Bio-economic evaluation of forage cultivation scenarios in crop-dairy systems in Lushoto District, Tanzania

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Period: September, 2015 – April, 2016

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Credits: 36

Code number/name course: FSE-80436/Farming Systems Ecology thesis

Period: September, 2015 – April, 2016

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ABSTRACT

Lushoto District is part of Tanzania's most important milk production regions; depending on the village, 25-95% of households own improved dairy cows. However, land pressure is high and both income and food security are low. The aim of this study has been to assess the potential of various forage cultivation intensification strategies ('scenarios') to improve physical production and income of smallholder crop-dairy farmers in Lushoto district, Tanzania. Representative farms were created in the FarmDESIGN model with data from household surveys, feed analyses, milk measurements, soil samples and GPS measurements from 20 farms in Ubiri village. Two baseline farms were modeled, to account for the sample range in labor availability: 4 farm households were headed by a single (grand)parent; as such, available labor was about half the level of households with at least two members active on-farm full-time. The baseline farm without such labor-constraints ('HL' for 'high labor') owns two dairy cows, the baseline farm with limited labor ('LL') does not own cattle. A participatory scenario development workshop revealed the most promising intensification strategy: Napier cultivation on the plots close to the homesteads. Bio-economic performance under this scenario was modeled for each representative farm, the main management difference between HL and LL being that the latter does not collect natural grasses from public land in addition to Napier cultivation. The scenario shows potential for substantial improvement compared to the baseline: a tripling of milk production, a net cash income increase of 147%, and no reduction in household food production on the representative farm without labor constraints. This scenario seems promising for both farms, but it should be noted that [1] the farms would become structurally reliant on mineral fertilizers and imported maize bran, and [2] the LL farm runs a negative carbon balance because it does not import natural grasses, thereby threatening long-term soil fertility. Results needs to be validated by future research, but they show potential for improving livelihoods of smallholder dairy farmers in Lushoto.

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Acronyms, abbreviations and notes

C	Carbon
CP	Crude protein
ha	Hectare
K	Potassium
LU	Livestock unit
ME	Metabolizable energy
N	Nitrogen
P	Phosphorus
TSh.	Tanzanian Shillings
USD	United States Dollars (March 5, 2016 exchange rate used)

1. Introduction

1.1. Context

Sub-Saharan Africa

Studies of Sub-Saharan African (SSA) agriculture have consistently shown so-called yield gaps: differences between actual and potential crop yield levels (Tittonell & Giller, 2013). These gaps held for Asian smallholder agriculture alike until the 1970s, when the Green Revolution—with its reliance on irrigation, mineral fertilizers and synthetic biocides—brought a boost to yields, effectively ending widespread famines and food insecurity. A Green Revolution equivalent for SSA never materialized. Studies of Asian agriculture, however, indicate that the Green Revolution style of farming might not be the best way forward either Irrigated arable farming has lowered groundwater tables; the region's reliance on mineral fertilizers has increased its dependency on petroleum oil and agriculture's environmental pollution from nutrient leaching and greenhouse gas emissions; and biocide application has led to health problems among farmworkers and consumers alike (e.g. Byerlee, 1992; Singh, 2000; Gupta et al., 2003). SSA and Asian agriculture can be stereotyped to two extremes of tropical farming: the former characterized by little inputs and low yields, the latter by a strong reliance on inputs and equally robust yields. Half a century later, a branch of agricultural science calls for "ecological intensification" (Tittonell & Giller, 2013, p. 76), i.e. more agricultural outputs—food, fibre, fuel and services—from less inputs—chemicals, fuel and oil-derived materials—by harnessing ecological processes.

In most of SSA, however, the ongoing importance of agriculture for rural livelihoods leads policymakers to focus on the 'intensification' component, whether ecological or not (Tittonell & Giller, 2013). Arable farmers in many SSA regions struggle to increase productivity in line with human population growth. In degraded or low-potential areas, characterized by soil losses from erosion and nutrient and organic matter deficiencies, the issue is most urgent; in higher-potential areas, where all suitable land has been cleared for cultivation, productivity improvements are the only way forward (Waithaka et al., 2006). SSA's cereal yield per hectare grows by around 1% per year, its tuber yields per hectare grow by 0.6% per year; with the inclusion of increasing land under cultivation, food production in SSA rises by around 2% per year while the population grows at 3% per year (Tittonell & Giller, 2013). Many smallholder farmers in SSA are trapped in poverty: without purchased inputs such as certified seeds and fertilizers, or livestock disease prevention and treatment measures, their enterprise will remain low-investment, low-return (Waithaka et al., 2006).

Tanzania

In certain respects, Tanzania's agricultural sector is typical for the East African region (FAO, 2016a). Its average farm size is 1.5 hectare, slightly smaller than in Ethiopia (1.82 ha) but larger than in Uganda (1.12 ha) and Kenya (0.86 ha). The average Tanzanian farm household income is 4,062 USD/year, compared to 3,132 USD/year for Kenya and 2,698 USD/year for Uganda. For Tanzania, 70 percent of the farm household income comes from on-farm labor, compared to 85 percent for Ethiopia and 56 percent for Kenya. Tanzanian farmers on average own 2.1 Tropical Livestock Units (TLU), slightly lower than both Uganda (2.3 TLU) and Kenya (2.2 TLU). The percentage of farm households using motorized equipment, as well as the percentage of agricultural land under irrigation are low in all East African countries: 1.2% to 4.3%. Average fertilizer use, finally, shows a wider range: only 1.3 kg/ha in Uganda, 20 kg/ha in Tanzania, and 74 kg/ha in Kenya (FAO, 2016a).

Tanzania's important cash crops include coffee, cotton, sisal and cashew nuts, among others. The region's climatic and geologic conditions dictate each cash crop's relative importance, so one will mostly find coffee in the moderate mid- and highlands, cotton wherever plenty of rainfall allows it, sisal in the dry lowlands, and cashew trees in marginally fertile coastal regions (Makoi, 2016).

After Ethiopia and Sudan, Tanzania has the largest cattle population in Africa; however, 96% is of the East African zebu breed with limited potential for milk production. The improved dairy cattle, i.e. crossbred or exotic, mainly Friesian or Ayrshire, are concentrated in the cooler highland regions of Kilimanjaro, Arusha, Mbeya, and Tanga provinces. At an estimated 480 million USD (Kurwijila et al., 2012), the Tanzanian production value of milk is comparable to that of beans, or of cassava, or cashew nuts, coffee, cotton and sisal combined (Bank of Tanzania, 2015). At 43 liters per capita/year production can be considered low (Maass, 2015). It is unable to keep up with rising demand, rendering Tanzania a net milk importer (Kurwijila et al., 2012).

Lushoto district

Lushoto is one of five districts in the northeastern Tanga province, located in the West Usambara Mountains, around 500 km south of the equator. The district has a temperate/sub-tropical climate and mid- and highland altitudes. The West Usamabara Mountains' population density is 120 people/km^2, although corrected for productive land the figure has been estimated at 900/km^2 (Jambiya, 1998); as such, land pressure is high. The agroecology can be characterized as humid midlands, on gneiss rock (Sakané et al., 2012). Agriculture employs 85 percent of its people (Mangesho et al., 2013). All households grow crops, albeit mostly at small scale: two-thirds of households have access to less than one hectare; one-third to 1-5 hectares. All households at least partially consume what they produce: 25 percent produces exclusively for own consumption, 75 percent sells products like fruits and vegetables as well. Sixty-one percent also grow one or more pure cash crops—primarily coffee. Lushoto agriculture is fairly diversified: 50 percent of households produce five to eight agricultural products, while another 34 percent produce more than nine (Lyamchai et al., 2011). Maize and beans are the most important crops in terms of (non-monetary) income; banana, cassava, sweet potatoes, pumpkins and tomatoes follow (Mangesho et al., 2013).

The Tanga region, to which Lushoto District belongs, is considered an important milk-producing region, so the average number of improved dairy cows per Lushoto farm can be expected to be higher than the national average. Data on the average number is unavailable, but 25-95% of Lushoto farms, depending on the village, owns improved dairy cows. The crossbreed's milk production potential is around 15 liters a day, but average actual production is 4 liters/day; the local breed produces 2 liters/day on average. At 1 liter/day/household, Lushoto dairy farmers keep little for own consumption (Mangesho et al., 2013). The cows are generally underfed in both quality and quantity, sometimes by more 30 percent of their metabolizable energy (ME) requirement (Maass, 2015), even though farmers sometimes go as a far as 20 kilometers to obtain fodder. Sixty percent of farmers supplement the fodder with crop residues, but the far majority of the cows' ME is from naturally occurring and collected fodder; only 9-14 percent comes from cultivated fodder (Mangesho et al., 2013). Nevertheless, improved fodder production and feeding practices are not the only crucial issues for higher milk production; animal housing should be improved as well. Particularly in Lushoto's zero-grazing systems, where cows are now typically tied to a tree, better housing and hygiene would have "a major effect on dairy cow performance" (Maass, 2015, p. 10).

Despite the diversification of food production in Lushoto, only 4 percent of households are "food secure", i.e. without struggle to feed all household members throughout the year; 53 percent of households is food secure during 6-9 months/year, while another 35 percent is food secure during less than 6 months/year (Lyamchai et al., 2011). Improved milk productivity could be a major step forward to food security, as the associated rise in cash income could buy food when household crop storages near exhaustion.

1.2. Objectives and hypotheses

Objectives

“In view of the rather disappointing impact of our efforts over the last half-century,” Tittonell et al. (2015, p. 126) argue for an ex-post impact assessment of the past two decades’ worth of modeling and systems analysis studies of smallholder farming “to enhance the livelihoods and the prospects of rural people across the developing world”. A considerable portion of SSA smallholder farming modeling studies, however, either focuses exclusively on the biological aspects while ignoring the economics and social aspects, or vice versa. This study joins biological and economic aspects of smallholder farming, so to illuminate pathways to improved household income and the associated environmental impact.

Academic literature on smallholder farming systems analysis often addresses the concept of trade-offs: simultaneous shifts towards and away from competing objectives due to a change in relative resource allocation among them. The use of crop residues as feed or soil amendment is one example (Tittonell et al., 2015). Financial decision-making by smallholder farmers is another: investments in crop and livestock production for cash compete with increasing household food consumption, health expenses, education and other needs (Waithaka et al., 2006). In the area here studied, farm management is dictated by various trade-offs, both of inputs—animal feed competes with soil amendment for crop residues, animal and crop management compete with one another for labor, crop yields compete with soil fertility for organic matter—and of outputs—leisure time vs. income, food self-sufficiency vs. cash income, and cash income vs. independence from purchased inputs. This study aims to shed more light on some output trade-offs that dictate management of smallholder crop-dairy systems in Lushoto District, Tanzania.

Main research question

To what extent could forage cultivation on smallholder mixed crop-dairy systems in Lushoto district, Tanzania sustainably improve their production and income?

Hypotheses

Tittonell et al. (2009) modeled smallholder farm performance in western Kenya. The representative farm model was configured with various intensification strategies for sustainably enhancing production and income. The strategies were made up of three intensification components: [1] increased use of external nutrient inputs, [2] changes in land allocation between food and fodder crops, and [3] changes in the productivity and efficiency of the livestock subsystem. Among their findings: the combination of P application with increased Napier cultivation at the expense of food crops would increase biomass productivity and milk production but decrease production of edible energy and protein. This underlines the trade-off between food self-sufficiency and cash income.

The MilkIT project (Maass, 2015) reported the most promising interventions for improved milk production in Tanzania. For intensive mixed crop-livestock systems, rainfed grass cultivation and irrigated fodder production (grasses as well as maize and sorghum) were prioritized.

Waithaka et al. (2002), also in western Kenya, found that smallholder farmers' primary objective is household food supply; cash income comes second. The modeling study that ensued (Waithaka et al., 2006) found that net income could be increased through smaller areas under maize and beans, and larger areas under cash crops.

Based on these three studies, the hypotheses for this study were:

1. Increased Napier cultivation combined with the application of mineral fertilizers can increase milk production;
2. Increased Napier cultivation can increase cash inflows corrected for management-related expenses ('net cash inflows' from here onwards);
3. Farmers prioritize food self-sufficiency over cash income; intensification strategies should thus minimize any loss of household food production to accommodate for increased cash inflows.

2. Materials & methods

2.1. Study site

Within the Lushoto district, a group of 20 farmers was identified in Ubiri who was to participate. The village is situated between approximately 1,180 and 1,260 meters above sea-level. Terracing is rare so nearly all fields are situated at a slope gradient. The majority of Ubiri's farmers own dairy cattle, usually kept in sheds made from wood, sheet metal and cloth.

The reason for selecting this specific group was twofold. Firstly, 15 out of 20 farmers were members of the village's 'Innovation Platform', a local organization with the aim of improved milk production; we suspected that they might be more forthcoming about their household and farm management than non-members (Paul et al., 2015). Secondly, the farmers live in close proximity of one another; taken together, their homesteads and nearby plots (< 500 meters from the homestead) form a small landscape. See Figure 1.

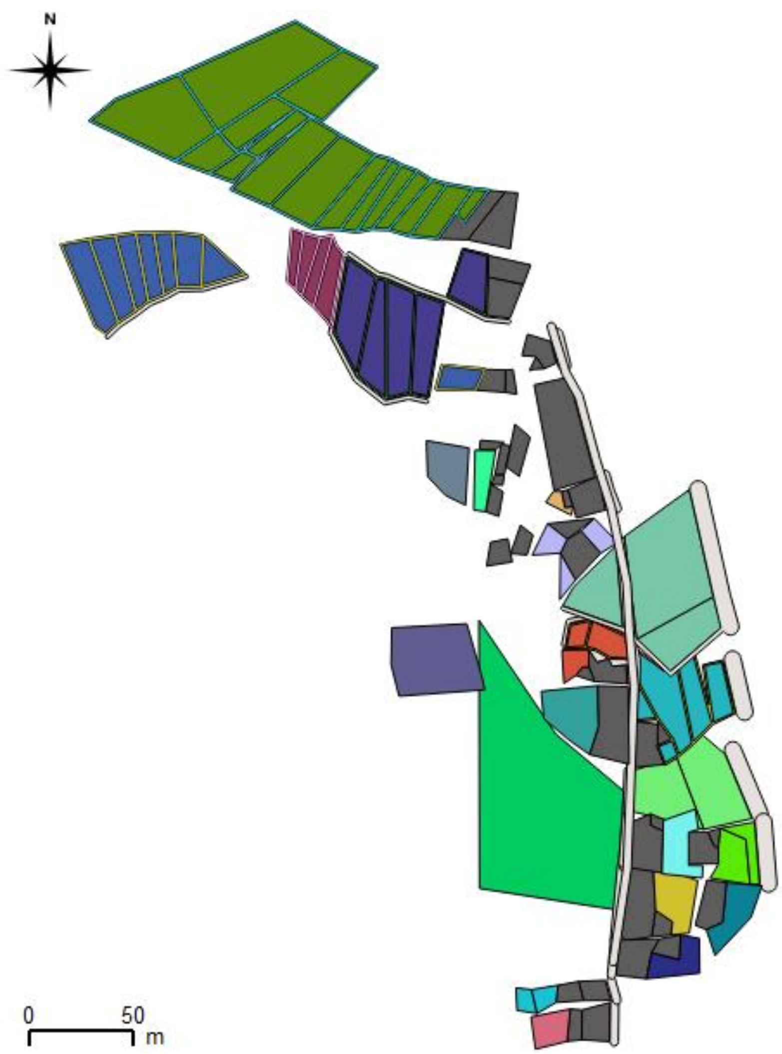

Figure 1. Map of 20 participating farms in Ubiri village. Each bright color denotes a farm; dark grey represents (cattle) housing; light grey represents roads and paths.

2.2. Tools

The primary motive for farm-scale modeling is "to achieve (...) a holistic view of the farming system, rather than a view of single components" (Waithaka et al., 2006, p. 246). Indeed, this study employed modeling to analyze farms as bio-economic systems made up of interdependent components, and to quantify some of the changes to those components brought about by adjustments to farm management. Farm performance was modeled with FarmDESIGN (Groot et al., 2012). For this study, nine of FarmDESIGN's components were used: [1] biophysical environment; [2] socio-economic setting; [3] crops; [4] crop products; [5] rotations; [6] animals; [7] animal products; [8] on-farm produced manure; [9] external fertilizers. The model is static, i.e. chemical and biological flows to, through and from the farm, the resulting balances, animal feed and manure balances, the labor balance, and the economic results are all for one period. The effects of period 1 farm performance on attainable yields and herd size during period 2 therefore aren't taken into account, although additional model scenarios could be developed for subsequent periods. In addition, the prices of inputs and outputs are external to the model because its boundaries surround a single farm. FarmDESIGN, so its creators argue, can be valuable for designing mixed farming systems and potentially supports the learning and decision-making of farmers, farm advisers and scientists (Groot et al., 2012).

To estimate potential maize yields with the application of mineral fertilizers, Janssen et al.'s (1990) Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model was employed. It takes soil fertility data (organic carbon, nitrogen, Olsen phosphorus, convertible potassium, pH), NPK crop parameters—for maize, in this case—and the mass of applied nitrogen, phosphorus and potassium to estimate maximum attainable yields per hectare. The model estimate is an aggregate of estimates [1] taking in to account each macronutrient separately, [2] from all possible sets of macronutrients (i.e. NP, NK, PN, PK, KN and KP, where e.g. the NP and PN estimates are similar but not identical). The model's three-step process and its estimates with each intermediate step show which soil macronutrient contents limit attainable maize yields most.

A subjective plot gradient ranking was formulated for the nearby plots, because the GPS device used was known for its unreliable altitude measurements: 1 signifies a flat plot; 2, a slight gradient estimated under 20 degrees; 3, a gradient estimated from 20 to 40 degrees; 4, a gradient estimated over 40 degrees.

We asked the farmers what they considered the major constraints to improved farm management in two ways: [1] the final question of the household survey addressed desired innovations and the barriers to those innovations; [2] the workshop included a group question, 'What would be your first farm-related purchase with a cash gift equal to your annual cash income?' to draw out their primary concerns.

2.3. Typology

The creation of a new farm typology specific to this study area was deemed unnecessary as the sample is rather uniform. Instead, Tittonell et al.'s (2009) typology of farmers in western Kenya can be used: 17 out of 20 farms belong to type 3; the remaining three farms, comparable to the rest except for their lack of cattle, belong to type 5.

Farm type 3 (Figure 2, from Tittonell et al., 2009):

- Own crossbred or local cattle who remain tethered near the homestead year-round, fed on natural grass complemented with crop residues, Napier and banana leaves;
- Most of the crops residues is removed from the fields to feed the livestock;
- Cattle manure is collected in a pit together with household waste and crop residues;
- Of the three macronutrients, soil P and K contents pose the largest constraints to enhanced crop yields.

Farm Type	Resource endowment* and production orientation	Main source of income	Family structure**	Major constraints
1	High to medium resource endowment, mainly self-subsistence oriented	Permanent sources of off-farm income (e.g. salary, pension, etc.)	Variable age of the household head, small families	Mostly land availability (lack of family labour compensated by hiring-in)
2	High resource endowment, market-oriented	Cash crops and other farm produce sold on the market	Aged household head, numerous family (land subdivision starts)	Mostly labour (hired-in) due to large farm areas
3	Medium resource endowment, self consumption and (low-input) market-oriented	Marketable surpluses of food crops or annual cash crops	Young to mid-aged household head, expanding family	Mostly capital and sometimes labour
4	Predominantly low to medium resource endowment, self-subsistence oriented	Mostly non-farm activities (e.g. ox-plough service, handicrafts) plus marketable surpluses	Young to mid-aged household head, variable family size	Availability of land and capital
5	Low resource endowment, self-subsistence oriented	Selling their labour locally for agricultural practices	Variable age of household head and family size, often women-headed farms	Land and capital, (becoming labour-constrained due to selling labour)

* Referring to assets representing classical wealth indicators (i.e. land size, livestock ownership, type of homestead, etc.).
** In relation to the position of the household in the 'farm development cycle' (Crowley and Carter, 2000).

Figure 2. Farm typology by Tittonell et al. (2009); this study's sample farmers belong to type 3 (17 out of 20) and type 5 (3 out of 20).

2.4. Data collection

Data collection and sampling was done by a team of three researchers: [1] a livestock scientist from Tanzania Livestock Research Institute (TALIRI) conducted household surveys with 20 farmers; [2] an intern with International Center for Tropical Agriculture (CIAT) spent a full day with each of 12 farmers to identify and weigh all given animal feed and measure the day's milk production; [3] the author of this report georeferenced 20 farms' homesteads, cow sheds and nearby fields; [4] together, we conducted a workshop with all participating farmers. This enabled the development of representative farms with FarmDESIGN (Groot et al., 2012; input with data from household surveys, feed and milk measurements, and georeferencing) and QUEFTS (Janssen et al, 1990; input with data from topsoil samples and nutrient contents of locally available fertilizers) and preparation of possible intensification strategies ('scenarios'). The workshop spawned the most promising scenarios for critical assessment with FarmDESIGN.

1. The household survey contained thirteen sections: [1] household composition, [2] plots, [3] crops, [4] crop products, [5] crop residues, [6] crop-related labor, [7] livestock, [8] livestock products, [9] livestock-related labor, [10] livestock feed, [11] manure, [12] off-farm income and [13] farm management innovation. Average duration per survey was around 90 minutes.
2. The CIAT intern responsible for data collection pertaining to feed, milk and manure has a BSc. Rangeland Science. As such, he was capable of identifying the majority of given animal feeds, including the naturally occurring grasses. He weighed all given feed, separated according to species, using a hanging scale. He measured milk production with a measuring cup. Finally, he collected three samples of the most common feeds from separate farms, as well as three manure samples from separate farms.

3. A short walk with each farmer around their homestead and nearby plots enabled the drawing of a schematic map of the plots, including each plot's estimated slope gradient and land use per rainy season. GPS measurements of plot corners enabled later creation of a farm map with GIS software. Finally, topsoil samples were taken from each plot.
4. A workshop with all 20 sample farmers to develop farm management scenarios in a participatory setting. We briefly presented three scenarios. The first implicitly dealt with constraints, explicitly asking the participants on what they would first spend a hypothetical gift equal to one's annual cash income: [1] increase herd size; [2] buy forage; [3] buy manure/mineral fertilizers; [4] buy casual labor; [5] buy cattle with improved genetics. This scenario was dealt with by the group as a whole. The other two—hypothetical farm-landscape configurations based on results from data collection methods [1] through [3]—were discussed in three sub-groups. Each sub-group was facilitated by a Swahili-speaking staff member of TALIRI or CIAT. Facilitation entailed two main responsibilities: [1] further explanation of scenarios if so required by the farmers; [2] guidance and stimulation of the discussion using a number of preconceived questions. Modeling of crop-livestock interactions at the farm level combined with participatory scenario development enables the assessment and fine-tuning of a farm management strategy before actually implementing it (Waithaka et al., 2006).

2.5. Statistical analysis

Data from the household surveys, feed and milk measurements, and GPS measurements were plugged into SPSS for linear regression analysis. Total income—cash inflows plus the value of own products consumed by the household—and total cash inflows were each used as explanatory variables. Both regressions employed five independent variables: [1] total plot size (in acres); [2] maize yield (kg/ha); [3] bean yield (kg/ha); [4] number of livestock units (LUs), where cows count for 1 and sheep/goats for 0.2; [5] labor investment (hours/ha). Explanatory value of the regressions was assessed via the adjusted R^2-, p- and F-values.

3. Results

3.1. Farm size and intensity

Household and farm size

The average size of the 20 sampled farm households was 5.6 persons, 3.3 of whom were active on the farm. The average farm consisted of 4.0 plots: 1.9 plots within 500 meters from the homestead and 2.1 plots farther away. We did not visit the faraway plots; as such, our GPS measurement data pertains to the plots close to the homesteads only.

Average total plot area, as reported by the farmers, was 2.1 acres. However, GPS data from the plots close to the homesteads showed that farmers overestimated their land size by an average of 80 percent, reducing their farms' average size to 1.16 acres. Only 3 farms were larger than 2.5 acres, or 1 hectare. There was no correlation between farm area and household size.

Plot slopes

One of 20 farms solely consisted of flat plots; 18 farms were composed of plots with varying slopes; one farm only had faraway plots we did not visit. Slopes were classified subjectively, because the GPS device used was known for its unreliable altitude measurement. A score of 1 signified a flat plot; 2, a slight gradient estimated under 20 degrees; 3, estimated 20-40 degrees; 4, estimated over 40 degrees. The average plot classification is 2.52, i.e. an estimated gradient of around 20 degrees. Terracing wasn't done on any of the sample farms.

Crop management

The sampled farmers reported growing nine crops in total. All farmers grew both maize and beans, nearly always intercropped. Bananas were grown by 10 farmers; cassava by 4 farmers; sweet potatoes by 3 farmers; potatoes and Napier by 2 farmers each; tomatoes and green peppers by 1 farmer each. All farmers applied farmyard manure, i.e. cattle manure mixed with feed-refusals and household waste. None applied mineral fertilizers.

Livestock

The sample farms owned an average of 1.05 FAO Sub-Saharan livestock units (LUs), with cattle as 0.5 LU and sheep/goats as 0.1 LU. (Chicken or ducks were not managed by the sample farms and their production was negligible, therefore they were excluded from the LU count.) Seventeen out of 20 sample farms owned cattle, of which 16 owned at least one adult improved dairy cow. Of the four farms without an adult dairy cow three were single-(grand)parent, female-headed households; the 16 farms with adult cattle include just one single-(grand)parent household.

Cattle feed

We identified and weighed all species in one day's cattle feed at the same 12 farms where we measured milk production. Early November being the end of the dry season, we expected the proportion of cultivated feed close to its annual minimum, and naturally occurring fodder near its maximum. Daily fresh feed per farm weighed 115 kg on average, of which we estimated that 91 kg was actually consumed. One day's consumed fresh feed per cow equivalent (1 per cow, 0.2 per goat or sheep) weighed 30 kg on average—substantially lower than a 350 kg dairy cow's estimated fresh weight requirement of 65-85 kg/day (Gachuiri et al., 2012).

We distinguished 26 species among the sampled farms' cattle feed, of which we identified 18. The five most common species—*Phragmites australis* or common reed, *Zea mays*or maize residues, *Pennisetum purpureum* or Napier grass, *Musa* or banana leaves, *Cynodon dactylon* or Bermudagrass—accounted for 62% of given feed and 59% of consumed feed.

The levels of metabolizable energy (ME) and crude protein (CP) in the above five feeds were extrapolated to the remaining 41% of consumed feed to come up with an estimate for daily ME and CP intake/LU: 88 MJ and 0.59 kg, respectively (see Table 1). The estimate for daily ME intake should enable a 300 kg dairy cow to produce 10 kg of milk, but the CP estimate would allow for just 4 kg of milk (FAO, 2016b).

Just 1 of 12 sampled farmers supplied water to the animals, and even then just 20 liters for four cows and two sheep.

Table 1. Estimated fresh weight (FW), dry matter (DM) content, metabolizable energy (ME), and crude protein (CP) in consumed feed across all studied farms; values are daily averages per livestock unit (LU)

	FW cons. (kg/LU)	**DM %**	**ME (MJ/kg DM)**	**CP (% DM)**	**ME cons. (MJ)**	**CP cons. (kg)**
Napier grass	4.9	18%	8.0	9.7%	7.0	0.09
Maize residues	4.1	93%	6.9	2.5%	26.3	0.10
Common reed	3.6	20%	8.0	8.2%	5.8	0.06
Bermudagrass	3.0	31%	8.1	5.8%	7.6	0.05
Banana leaves	2.9	17%	10.0	10.6%	4.9	0.05
Others	11.7	n/a			36.2	0.24
TOTAL	**30.2**	**n/a**			**87.9**	**0.59**

3.2. Productivity indicators

<u>Crop yields</u>

Farmer-reported total fresh yield figures were combined with GPS-measured plot sizes to calculate values for fresh yield per hectare. Both the average and median were included to account for the disproportionate influence of outliers. See Table 2 for the results.

Table 2. Ubiri sample's crop cultivation, yield figures, and commercialization

	# farmers (out of 20)	Average yield (kg/ha)	Median yield (kg/ha)	For sale (% of farmers)
Maize	20	2,229	2,042	0
Beans	20	979	853	100
Bananas	10	10,615	6,753	30
Cassava	4	3,920	3,151	0
Sweet potatoes	3	1,626	1,661	0
Napier (trials)	2	4,586	4,586	0
Potatoes	2	5,853	5,853	0
Green peppers	1	1,286	1,286	100
Tomatoes	1	263	263	100

Milk production

Thirteen out of 20 interviewed farmers reported milk production during the previous year. They were asked to estimate minimum and maximum daily milk production, to account for seasonal variability. The lowest reported minimum is 2 liters/day; the highest reported maximum is 15 liters/day. In an attempt to verify their responses, we measured one day's milk production at 12 farmers. This happened during the first half of November, the end of the dry season when milk production is expected to reach its minimum. With 5 of 12 farmers, measured milk production was lower than their reported minimum. The average (median) farmer-reported minimum milk production, however, was nearly equal to our measurements: 4.7 (4.0) reported versus 4.8 (3.9) measured liters/day.

Farm-labor requirements

The average (median) annual labor requirement per farm household was 4,446 (3,956) hours, or 12.2 (10.8) hours per day. All 20 interviewed farmers evidently reported crop-related labor; 18 farmers also reported livestock-related labor, i.e. caused by ownership of cattle, goats and/or sheep. The average (median) labor division between crop-related and livestock-related activities was 47 (44) and 53 (56) percent, respectively. In terms of labor requirement, feed collection was the largest single activity: its average (median) proportion of livestock-related labor was 59 (64) percent, or 31 (32) percent of all farm labor. See Table 3 for a sample distribution of labor hours per year.

Table 3. Distribution of sample farms according to crop- and cattle-related labor

		Cattle-related labor (hours/year)				TOTAL COUNT
		< 1,000	**1,000 - 2,000**	**2,001 - 3,000**	**> 3,000**	
Crop-related labor (hours/year)	**< 1,000**	1	2	2	1	**6**
	1,000 - 2,000	0	0	2	2	**4**
	2,001 - 3,000	1	1	0	0	**2**
	> 3,000	1	0	3	2	**6**
TOTAL COUNT		**3**	**3**	**7**	**5**	**18**

Total income

Average (median) total income—cash inflows plus the value of own products consumed by the household—amounted to 1.7 million (1.3 million) Tanzanian Shillings, or 772 (618) US Dollars. Excluding the two farm households without large livestock, i.e. cattle, sheep or goats, the average increased to 1.8 million TSh. or 803 USD. The average (median) distribution of total income between crop and animal products was 59 (51) versus 41 (49) percent, respectively. See Table 4.

Table 4. Distribution of sample farms according to total income from crop and animal products

		Income from animal products (TSh./year)			TOTAL COUNT
		< 500,000	**500,000 - 1,000,000**	**1,000,000 - 2,000,000**	
Income from crop products (TSh./year)	**< 500,000**	2	3	2	**7**
	500,000 - 1,000,000	3	2	1	**6**
	1,000,000 - 2,000,000	2	0	2	**4**
	> 2,000,000	1	0	2	**3**
TOTAL COUNT		**8**	**5**	**7**	**20**

Cash inflows

The sample's average (median) reported annual cash inflows amounted to 818,875 (470,000) Tanzanian Shillings, or 375 (215) US Dollars. Excluding the two farm households without large livestock, the average was 8 percent higher at 883,972 TSh. or 405 USD. Across the farm households with large livestock, crop products generated 43 percent of cash inflows and livestock generated 57 percent, nearly all in the form of milk. It is worth noting that 5 of 18 farmers with large livestock reported zero cash inflows from livestock products because their cow(s) didn't lactate during the previous year; livestock products from the 13 farms with lactating cows generated 78 percent of their annual cash inflows. See Table 5.

Table 5. Distribution of sample farms according to cash inflows from crop and animal products

		Cash inflows from animal products (TSh./year)				TOTAL COUNT
		< 100,000	100,000 - 500,000	500,000 - 1,000,000	> 1,000,000	
Cash inflows from crop products (TSh./year)	< 100,000	0	4	3	1	**8**
	100,000 - 500,000	6	0	2	0	**8**
	500,000 - 1,000,000	1	0	0	0	**1**
	> 1,000,000	0	0	1	2	**3**
TOTAL COUNT		**7**	**4**	**6**	**3**	**20**

3.3. Statistical relationships

In order to discern possible statistical relationships between various farming aspects and (financial) performance, I ran six regressions. The analyses shared the same five independent variables: [1] total plot size (in acres); [2] maize yield (kg/ha); [3] bean yield (kg/ha); [4] number of livestock units (LUs), where cows count for 1 and sheep/goats for 0.2; [5] labor investment (hours/ha).

Total income—cash inflows plus the value of own products consumed by the household—as dependent variable yields an adjusted R^2 of 36% and is significantly determined by [3] bean yield (α=10%). Total income from crop products: adjusted R^2 is 52% and significantly determined by [1] total plot size and [3] bean yield (α=5%). Total income from animal products: adjusted R^2 is 28% and significantly determined by [4] number of LUs (α=1%).

Total cash inflows yields an adjusted R^2 of 58% and is significantly determined by [1] total plot size, [3] bean yield and [4] number of LUs (α=5%). Total cash inflows from crop products: adjusted R^2 is 70% and significantly determined by [1] total plot size and [3] bean yield (α=1%). Total cash inflows from animal products: adjusted R^2 is 37% and significantly determined by [4] number of LUs (α=5%).

Notably, neither [2] maize yields nor [5] labor investment significantly determine any of the six income Figures at α=10%. In short, the farm household survey data better explains cash inflows than total income. Table 6 summarizes the regression results.

Table 6. Summary of regression analyses of income. Independent variables: [1] total plot size; [2] maize yield; [3] bean yield; [4] number of LUs; [5] labor investment.

Dependent variable	**Adjusted R^2**	**Significant variables**	**Significance level**
Total income	36%	[3] bean yield	α=10%
… from crop products	52%	[1] total plot size; [3] bean yield	α=5%
… from animal products	28%	[4] number of LUs	α=1%
Total cash inflows	58%	[1] total plot size; [3] bean yield; [4] number of LUs	α=5%
… from crop products	70%	[1] total plot size; [3] bean yield	α=1%
… from animal products	37%	[4] number of LUs	α=5%

Regression analyses with milk production (liters/day/lactating cow) against the consumed mass of various combinations of feed species (kg/day) yielded no significant results: F Significance with the 4 most given feeds as independent variables was 0.65; with the 5 most given feeds, 0.80. It appears that the variation in milk production could be explained by other factors, like the cattle's age, genetics, or point in lactation phase at the time of measurement; however, there is no sample data on these factors.

3.4. Participatory scenario development

Scenario 1: An immediate doubling of annual cash income

The hypothetical situation was posed as 'If your annual cash income would double overnight, which farm management change would you implement first?'. The farmers were asked to vote for one of five categories: [1] increase herd size; [2] buy forage; [3] buy manure/mineral fertilizers; [4] buy casual labor; [5] buy cattle with improved genetics.

Nine out of 20 voting farmers chose '[3] buy manure/mineral fertilizers'; six farmers voted '[2] buy forage'; three farmers voted '[5] buy cattle with improved genetics'; '[1] increase herd size' and '[4] buy casual labor' received one vote each.

Scenario 2: Forages on all nearby plots

Fifteen out of 21 participating farmers had less than half of their total acreage close (< 500 m) to the homestead; the majority of these farmers' acreage was 500-3000 m from their homestead. However, except for fruit trees and some occasional cassava on the nearby plots, we observed no land management differences between the nearby and faraway plots.

The scenario posed was thus: all participating farmers fully commit their nearby plots to forage crops (mainly Napier, but also Bracchiaria, Desmodium or Guatemala grass) and manage the faraway plots as they wish. The overarching question to the farmers: what do you think about this idea?

The sub-group discussions' guiding questions

1. If ¼ acre could provide enough forages to feed an adult milk cow year-round, would that change your opinion about this scenario?
2. If your milk production would increase, would that change your opinion? If so, how much extra milk production would you want under this scenario?
3. If you could sell the Napier your own cattle don't need, would that change your opinion? If so, what Napier price would you want under this scenario?
4. If both your cash income but also your labor requirements would increase under this scenario, would you consider realizing it?

After about 30 minutes, each sub-group presented their discussion results to the group as a whole. Guiding questions 1. and 2. were addressed implicitly, questions 3. and 4. were addressed explicitly.

General opinions

Two out of three sub-groups named an expected increase in milk production and reduction of labor as this scenario's main benefits. One of those two sub-groups additionally mentioned increased ease of applying manure as an expected benefit. The third sub-group, less total acreage between them than in the other sub-groups, wasn't as positive about the idea. To them, forage crops on all nearby plots would sacrifice too much of their food crop production; they proposed a compromise with only part of the nearby plots under forage and all other plots under food crops.

Excess Napier sales

None of the sub-groups saw Napier sales as a particularly interesting or even feasible possibility. Two out of three sub-groups explained that their cattle would need all forages grown on the nearby plots.

Cash income but also labor requirements increase

None of the sub-groups perceived this hypothetical trade-off as particularly challenging. Two sub-groups explained that during a few brief periods per year households were labor-constrained, which could be alleviated by labor-sharing between neighbors. The third sub-group simply said that the households have sufficient spare labor to cope with the trade-off.

<u>Scenario 3: Feed or food crop specialization</u>

Currently, all participating farmers grow food crops; some additionally grow forage crops. We thus posed the somewhat extreme scenario that all farmers fully commit to either forage or food crops. Regardless of their specialization under this scenario, the farmers would be free to choose their cattle herd size. Each sub-group was further divided in two: only forage crops, and only food crops. Again, the leading question was 'What do you think about this idea?'.

The sub-group discussions' guiding questions

1. Exclusive forage cultivation
    a. At what level of milk production would you consider cultivating *forages only*?
    b. At what Napier price would you consider cultivating *forages only*?
    c. At what manure price would you consider cultivating *forages only*?
2. Exclusive food crops cultivation
    a. At what maize price would you consider cultivating *food crops only*?
    b. At what maize residues price would you consider cultivating *food crops only*?

General opinions

Exclusive forage cultivation

Two out of three sub-groups listed expected increased in milk and manure production as the main benefits of becoming a forage-only farmer. One of those sub-groups additionally mentioned expected income from selling bulls as well. The third sub-group, with relatively little land, would only consider it if combined with cattle with improved genetics; yet, even then they would prefer a combination of food and forage crops as the cattle can eat food crop residues as well. The main drawback of this scenario, agreed on by all sub-groups, is increased exposure to risks of livestock or drought. Without food crop cultivation, there would be no back-up. Further, two sub-groups mentioned a general lack of extension and veterinarian services, which further increases the risk of livestock diseases and genetic erosion.

Exclusive food crop cultivation

The sub-groups saw mostly drawbacks to this scenario. If combined with a smaller herd size, it would make them dependent on other farmers' manure or mineral fertilizers. In addition, two sub-groups mentioned increased exposure to maize price risks as a drawback. One sub-group would only consider food crop specialization with improved seeds.

Forage farming thresholds

Two sub-groups would consider cultivating forages only if combined with milk production of least 10 liters/day (currently around 5 liters/day on average). One sub-group put the threshold at 20 liters/day, or a milk price of 800 TSh./liter (currently 500 TSh./liter). Two sub-groups put the minimum Napier price at 40 TSh./kg fresh material; the third sub-group didn't set a minimum because they believed they would need all Napier for their own cattle. All sub-groups demanded a minimum manure price of 25 TSh./kg residue-free (currently 10 TSh./kg).

Food crop farming thresholds

Only one sub-group was able to set minimum prices before they would consider cultivating food crops only: 1000 TSh./kg of maize (currently 500 TSh./kg); 80,000 TSh./acre's worth of maize residues (currently 60,000 TSh./acre); 2,800 TSh./kg of beans (currently 1,250 TSh./kg).

3.5. Bio-economic farm modeling

<u>The representative Ubiri farm</u>

In order to simulate farm performance under specific scenarios or optimize for various objectives, a fictional farm representative of the 20-farm sample is needed. In terms of household size, farm size, and number of plots this farm closely approximates the sample's average values: five household members; one acre of arable land; three plots, of which one half-acre plot near the homestead and two quarter-acre plots farther away. Although smaller than the sample average (1.16 acre), the representative farm size was set at 1 acre (0.4 hectare) for ease of calculation and presentation.

For crop yields (kg/ha) two figures were used, so to show Ubiri farms' current as well as potential performance. Baseline ('standardized') crop yields were taken as the sample average after exclusion of the top and bottom two, so to account for possible inaccuracies in the farmer-reported data.

With a combination of soil sample data from Ubiri and nearby Mbuzii (see Table 7), QUEFTS estimated attainable maize yields at 3,104 kg/ha without fertilizer application. This was 44% higher than the 2,158 kg/ha sample average. Potential yields with fertilizer application, as modeled by QUEFTS, were therefore converted to relative increases from the 3,104 kg/ha baseline. The model estimate is an aggregate of estimates [1] taking in to account each macronutrient separately, [2] from all possible sets of macronutrients (i.e. NP, NK, PN, PK, KN and KP, where e.g. the NP and PN estimates are similar but not identical). The model's three-step process and its estimates with each step show which soil macronutrient contents limit attainable maize yields most. As such, the model estimated that the Ubiri/Mbuzii soils would primarily benefit from phosphorus application, secondarily from extra potassium and thirdly from nitrogen application. It further estimated that the application of diammonium phosphate (DAP), which consists of 18% nitrogen and 46% phosphorus, and NPK (18%, 22%, 17%) could increase attainable maize yields beyond the 3,104 kg/ha baseline level.

Table 7. Soil nutrient contents and pH used for QUEFTS; based on samples from Ubiri and Mbuzii, Lushoto.

Organic carbon (C g/kg)	**Nitrogen (N g/kg)**	**Total phosphorus (P g/kg)**	**Olsen phosphorus (P-OLSEN mg/kg)**	**Extractable potassium (K mm/kg)**	**pH-H2O**
24.3	2.3	120	1.2	7.6	6.8

With QUEFTS and the local fertilizer prices, it was possible to calculate a tentative estimate of optimal application levels. The estimate is tentative for its foundation on three assumptions: [1] current maize yields are 2,000 kg/ha despite a sample range of 410-4,839 kg/ha; [2] fertilizer application would only affect maize yields, even though the sample farmers nearly always intercrop maize with beans, and in some cases with bananas or tubers; [3] the commercial value of maize is independent of yields. I ran QUEFTS with DAP and NPK applications at 50 kg/ha increments, up to total fertilizer application of 600 kg/ha. Considering that fertilizers cost 1,500 TSh./kg and maize commands 500 TSh./kg, QUEFTS can be used to find the optimal level of DAP and NPK applications: 100 and 400 kg/ha or 50 and 450 kg/ha, respectively. See Table 8.

Table 8. Attainable maize yield increases at various DAP and NPK application levels, relative to the baseline without any application of external fertilizers. Green (red) cells represent profitable (unprofitable) application increments; bold (italic) percentages represent optimal (dominated) application levels. For the scenarios, the attainable maize yields estimated with 100 kg/ha of DAP and NPK each, i.e. +63% than the standardized average, were used.

	DAP (kg/ha)												
NPK (kg/ha)	**0**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
0	0%	24%	42%	*50%*	57%	63%	68%	72%	76%	79%	82%	84%	86%
50	*14%*	*36%*	53%	*61%*	68%	74%	79%	83%	87%	90%	93%	96%	
100	*28%*	*48%*	63%	*71%*	78%	84%	89%	94%	98%	101%	105%		
150	*40%*	*60%*	73%	*81%*	88%	94%	99%	104%	108%	112%			
200	*52%*	*71%*	83%	*91%*	98%	104%	109%	114%	119%				
250	*64%*	*82%*	93%	*101%*	108%	114%	119%	124%					
300	*76%*	*92%*	103%	110%	117%	123%	129%						
350	*87%*	*102%*	113%	120%	126%	133%							
400	*98%*	113%	**121%**	128%	134%								
450	*108%*	**121%**	128%	134%									
500	*118%*	127%	134%										
550	*126%*	133%											
600	132%												

On a 1 acre farm, however, 500 kg/ha of fertilizers adds up to 200 kg at 300,000 TSh., nearly half the sample's standardized average cash income of 636,700 TSh./year. In other words, farmers might consider the optimal fertilization strategy for maize production excessively risky for implementation. To account for risk aversion, a non-optimal but less costly fertilization strategy would be to combine 100 kg/ha DAP with some amount of NPK below 400 kg/ha. For the scenarios, I used the attainable maize yields estimated with 100 kg/ha of DAP and NPK each, i.e. +63% than the standardized average.

For beans, bananas and cassava, the sample's top reported values for attainable yields were used after exclusion of the top 10 percent to account for possible inaccuracies in the farmer-reported data. For Napier the sample offered insufficient data; consultation of various forage researchers active in Lushoto and western Kenya yielded a conservative estimate of 50 Mg/ha/year fresh weight.

See Table 9 for the Baseline and locally attainable dry matter yields.

<u>Scenarios</u>

Based on the workshop results, Scenario 3, 'Cropping specialization', wasn't taken up in the model: the sample farmers showed little interest to follow the—indeed rather extreme—intensification strategy unless milk production, crop yields and prices improved considerably. Therefore, in the following, two versions of Scenario 2, 'Forages on all nearby plots'—with Napier as cultivated forage—are described. Farm management indicators under Baselines ('HL' for 'high labor', 'LL' for 'low labor') and Scenarios 2HL and 2LL can be found in Table 9; economic performance, as modeled by FarmDESIGN, is shown in Table 10. The reason for developing two versions of what is essentially the same scenario: to accommodate for 20% of the sample farms, where labor availability is limited due to the death of one or both parent(s) (in the latter case of which a grandparent heads the household).

Table 9. Representative farm's management indicators (Baseline HL; Scenario 2HL; Baseline LL; Scenario 2LL).

Farm aspect	Baseline HL	Scenario 2HL	Baseline LL	Scenario 2LL
Farm size (acres)	1.0	1.0	1.0	1.0
Cultivated crops (acre)	maize (1), beans (1), banana (0.25), cassava (0.25)	Maize ($^5/_8$), beans ($^5/_8$), Napier ($^3/_8$), banana ($^3/_8$), cassava (0.25)	maize (1), beans (1), banana (0.25), cassava (0.25)	Maize ($^5/_8$), beans ($^5/_8$), Napier ($^3/_8$), banana ($^3/_8$), cassava (0.25)
Maize yield (DM kg/ha/year)	1,877	3,060	1,877	3,060
Beans yield (DM kg/ha/year)	786	1,745	786	1,745
Banana yield (DM kg/ha/year)	2,025	3,537	2,025	3,537
Cassava yield (DM kg/ha/year)	3,646	3,669	3,646	3,669
Napier yield (DM kg/ha/year)	0	8,950	0	8,950
Grass imports (DM kg/year)	1,800	1,800	0	0
Maize bran imports (DM kg/year)	0	1,000	0	300
NPK application (kg/year)	0	40	0	182
DAP application (kg/year)	0	40	0	40

Representative Baseline farms

In line with the sample average, the representative Baseline HL farm owns two adult, crossbred milking cows. Forage cultivation among the sampled farms is rare to the point of non-existent. It was therefore not included in the Baseline farm's crop management. Instead, the representative Baseline farmer grows maize and beans on all three fields, intercropped with banana on 0.25 acre and cassava on another 0.25 acre. Two household members work on the farm full-time. The cattle are fed with crop residues, and natural grasses collected from public land. The nutrients imported via the natural grass prevent nutrient mining within the farm, so there is no need for mineral fertilizers.

The Baseline LL farm reflects the sample's four single-(grand)parent, female-headed households. Labor availability is around half the level of Baseline HL; as a result, Baseline LL does not own cattle. Crop management and yields are the same as for Baseline HL, although Baseline LL risks nutrient mining as it doesn't import natural grasses as feed nor purchases mineral fertilizers. LL farmers generally help each other during labor-intensive periods, leading to somewhat more crop-related labor than on Baseline HL.

See Table 9 for the Baseline farms' management indicators; see Table 10 for economic performance.

Table 10. Representative farm's performance indicators (Baseline; Scenario 2HL; Baseline, no cattle; Scenario 2LL).

Farm aspect	Baseline HL	Scenario 2HL	Baseline LL	Scenario 2LL
Total labor (hours/year)	**3,528**	**3,423 (-3%)**	**1,463**	**2,485 (+70%)**
Crop-related labor	1,303	1,172 (-10%)	1,463	1,172 (-20%)
Cattle-related labor	2,226	2,226 (=)	0	1,313
# of adult milk cows	**2**	**3 (+50%)**	**0**	**2**
Milk prod. (liters/cow/day)	**1.38**	**2.8 (+103%)**	**0**	**2.6**
Gross total income (TSh./year)	**1,609,250**	**3,027,265 (+88%)**	**1,105,550**	**2,443,265 (+121%)**
Gross annual income (crops)	1,105,550	1,494,265 (+35%)	1,105,550	1,494,265 (+35%)
Gross annual income (milk)	503,700	1,533,000 (+204%)	0	949,000
Total labor return (TSh./hr)	**453**	**884 (+95%)**	**756**	**983 (+30%)**
Gross cash income (TSh./year)	**636,700**	**1,860,755 (+192%)**	**238,000**	**1,276,755 (+436%)**
Gross cash income (crops)	238,000	432,755 (+82%)	238,000	432,755 (+82%)
Gross cash income (milk)	398,700	1,428,000 (+258%)	0	844,000
Total input costs (TSh./year)	**40,000**	**389,885 (+875%)**	**20,000**	**441,966 (+2,110%)**
Fertilizer costs	0	120,000	0	333,000
Maize bran costs	0	229,885	0	68,966
Misc. costs	40,000	40,000 (=)	20,000	40,000 (+100%)
Net cash income (TSh./year)	**596,700**	**1,470,870 (+147%)**	**218,000**	**834,789 (+283%)**
Net cash labor return (TSh./hr)	**168**	**430 (+156%)**	**149**	**336 (+125%)**

Representative farm under Scenario 2HL, 'Napier cultivation supplemented with natural grasses'

Scenario 2HL can be considered a hybrid of the workshop's Scenario 2 and Baseline HL, i.e. Napier cultivation on the plot near the homestead while still collecting natural grasses from the public wetlands. It assumes that a ⅜ acre plot close to the homestead is planted with Napier and banana trees; the faraway plots are planted with maize and beans (⅜ acre) and maize, beans and cassava (¼ acre).

The additional forages increase milk production and thereby cash income: this expanded feeding strategy enables herd expansion from two to three milk cows. The three adult crossbred milk cows are fed with Napier, residues from all crops except beans, natural grasses—common reed (*Phragmites australis*) and Bermudagrass (*Cynodon dactylon*) at a 2:1 ratio—and purchased maize bran. The natural grasses and maize bran sufficiently enrich the farmyard manure that external fertilizers are not needed to restore soil nutrient balance, but to reach locally attainable maize yields 40 kg NPK and 40 kg DAP are needed. See Table 9 for a summary of farm management under Scenario 2HL.

Under Scenario 2HL, average milk production could reach 2.8 liters/cow/day—double Baseline HL's 1.4 liters/cow/day. Labor requirements total 3,423 hours/year—within 3 percent of the Baseline. In sum, Scenario 2HL shows the greatest potential for cash income without increasing the Baseline's labor requirements. See Table 10 for Scenario 2HL's performance indicators relative to the Baseline HL. Compared to Baseline HL, the farm under Scenario 2HL has less land available for food crop cultivation. However, the model simulation with the third-highest yields for maize, beans, cassava and banana shows that a five-person household with one acre under Scenario 2HL can be self-sufficient for food calories. The household under Scenario 2HL would sell a portion of the bean and banana yields and keep all other food crops; it would additionally keep one liter of milk per day during the year's seven-month lactation period. Both under Baseline HL and Scenario 2HL, the representative farm would be self-sufficient for food calories at 2,653 and 2,697 kcal/person/day[1], respectively, around half of which in the form of maize (see Figure 4).

Compared to Baseline HL, gross annual income under Scenario 2HL—gross cash income plus the value of own products consumed by the household—is +88% at 3.0 million TSh. or 1,387 USD. This difference can be separated into +35% income from crop products and +204% income from milk.

Gross annual cash income under Scenario 2HL is +192% than on Baseline HL at 1.9 million TSh. or 853 USD, separable into +82% cash from crop products and +258% cash from milk. Due to the recommended purchases of 1,000 kg maize bran and 80 kg fertilizers, the resultant net cash income difference is smaller at +147%.

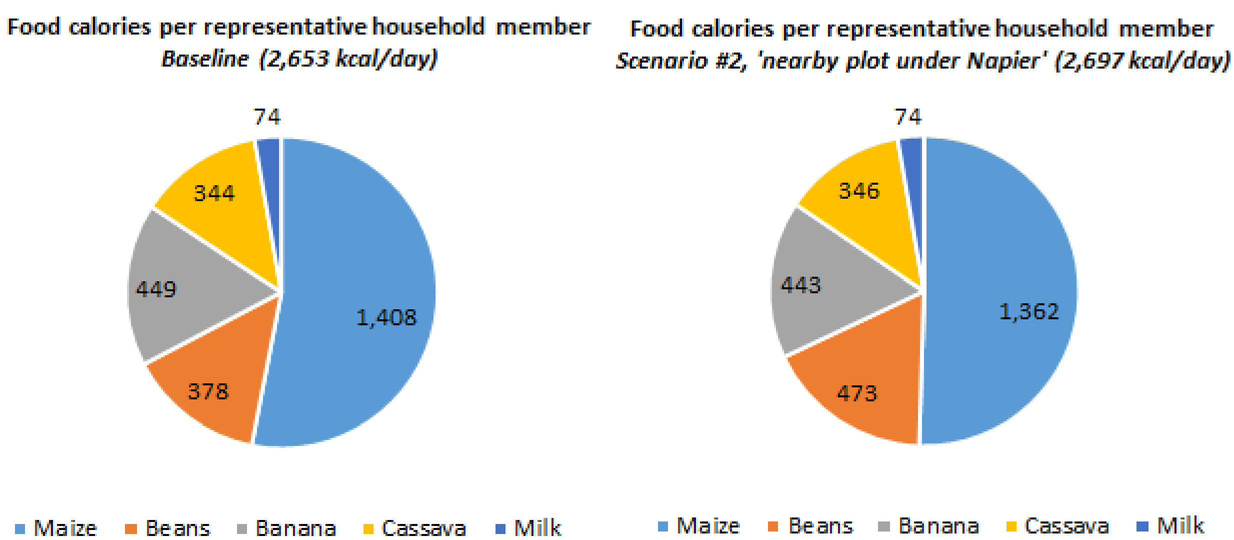

Figure 3. Farm-produced food calories available for household consumption; Baseline and Scenario 2.

[1] Based on nutritional data from SELFNutritionDATA (http://nutritiondata.self.com/).

Representative farm under Scenario 2LL, 'Napier cultivation on nearby plots'

Scenario 2LL is similar to 2HL but less labor-intensive, i.e. it combines food crop and forage cultivation with dairy cattle ownership without natural grass collection from public land. It reflects the relatively constrained labor availability among 20% of the sample, which are single-(grand)parent households. As such, performance under Scenario 2LL is compared to the Baseline LL farm, which does not own cattle. Crop allocation is identical for Scenario 2HL and 2LL: ⅜ acre close to the homestead under Napier and banana trees, ⅜ acre under maize and beans, ¼ acre under maize, beans and cassava. The representative household thus remains self-sufficient for food calories. Napier and crop residues are fed to two adult crossbred milk cows, although part of the bean residues directly go to the farmyard manure; a modest maize bran purchase (300 kg/year) would be required to fill the cattle's energy and protein requirements. In addition to the farmyard manure, the plots are fertilized with NPK and urea to prevent nutrient mining. (Note that, under Scenario 2HL, there would be no need for purchased mineral fertilizers to prevent nutrient mining because it imports natural grasses). In other words, Scenario 2LL is less labor-intensive but more capital-intensive. See Table 9 for a summary of farm management under Scenario 2LL.

None of the interviewed farmers were self-sufficient for cattle feed; all relied on public wetlands for the collection of natural grasses, mainly common reed (*Phragmites australis*) and Bermudagrass (*Cynodon dactylon*). These grasses were generally of low nutritive value, i.e. high in structural value but low in energy and protein, and leave the cattle structurally underfed at all sampled farms. Furthermore, feed collection was the sample's most labor-intensive single activity, accounting for 31 percent of total labor hours. Under Scenario 2LL, however, the farm approaches self-sufficiency for cattle feed. This would affect the farm in two main respects: [1] the farmer no longer needs to collect feed from the public lands but cuts Napier from the nearby plot or uses crop residues, which frees up 2.8 hours/day on average; [2] Napier has higher nutritive value than the area's natural grasses, which allows the cattle to meet their energy and protein requirements at higher levels of milk production. Total labor under Scenario 2HL amounts to 2,485 hours/year, i.e. only slightly more than one full-time worker's capacity. In sum, it shows promise to reduce labor and increase income at the same time. See Table 10 for Scenario 2LL's performance indicators relative to Baseline LL.

Compared to Baseline LL, gross annual income under Scenario 2LL—gross cash income plus the value of own products consumed by the household—is +121% at 2.4 million TSh. or 1,119 USD. Annual cash inflows under Scenario 2LL is +436% than on Baseline LL at 1.3 million TSh. or 585 USD.

The final notable difference between Baseline LL and the farm under Scenario 2LL can be found in the net cash inflows, i.e. cash flows corrected for management-related expenses. Baseline LL risks nutrient mining, as it doesn't import natural grasses or mineral fertilizers. The representative farm under Scenario 2LL only imports 300 kg dry maize bran. In order to prevent nutrient mining, the farmer could add 142 kg NPK; in order to reach the locally attainable maize yield, another 40 kg NPK and 40 kg DAP are applied. This 222 kg fertilizers would come at a cost of 26% of total cash inflows. Resultant net cash inflows under Scenario 2LL are +283% than on Baseline LL, considerably less than the +436% total cash inflows.

4. Discussion

The results of this study reveal potential to improve milk production and income among smallholder farmers in Lushoto, Tanzania without threatening household self-sufficiency for food calories.

Waithaka et al. (2002) found that smallholder farmers' primary objective is household food supply; cash income comes second. It is not entirely clear from the results what the Lushoto sample farmers considered their primary objective, though Scenario 1 from the workshop (how to spend a hypothetical gift equal to one's annual cash income) offered a hint. Nine out of 20 farmers voted to spend it on (mineral) fertilizers, i.e. on their crops, while another nine voted to spend it on their cattle. Furthermore, the group rejected Scenario 3, "feed or food crop specialization". Roughly speaking, crop cultivation increases household food supply and cattle improves cash income through milk sales. In other words, the Lushoto sample as a whole does not clearly prioritize one objective over another.

Economic performance on the representative farm household, as modeled in FarmDESIGN, shows considerable improvement from Baseline HL to Scenario 2HL, 'Napier cultivation supplemented with natural grasses'. The adjusted feed mix increases production and income: triple the milk production thanks to herd expansion from two to three cows and double the milk production per cow; double the return to labor; and more than double the net cash inflows. However, Scenario 2HL implementation would increase the farm's reliance on purchased inputs: farm-related costs rise from 6% (Baseline HL) to 21% (Scenario 2HL) of gross cash income.

Modeled farm performance under Scenario 2LL shows that Napier cultivation could lead to considerable improvement for the representative labor-constrained single-(grand)parent household as well. In comparison to Baseline LL, which is without cattle, total income more than doubles and net cash inflows nearly quadruple under Scenario 2LL, mainly because of milk production from two cows. However, this strategy has two serious drawbacks: [1] like under Scenario 2HL, the farm becomes much more reliant on purchased inputs—primarily on mineral fertilizers to prevent nutrient mining—at a cost of 35% of cash inflows, up from 8% for Baseline LL; [2] although still within one person's availability, the labor requirement under Scenario 2LL is 70% higher than under Baseline LL. A single-(grand)parent household could alternatively choose to implement Scenario 2LL with one instead of two cows. This would reduce required labor by max. 650 hours/year, but total income and net cash inflows would drop by max. 19% and 51%, respectively.

In a way, the results are similar to earlier outcomes. Tittonell et al. (2009) found that P application combined with increased Napier cultivation and decreased food crop cultivation could increase biomass productivity and milk production. Although biomass productivity was not included as a performance indicator in this study, Napier's estimated yield of 50 Mg/ha/year is substantially higher than any other evaluated crop's yield estimates. Furthermore, soil sample analysis indeed identified P as the most-limiting macro-nutrient, but based on estimates generated with QUEFTS, application of P and N could do more to increase yields than application of P alone.

As part of a project to improve milk production on mixed systems in Tanzania, Maass (2015) identified rainfed grass cultivation and irrigated fodder production as the most promising strategies. Irrigated fodder production was not taken in to account here, but rainfed grass cultivation indeed shows potential to improve milk production.

4.1. Critical issues

Potential farm performance under Scenarios 2HL and 2LL, although seemingly promising, is partially determined by assumptions and simplifications; this is inherent to modeling studies. Due to the static character of FarmDESIGN models, two important issues were ignored in the analysis: [1] relevant market dynamics, i.e. the effect of changes in farm performance and strategy on prices; [2] the possibilities of (a) a long Napier establishment period, (b) slow responsiveness of maize to fertilizer application, (c) and degrading soil fertility.

1. If Scenarios 2HL and 2LL would be implemented at a large scale, with the expected increases in crop and milk production as a result, local prices would be expected to change. The prices of mineral fertilizers and maize bran might rise with increased demand, whereas the price of beans could be depressed by boosts to production and marketing. This possible combination of increased costs and reduced revenues could hurt the farmers involved, and might lead to feedback loops which cannot easily be quantified. (The price of milk can be considered independent from local development because the sample farms are connected to a national milk processor.) Mineral fertilizers merit a final note: 222 kg on 1 acre, as modeled under Scenario 2LL, equals 555 kg/ha. At a national level, 555 kg/ha would put Tanzania among the world's 16 heaviest fertilizer-consuming countries (World Bank, 2016). Such demand from Lushoto farmers would undoubtedly disturb the currently small local market for mineral fertilizers. Perhaps most importantly, one should wonder if a push for a global-top-16 level of fertilizer consumption could really be the right path to improved rural livelihoods.
2.
    a. Napier grass needs several seasons for robust establishment, as was observed among multiple local farmers. The 50 Mg/ha/year fresh yield here used—and the associated milk production—thus might not be observable in the first few years. In addition, Napier is known to be a heavy nutrient miner, perhaps even more so than the model accounted for. Special efforts might therefore be required to maintain soil fertility (Waithaka et al., 2006).
    b. None of the sample farmers applied mineral fertilizers to their plots—to borrow from Tittonell & Giller (2013), they have remained rather 'ecological'. One possible reason could be slow yield responsiveness to mineral fertilizers, which come at substantial costs to the farm household. The potential 63% boost to maize yields, as estimated with QUEFTS, might not be realistic in the short term: before poor fields can respond to nutrient inputs, they should be rehabilitated with long-term additions of organic matter (Tittonell & Giller, 2013). "Adequate soil organic management is thus a prerequisite to get good responses to fertilizer investments" (Tittonell et al., 2015, p. 122).
    c. At an average of 24.3 g/kg, the organic carbon content in the sample farms' topsoils is substantially lower than in the Ubiri's natural feed area (40.2 g/kg). This difference between cultivated and semi-natural land is in line with Winowiecki et al. (2015). Furthermore, the C balances on the representative farm under Baseline LL and Scenario 2LL are estimated at -729 kg/ha and -860 kg/ha, respectively. Carbon mining to this extent won't hurt the C content in the

short term—30 cm deep topsoil with a 1 g/cm^3 mass density would contain 72,900 kg/ha of carbon—but it undermines the sustainability of Scenario 2LL nevertheless.

The overarching limitation here is the sensitivity of the model output to differences between the model input and reality. Prices might change, yields might disappoint, more time between lactations might hurt milk production. For instance, a milk price reduction from 500 to 300 TSh./liter *ceteris paribus* would reduce net cash income by 39% under Scenario 2HL (by 40% under Scenario 2LL), and lower Napier yields under Scenario 2HL would mean that herd expansion might not be possible after all. Perhaps the only way to deal with these uncertainties would be to implement one of the strategies here analyzed, after possible adjustment by the farmer(s) involved, on a demonstration farm (see Waithaka et al., 2006). This would allow us to assess the amount of time and, possibly, additional investments of labor and money before the modeled performance becomes realistic.

The idea of a demonstration farm spawns perhaps the most important question concerning this study's results: why, if the combination of Napier cultivation and purchased inputs can boost farm performance so strongly, aren't any of the sample farms following this path? One possibility is the value that farmers attach to food self-sufficiency: the results indicate that Napier cultivation at the expense of maize and beans doesn't necessarily hurt food crop production if combined with mineral fertilization of the maize fields, but reduced acreage under food crops might reduce food production *expectancy*. Another possible reason for farmers' unwillingness to intensify might be that the scenarios here analyzed are relatively capital-intensive. The costs of purchased inputs pose a financial risk. A risk-averse farmer might therefore decide against the purchases considered in the model, so to ensure the farm's financial independence. In this case, locally attainable yields and milk production levels are unlikely to be realized, and household income cannot be expected to improve.

4.2. Recommendations for future studies

As underlined under point 2c. above, the soil carbon content of the sample farms is lower than that of the area's semi-natural land, and the negative C balance under Baseline LL and Scenario 2LL would degrade it further. A better understanding of the importance of soil carbon contents to crop yields in the middle and long term could deepen the value of this study's results.

Under Baseline HL and Scenario 2HL, the representative farm relies on natural grasses from public land for a portion of the cattle feed. It was modeled that 1,200 kg DM common reed and 600 kg DM Bermuda grass are collected each year, which would require up to 0.8 acres (0.32 ha)[2] of public land, which is 80% of the farm's total plot size. Landscape analysis might be able to assess strategies that rely on public land such as these, especially their resilience in the face of population growth. Another limitation to this study is that Lushoto might stand out among similar socio-ecological systems, because natural grass from public land is available *ad libitum*. It might reduce these results' representativeness for other parts of Sub-Saharan Africa.

This study's sample farmers clearly prefer the use of crop residues as animal feed over soil amendment: the latter tactic wasn't observed on any of the 20 sample farms. A relevant aspect left unexamined in this

[2] Based on minimum yields of *Arundo donax* and *Phragmites australis* as listed on Feedipedia.org

study is the size of this trade-off, i.e. between relatively fast (animal responses to feed) and slow (soil quality improvement) effects (see Tittonell et al., 2015). Because the sample farms undertake no soil protection measures, local soil losses from water erosion are also part of the knowledge gap. Naturally horizontal fields are non-existent in the study area, and terracing is rare; as a result, nearly all fields are located at a gradient and undoubtedly lose soil during heavy rains. FarmDESIGN can take into account nutrients and organic matter lost due to erosion, but estimates for this study area weren't available. Quantitative comparison of different management styles pertaining to crop residue use, or estimates of soil loss from erosion, might give a better idea of the local feed-versus-soil-amendment trade-off.

An adjusted feed strategy from Baseline HL—in this case a combination of crop residues, Napier grass, and natural grasses—is likely to improve milk production. Under Scenario 2HL, it can meet the nutritional requirements of three instead of two cows, each producing twice the amount of milk produced under Baseline HL. Yet, based on our observations, another two management adjustments could further improve milk production: [1] the addition of water to the feed, and [2] better manure management.

1. Out of 12 farmers visited to identify and weigh given livestock feeds, only one farmer supplied water to the animals, and even then just 20 liters to four cows and two sheep. It is unlikely that crossbred dairy cows are able to meet their water requirements with the water contained in the feed alone. Extra water is thus likely to improve milk production. The size of that improvement, however, is not clear. Future research and interventions is advised to address this issue.
2. The cows owned by the sample farms are tethered in wooden sheds that are only slightly larger than the animals. There is little space to move around, and little freedom to choose where to lie down. Unless the farmer removes the manure and dries the shed floor once or twice daily, the cow will be less inclined to lie down and ruminate. Few sample farmers indeed clean the shed daily, which might limit milk production. Furthermore, better management could increase nitrogen use efficiency. Based on Rufino et al. (2011), who studied cattle farmers in northeastern Zimbabwe, poor manure management and storage for up to 12 months led to low nitrogen efficiency of 20-30% between N excreted and N applied. At the other end, optimal manure management as studied in the highlands of East Africa, where storage was up to 6 months, leads to much higher nitrogen efficiency of 80% (Rufino et al., 2007, as cited in Rufino et al., 2011). Farmyard manure nitrogen efficiency on this study's sample farms—where manure management probably wasn't optimal but storage was up to 6 months—can be expected somewhere between the two extremes. The FarmDESIGN model included a 60% farmyard manure availability rate—a lower actual rate would increase the external fertilizer requirement to prevent nitrogen mining, which would unnecessarily hurt farm income and increase its environmental impact.

Finally, well outside the scope of this study but undoubtedly instrumental to improving smallholder farm management and income, are the roles of formal education—many Lushoto children still leave school at age 12—and extension services, which are hardly present in the study area. These observations are in line with Waithaka et al.'s (2006) work in western Kenya.

5. Conclusion

Half a century since the Green Revolution transformed agriculture in Asia, farmers in SSA still struggle to increase productivity in line with the continent's population growth. Some agricultural scientists propagate ecological intensification—more agricultural outputs from less synthetic and petroleum-derived inputs by harnessing ecological processes—but in most of Africa, the economic importance of smallholder agriculture has led policymakers to focus more on intensification than ecological processes.

In Lushoto District in Tanzania, 25-95% of households own improved dairy cows (Mangesho et al., 2013) but milk production levels have struggled to realize their potential. Both at the district and national level, milk production has therefore been identified as a promising mode of intensification. Because grazing is nearly non-existent in Lushoto, this study's focus has been on the extent to which fodder cultivation could sustainably improve the sample farms' milk production and income, and on the associated trade-offs with household food production and required labor. The first *ex ante* hypothesis was that increased Napier cultivation combined with the application of mineral fertilizers could increase milk production and net cash inflows. Based on the second hypothesis, that farmers prioritize household food production over cash income, intensification scenarios were developed so that household food production would not suffer.

In the participatory scenario development workshop, Napier cultivation on the plots close to the homestead was confirmed as a promising strategy to improve milk production and cash income. Estimates generated with QUEFTS and FarmDESIGN showed that increased area under Napier doesn't necessarily reduce household food production if combined with structural NPK and DAP application. With additional maize bran imports, a household without labor constraints could triple total milk production, increase its return to labor by 95%, and improve net cash income by 147% compared to the Baseline HL farm. A single-(grand)parent household, where farm labor availability is more limited, could increase total income by 121% and net cash income by 283% compared to Baseline LL.

Before interventions could be developed from the scenarios, however, further research should fill a number of remaining knowledge gaps. Little is known on the local establishment period of Napier and crop responsiveness to mineral fertilizers, or of the required labor and capital investments before improvements to production and income become observable. Furthermore, it might be more rewarding for local farmers to focus on improved watering and cattle housing instead of Napier cultivation. Those strategies' return on investment is unclear, however, and as such cannot be assessed in relation to this study's results. Finally, the apparent benefits of Napier cultivation come with two caveats. Firstly, it adds risk to the farm household: financial risk through structural and substantial purchases of mineral fertilizers and maize bran, and risk to food self-sufficiency due to reduced acreage under maize and beans. Secondly, the mineral fertilization levels included in the intensification scenarios are not only much higher than the SSA norm, they surpass the European norm. One should wonder if such external nutrient dependency is desirable, even if it would lead to improved rural livelihoods.

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