the same hill and was cleared and burned one year before. On both farm, mostly cassava is cultivated, followed by plantain and a few flowers, other fruits, and root-crops at less than 10% of all crops. The soil is sandy clay that contains at least 35% clay and a minimum of 45% sand. The closer farm, which covers 0.42 ha, was considered suitable as permanent farmland because it is located outside the river flood plain, but still close to the hamlet. That is why all further calculations referring to farmland and its soil refer to the above-mentioned farmland.

Nutrient concentration of soil and river sediments

The pH of the sediments is almost neutral, while acidic in the farmland (Table 4). Both sediments have higher total K, P, Ca, and Mg concentrations and lower S and C concentrations than the farmland at each depth. The clayey sediment shows the highest concentration for almost all nutrients. It has more than 10 times more Ca, 7 times more Mg, 5 times more K, and 2 times more P than the farmland at both depths. The clayey river sediment contains the highest concentrations of plant available K, followed by the first 20 cm of the farmland. Plant available P was detected in the following order from highest to lowest concentration: in the clayey sediment, the first 20 cm at the farmland, the sandy sediment, and the farmland's soil between 20 and 40 cm. The CEC_{eff} of the clayey sediment is more than four times larger than that of the farmland and sandy sediment. Compared to the farmland, the base saturation of both sediments is very high.

Table 4. Total nutrient concentrations, pH, plant available K and P, effective cation exchange capacity (CEC_{eff}), and base saturation (BS) of the farmland and the river sediments. Number of analyzed samples was n = 2, with the exception of pH and BS (n = 1).

	Unit	Sandy river sediment	Clayey river sediment	Farmland 0-20 cm	Farmland 20-40 cm
N_{tot}	mg/kg	133 ±1	1020 ±6	2199 ±19	1176 ±3
P_{tot}	mg/kg	154 ±1	339 ±1	133 ±8	96 ±1
K_{tot}	mg/kg	3185 ±37	10743 ±4	2093 ±50	2249 ±14
C_{tot}	mg/kg	764 ±49	11216 ±38	23132 ±151	9675 ±39
Ca_{tot}	mg/kg	3832 ±1	7538 ±1	560 ±8	321 ±1
Mg_{tot}	mg/kg	2816 ±26	8572 ±46	1286 ±3	1362 ±3
S_{tot}	mg/kg	52 ±<0.1	158 ±17	280 ±2	160 ±0,3
pH_{CaCl2}		6.11	5.98	4.05	3.92
$K_{avail.}$	mg/kg	10 ±3	59 ±1	51 ±2	10 ±1
$P_{avail.}$	mg/kg	1.5 ±<0.1	8.6 ±<0.1	4.3 ±<0.1	0.6 ±<0.1
$CEC_{eff.}$	cmolc/kg	3.23 ±0.1	21.98 ±0.3	4.26 ±0.1	4.33 ±0.1
BS	%	97.3	99.5	42.3	19.0

Nutrient balance of the soil

The total nutrient stock at the farmland in the first 40 cm is 6615 kg N ha^{-1}, 447 kg P ha^{-1}, and 8511 kg K ha^{-1}. Soil erosion was estimated as moderate with an erosion potential of 2.78 t/ha, as a result of no tillage practice, low erosion signs (no water channels, a moderate hillslope of around 5%, and still litter lying above-ground) but low soil cover by plants, which intensifies erosion (compare to Wiersum 1984). Overall nutrient dynamics of the farmland after burning, but without further human activity, are negative in the case of N and positive for P and K (Fig. 2).

Fate and concentration of household nutrients

The main food consumed by the family was plantain and cassava, the latter in the form of *asua*. Approximately half of the cooked meals were complemented by fish, and half with eggs. The most important food supply for K was cassava and plantain. Fish and eggs appeared to be the most important supply of P. The quantitative summary of the food supply is similar to another study made in Sarayaku (Table 5).

The residue of the food was, in order of the accruing amount, residue of *asua*, plantain peel, cassava peel, fish bones and meat, ash, and eggshells. The largest amount of K per capita and year was detected in plantain peel and urine, in the case of P in urine and fish bones and meat. The highest amount of nitrogen was detected in urine, fish bones and meat, and feces (Table 2).

Table 5. Food supply in kg/capita day^{-1}; raw material. Comparison between present study and another study made in Sarayaku.

	Present study	Sirén and Machoa 2008
Cassava	1.03	1.55
Fish/wild/eggs	0.64	0.34
Plantain	0.83	0.72
Total	2.50	2.62

Nutrient balance of the scenarios

Scenarios II to V are able to accumulate N, P, and K at the farmland (Table 6). Scenario I shows lack of N and K. Scenario V shows a higher accumulation of all considered nutrients than scenario IV (Table 6). Compared to I, the additional nutrient recycling is, in order of scenarios II to V, 420, 466, 420, and 413% for nitrogen, 170, 203, 170, and 180% for phosphorus, and 157, 178, 157, and 158% for potassium.

DISCUSSION

Considering the results, this case study shows that it is feasible to accumulate nutrients at the farmland as a prerequisite for generation of permanent farmland by combining knowledge of TPP and the way of life of indigenous communities. Prolonging crop periods or substitution of slash-and-burn-practice seem possible.

Utilization of river sediments

The clayey sediment showed good results in nutrient concentration, alkalinity, and CEC$_{eff}$ and might, thus, be useful to enhance the composting process. Other river sediments, located near Sarayaku, showed similar concentrations of exchangeable basic cations (Martinelli et al. 1993). The closer the sediments are to the Andes, from where the Amazon rivers carry plutonic, nutrient rich material downstream, the higher their percentage of illites and smectites (clay minerals with a high CEC$_{eff}$; Guyot et al. 2007). The high pH of the analyzed sediments could have a positive impact on soil acidity and reduce Al-toxicity, increase P availability and activity of microorganisms when added to the soil (Giardina et al. 2000). The higher concentration of some nutrients compared to the soil of the farmland could also improve nutrient status. Furthermore, the high CEC$_{eff}$ of the clayey sediment leads to increased adsorption capacity to K and ammonium. However, concentrations of available K and P of both sediments were only slightly higher than those of the upper layer of the farmland's soil and seem therefore not suitable as soil amendment. To generate real impact by adding sediment to the farmland, the amount needed would thus be tremendous. In a study pertaining to the lowlands of Colombia, Herrera et al. (1992) calculated a requirement of 245 t/ha^{-1} a^{-1} river sediment to significantly increase soil fertility. It seems unlikely that this could be done by hand and therefore it could be considered futile with respect to farmlands out of the flood plains. Local farmers prefer sandy instead of clayey patches for planting in the flood plains, because of an improved soil structure, leading to better permeability for water and easier workability. However, in the creation of persistent soil organic matter, clay could play a major role. In the composting process, organic matter can interact with clay-minerals and create clay-humus-complexes, enhancing soil fertility (Evans and Russel 1959) and nutrient retention (Nguyen and Marschner 2013). In conclusion, mixing clay with compost is most likely to result in a positive impact and its implementation does not require too much effort.

Nutrient dynamics of the soils

When comparing total nutrient stock at the farmland with the annual output through soil dynamics without human activity, the accumulation of P and K is far lower than 1%, and only in the case of N with a loss of 1.1% it shows significant change to the nutrient status. The results of the nutrient dynamics are mostly based on literature and are not satisfactorily fitting in all cases, especially pertaining to leaching of N.

Nutrient dynamics of the farmland's soil were calculated without further human changes like the added compost, although nutrient leaching from these amendments is likely. The precise values were not further investigated, but some possible changes shall be discussed. Whereas Schulz and Glaser (2012) detected increased leaching of phosphorus and nitrogen in the first year after application of compost and biochar, other studies have shown decreased leaching of N (Lehmann et al. 2003b) and of P (Agegnehu et al. 2015). The recalcitrant biochar might remain in the soil for centuries and lead to better nutrient and water holding capacity (Verheijen et al. 2010). When the biochar is annually given as a part of the compost to the farmland, it would be a small amount relative to the soil in the early years. Thus, the nutrient leaching of the urine, as liquid fertilizer, may be high because of the still low CEC$_{eff}$ of the soil. Erosion could potentially become a problem, if the upper layer of the permanent farmland, enriched with compost and urine, erodes and reveals the unimproved soil below. However, biochar and vermicompost (composting with worms) as soil amendment have shown decreased erosion and run-off (Thu Doan et al. 2015). In conclusion, parts of the nutrients might be lost after their addition to the field and the balances might be affected negatively. However, in the long run carbon content and sorption capacity should improve through repeated amendment of biochar and other resilient organic matter from the compost. The nutrient dynamics of the tree plantation's soil were not further investigated. It was assumed to be low in nutrient losses because of the almost undisturbed plant situation and soil cover (see also Vitousek and Sanford 1986).

Household nutrients and composting

High amounts of P and N were contributed by fish and eggs. Potassium was mostly given by plantain and cassava. If nutrient supplies by fishing decrease, the balance could, thus, become negative. This could be compensated by introducing poultry, increasing farm yield, or other food supply.

Only one family's nutrition was investigated in this study, and the family was not randomly chosen. The short sample period could furthermore increase errors by seasonal bias. One deviation was the fact that the family hunted less frequently than an average family in Sarayaku (see also Sirén and Machoa 2008). With regard to Sirén and Machoa (2008), the consumption of wild game corresponds to about one quarter of the consumption of fish. The nutrient composition of wild game is similar to fish for N and K, but less in P (USDA 2015b, 2019), so that the investigated family might have a slightly higher input of P than others. Because the balance of P is very positive in all scenarios, this would not prevent its accumulation on the farmland (see Table 5).

Table 6. Nutrient cycling balance of all scenarios [g/capita a⁻¹].

	N		P		K	
	input	output	input	output	input	output
Scenario 1						
Harvest		-2196		-343		-4413
soil dynamics	859	-6168	40	-22	446	-112
Compost	2003		592		3304	
Clay	10		3		103	
Biochar	51		32		108	
Total		-5442	302			-566
Scenario 2						
Scenario 1		-5442	302		566	
Urine	6609		355		1374	
Total	1167		658		808	
Scenario 3						
Scenario 2	1167		658		808	
Feces	760		79		1099	
Total	1927		736		1907	
Scenario 4						
Scenario 3	1927		736		1907	
Tree plantation, feces fertilized		-760		-79		-1099
Total	1167		658		808	
Scenario 5						
Scenario 3	1927		736		1907	
Tree plantation, compost fertilized		-485		-50		-284
Total	1442		686			

C/N-ratio of the compost would drop to around four in all scenarios, resulting in mobilization and loss of N (e.g., by leaching and volatilization), if the urine would be added to the compost. Without urine, the resulting ratios of the compost were between 17 and 22 in the scenarios II to IV and were therefore still below the optimal ratio of C/N equal to 25 (Finck 2007). Only scenario V showed a higher C/N-ratio of 32. The low C/N-ratio of the other scenarios could be managed by addition of C-rich materials like sawdust or rotten wood. As mentioned, the by-production of sawdust is rare or very work intensive in Sarayaku. Rotten wood would need to be carried from the forest. Thus, application of urine as liquid fertilizer for crops seems preferential to secure N availability for the crops, other than the addition of urine to the compost. However, direct fertilization could increase volatilization of ammonia, which should be decreased by fast incorporation of the urine into the soil (Sommer and Hutchings 2001).

Leaching and volatilization of nutrients during the compost procedure were not calculated as part of the balances because it depends greatly on the design of the composting process (Hao and Benke 2008) and was therefore difficult to predict. However, especially in the case of nitrogen, it is most likely to affect the balances negatively.

Evaluation of the scenarios
All scenarios (except for scenario I) exhibit potential to accumulate nutrients at the farmland. Scenario III is the best with respect to the overall quantity of recycled nutrients. The integration of human excreta, at least urine, is necessary for a positive nutrient balance. Furthermore, recycling both urine and feces leads to a better nutrient recycling, even though feces contribute less nutrients than urine. Regarding the nutrient amounts, scenarios IV and V are only slightly different to each other. Also, others, especially the high nutrient input by fish and eggs, result in the positive balance of the scenarios.

The lack of N in the first scenario could be compensated by intercropping with leguminous plants. Pulses, like soybeans, which also grow in the tropics and are important dietary components, are able to incorporate atmospherical N into the soil through symbiosis with bacteria (Döbereiner 1997). Salvagiotti et al. (2008) detected an N intake of 129 kg ha⁻¹ a⁻¹ into the soil when 100 kg ha⁻¹ a⁻¹ N was additionally applied as fertilizer. In contrast, K requires external sources. Considering that, scenario I does not seem to be able to facilitate permanent farmland. Instead, Scenario II seems particularly suitable because of its accumulation of nutrients and its low hygienic risks.

Both scenarios with tree plantation have their special advantages. Although scenario V shows more accumulation of N, P, and K, scenario IV has the benefit of a lower hygienic risk. The feces could be sampled, dried separately, and fertilize the tree plantation, e.g., the trees could be planted on top of the buried feces. In this way the recycling of the feces could be managed with less risk of hygienic problems than by fertilizing the crops with it or its integration into compost. Although hygienization of feces through composting is an approved method (Heinonen-Tanski and van Wijk-Sijbesma 2005, Krause et al. 2015), it could increase hygienic problems in the case of Sarayaku. Most likely, the compost would be located near the house and insects might cross the compost and the household and thus spread pathogens. In order to avoid diseases, scenario III and V should only be implemented under scientific monitoring. In discussions about the reuse of feces for agriculture in Sarayaku, the idea was always rejected by locals, for the very reason of diseases in the past because of bad treatment of human excreta.

Situated in a huge, intact rain forest, the external input of wood does not seem to pose a problem in Sarayaku. However, in other communities the situation could be different. Even in Sarayaku present conditions could change as population grows or by expropriation through government or private companies. Furthermore, the consequences of disturbing the rain forest near indigenous communities through tree harvesting remain unclear (Sirén 2014). When crop periods are extended because of the application of a scenario, less shifting of farmlands will be necessary, leading to less fallow periods and more space for tree plantations. Despite the limitations, this concept shows potential to improve resilience and sustainability for subsistence farming far beyond Sarayaku as many indigenous communities who have gotten access to markets and/or have settled down permanently confront similar problems (Sirén 2007).

Comparing the scenarios with substances found in TP soils, like bone material and excreta (Glaser and Birk 2012), the third scenario including excreta and bone material from household waste seems to be the closest with respect to its ingredients. However, the comparability to the TP process remains unclear. According to the calculations, it would take approximately 125 years (scenario II) to reach total phosphorous concentrations like those found in the terra preta of 300 mg/kg (Novotny et al. 2009). Still, it is uncertain whether other macro- and micronutrients accumulate or not. Moreover, food residue, especially from animals, are presently given to poultry and dogs, which seems to contradict the concept.

Practical implementation

The integration of the compost's nutrients into the land use system demands particular attention for a genuine application of the concept. Within one year, a compost amount of almost 100 kg per person is produced, and its addition to the upper 20 cm of the farmland would result in less than 0.1 wt% compost in the soil. This study thus proposes to mix the compost into the first 20 cm of the soil near perennial crops with a large nutrient demand, such as plantain, or to mix compost into the soil in special areas for planting new crops. In a step-by-step process to be carried out over time, the compost would be distributed over the whole farmland, whereas some of the very recalcitrant substances might improve the soil for decades, such as biochar and clay-humus-complexes. High yields of 25 t/ha were obtained in a Colombian cassava field when 150 kg of N per year was fertilized (Howeler 2012). Assuming 150 kg as an appropriate upper limit for N-fertilization, the amount of recycled N in the case of scenario II could fertilize almost 600 m² of the permanent farmland. The amount of K and P would be 83 and 16 kg/ha, respectively. To ensure the food demand of the investigated family, 550 kg harvest is required per year and per person, which corresponds to almost 8 t ha^{-1}, when only 600 m² would be cultivated. Thus, the permanent farmland requires at least this productivity to become an alternative to the present system. Regarding differences in the soil, exposition, and other parameters, one third of the mentioned yield of 25 t ha^{-1} might be achievable as total yield of all crops. The present system that yields 2.7 t ha^{-1} a^{-1}, would thus need to become three times more productive, which seems very ambitious. To reach compost fertilization of at least 1 wt% of the upper 20 cm of the soil, 55 m² could be fertilized by compost per year. In 11 years, the farmland of 600 m² would be supplied by 1 wt% compost and

biochar. To reduce leaching and volatilization of nutrients, urine should be used to fertilize foremost areas with compost amendment. After a few years, biochar should be distributed over most of the parts of the farmland and the retention of the nutrients of urine should be enhanced over the entire farmland.

To prevent high nutrient loss, a closed compost bin, or at least a protected location situated under a roof or big tree is highly recommended. The residues of *asua* might enhance the composting process by supplying lacto-fermentation bacteria (see also Vallejo et al. 2013). Furthermore, slash-and-char, or charring the biomass instead of burning, is described as a new method to improve food production, whereas 50% of the above-ground C can be converted into charcoal, compared to 1.7% in the case of slash-and-burn (Fearnside et al. 2001). It can thus be included in the developed scenario in order to improve nutrient retention by charcoal from the outset.

Cultural factors might also influence practical implementation. Although older people were much more skeptical about the concept, especially about reusing human excrement, younger people were more interested. The younger generation is increasingly seeking contact with the capitalist market economy because the subsistence economy is more strenuous than other jobs. The present concept supports the desire to invest less time and energy in field work because it could shorten walking distances and make very time-consuming clearing of fallows unnecessary.

FINAL REMARKS AND PERSPECTIVES

Recycling nutrients in the proposed scenarios exhibits potential to enhance soil fertility and could improve resilience and sustainability of indigenous communities and subsistence farming in the Amazon. The amendment of clayey sediment can enhance the compost quality and the high CEC$_{eff}$ may increase retention of ammonium and K. This might be a good supplement to the biochar, which is foremost able to increase retention of nitrate and P.

Which scenario may be the best depends on the present condition of the agriculture, wood availability, and the willingness and capacity to recycle feces. Regarding the circumstances of Sarayaku, this study proposes scenario II, because of its low risk of pathogen contamination and its potential to generate permanent farmland. The first step of implementation could be to complement common shifting cultivation by gradually increasing permanent farmlands. Depending on the success of the permanent agricultural system, permanent farmland could substitute the slash-and-burn shifting cultivation in a step-by-step process over time.

The treatment of feces, the composting process, and its mixing with the soil of the farmland turned out to be the most complex steps regarding the implementation of the presented scenarios. Eventually, preparing compost and managing of the permanent farmland close to settlements might amount to less work than continuous clearing and preparing fallows with increased walking distances to the farmlands due to population growth linked with rising demand for arable land. Progressive enlargement of fertilized farmlands or gardens near the houses might become the exclusive cropping system. The transferability of the scenarios to other indigenous communities or subsistence farmers is likely, but

would need further discussion. The proposed scenarios may only with many assumptions be applicable to the whole year or other families. The presented concept might help growing communities to cultivate on less area leading to extended fallow periods with better regeneration of soils and more space for undisturbed rainforest, which probably results in better food production and more hunting success. Furthermore, a sustainable and productive mode of agriculture might contribute to allowing the communities to reach a position in which they can maintain their lifestyle and counteract the ongoing exploitation of natural resources and deforestation.

Ultimately, the question as to whether an applied scenario (II to V) has the chance to create TP and has the possibility to generate permanent farmland demands further field studies, more surveys and long time experiments with focus on practical implementation. To ensure results, further studies of sediment characteristics and their utilization as compost amendment are suggested. Additional studies should analyze nutrient accumulation at the permanent farmland and crop productivity after implementation of scenario II. Surveys about food procurement, especially regarding seasonal differences and other communities, would also be essential.

At first attempts to apply the concept in practice, conducted in March 2016 in Sarayaku, the composting process and the necessary patience until success turned out to be the most critical points hindering implementation. Therefore, long-time experiments with a focus on creating regional models would be necessary to convince indigenous communities to transform their traditional shifting cultivation into permanent cropping systems. Training to learn how to produce biochar and improve composting are, furthermore, essential.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/11252

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