land

MDPI

Article

# Gender and Water-Energy-Food Nexus in the Rural Highlands of Ethiopia: Where Are the Trade-Offs?

**Grace B. Villamor** [1,2]

[1] Scion (New Zealand Forest Research Institute, Ltd.) Titokorangi Drive, Private Bag 3020, Rotorua 3046, New Zealand; grace.villamor@scionresearch.com
[2] Department of Ecology and Natural Resources Management, Center for Development Research, University of Bonn, 3 Genscherallee, 53113 Bonn, Germany

**Abstract:** The introduction of modern bioenergy alternatives is promoted to address water–energy–food (WEF) security in the rural highlands of Ethiopia. While the role of women in WEF security is an essential component of these challenges, gender dimensions remain invisible in the nexus debate. This study explores the impact of gender-specific roles between female- and male-headed households on the nexus resources in the rural highlands of Ethiopia using an agent-based modeling approach. This includes capturing the gender-specific responses to modern bioenergy interventions to address current energy crises that may reduce or enhance synergies among nexus resources and whether the introduction of modern bioenergy technology would improve the quality of life for both men and women. Using the participatory gendered mental model of the food–energy–land nexus, a base ABM was developed to simulate the predicted effects under scenarios of population growth and labor reallocation. Initial simulation results show that there is low adoption of alternative bioenergy (i.e., biogas digesters), and the majority remain dependent on traditional energy sources (e.g., fuel wood and animal dung), suggesting further land degradation. Female-headed households that adopt biogas increase their burden of collecting water needed for the operation. Reallocation of labor from crop production to fuelwood collection would result in the reduction of crop yields. It is expected that male-headed households have better crop yields than female counterparts due to gender-specific roles. However, by shifting 10% of labor allocated from energy collection to crop production, yields (i.e., teff and wheat) produced by female-headed households would be comparable to their male counterparts, enhancing their food security. However, the reduced workloads for women resulting from the adoption of biogas digesters will not necessarily enhance their quality of life. This study suggests that trade-offs may arise between efficiency (in resource use) and social equity, which deserve to be further analyzed.

**Keywords:** agent-based model; bioenergy; fertilizer choices; fuelwood; gender roles; labor allocation; quality of life

check for updates

**Citation:** Villamor, G.B. Gender and Water-Energy-Food Nexus in the Rural Highlands of Ethiopia: Where Are the Trade-Offs?. *Land* **2023**, *12*, 585. https://doi.org/10.3390/land12030585

Academic Editors: Sima Fakheran, Christine Fürst, Li Li, Jin Kyoung Noh and Pinar Pamukcu Albers

Received: 2 December 2022
Revised: 10 January 2023
Accepted: 25 February 2023
Published: 28 February 2023



## 1. Introduction

The water–energy–food (WEF) security nexus is an important approach to achieving sustainable development goals. The WEF nexus concept describes and addresses the complex and interrelated nature of global resource systems in order to help achieve different social, economic, and environmental goals. There are inherent trade-offs among water, energy, and food outputs, as well as a declining capacity of natural resource bases that are needed to support demand [1,2]. In recent years, many studies have used the WEF nexus framework in efforts to find a balance between water, energy, and the use and production of food [3]. A recent review [4] identified several types of nexus research, such as linkages among water and food; water and energy; and water, energy, food, and climate. Most of these nexus studies revolve around economic efficiency, resource efficiency, and improved livelihood options [5,6]. However, exploring synergies and reducing trade-offs, social inequality, and access with respect to these resources should be part of the nexus challenge, especially in the context of developing countries, where the well-being of local people is closely interrelated with the availability of these resources [7–10]. One of the shortcomings of existing nexus frameworks is that they generally ignore daily realities, priorities, and needs at the local level [7].

While the role of women in water, energy, and food security is an essential component of these challenges, gender dimensions remain invisible in the nexus debate. In many cases, development and conservation efforts have been gender-blind and/or excluded women, sometimes exacerbating gender inequalities [11]. For example, in Africa, people in most countries are dependent on biomass and fuelwood for household energy needs, and the collection and management of biomass and fuelwood is a gender-specific responsibility of women [12]. Women in this region are also heavily involved in the full range of agricultural production activities, which typically involve traditional technologies and both land and labor-intensive practices [13,14]. The introduction of modern bioenergy technologies (i.e., improved household stoves) may reduce reliance on traditional biomass energy (including corresponding reductions in individual workloads) while increasing energy efficiency in the region. Nevertheless, the use of modern bioenergy technologies by households and communities is uncommon in sub-Saharan Africa [15]. Ethiopia is one of the fastest-growing economies in Africa, and yet, almost all rural area households depend on traditional fuels (charcoal, fuel wood, dung cake) for cooking [16]. The Ethiopian Government has a high-level plan and strategy to pursue agricultural-based industrialization in order to become a middle-income nation in a sustainable, climate-compatible manner by 2025 [17,18]. Among the strategies are to leapfrog from existing labor-intensive technologies to modern and more energy-efficient technologies and to improve crop and livestock production practices to increase food security and farming income [18]. These development plans highlight major interface areas of the WEF security nexus.

Few studies have investigated the dynamic linkages between gender and WEF nexus resources [3,19–21]. Hence, this study explores the nexus-related dynamics at the local level and associated gender equity issues in the context of Ethiopia's rural highlands. This study attempts to address the research question of "How does the reallocation of labor brought by modern energy options affect male-headed households and female-headed households differently?". Incorporating a gender perspective into WEF nexus-related projects (particularly for the introduction of bioenergy alternatives in developing nations), policy, and planning may help ensure their effectiveness. To do this, an agent-based model (ABM) is applied as a tool to explore the interactions between social and ecological systems within WEF security nexus scenarios. This study focused on food, energy, and land resource linkages as opposed to a nexus concept involving water resources.

*WEF Modeling Approach and Conceptual Framework*

An agent-based model (ABM) is a computational modeling tool in which decision-makers (agents) are explicitly represented, and their decisions generally affect their inter-relationships with other agents and the environment in which they are placed [22]. Agent-based models can incorporate details about human behavior, decisions, and interactions. According to a recent review [23], the number of ABM applications to investigate the WEF nexus dynamics has increased over the last decade. This is because ABM has the advantage of exploring the effects of alternative scenarios as the result of interactions among individual agents and informing the design of policy interventions to overcome diverse behavioral barriers to transition to production/consumption patterns that maximize benefits across WEF systems [23]. Additionally, ABM has the advantage of treating the process of adopting new technologies and diffusion of knowledge [24], making it a useful tool for applying a complex systems lens to sustainable development problems [25], such as resource efficiency and gender equality [26]. However, Magliocca [23] pointed out that the social dimensions of WEF issues remain underdeveloped, and consideration of gender in this context is still nascent [27].

The concept of ecofeminism links gender, and more specifically feminism, with environmental sustainability [28]. Proponents of ecofeminism argue that women have a distinct relationship with nature than males by their biology (predominantly as actual or potential child bearers) and that this closer 'proximity to nature' qualifies women to behave and speak more eloquently on nature's behalf [29]. Three aspects are central to ecofeminist theory [30].

1. A greater percentage of global environmental problems affect women through traditional gender divisions of labor.
2. The dualistic structure (that women can be perceived as culturally and symbolically connected to nature) continues to be reinforced by religion, philosophy, and other (social) restrictions that value women as inferior to men.
3. The epistemological claim that women are more adversely affected by environmental problems than men (i.e., that women's workloads often increase relatively more than men's when natural resources are degraded) puts women in a critical position to address anthropogenic problems concerning natural systems.

Drawing on the argument that women are closer to nature, ecofeminists were skeptical of mechanistic, reductionist, and fragmented approaches to understanding the natural world that result in the development and use of unsafe, harmful technologies that are meant to conquer and subdue nature [31]. Meinzen–Dick et al. [28] viewed the ecofeminism approach as a valid response to the tendency to overlook the importance of women's roles in managing natural resources. However, considering different gender roles and their dependence on resources for livelihoods, as well as understanding the specific constraints to the adoption of new practices or technologies, is fundamental to the development of solutions that can help ensure resource use sustainability [28,32].

For this study, a conceptual framework was adopted that explicitly addresses gender-specific roles and access to WEF nexus resources (Figure 1). This framework was based on the Actors, Resources, Dynamics, and Interaction (ARDI) method [33], a participatory development of a gendered mental model of the WEF nexus concept at the local level [20,34]. Using the ARDI approach, the conceptual framework represents the shared knowledge of the stakeholders involved [35]. The framework recognizes gender-specific differences in access to and the utilization of related nexus resources, including the nexus resource management roles [20]. This framework was simplified and translated to ABM, where agents are male- and female-headed farm households with respective decision-making responsibilities. The dynamic sub-models (i.e., processes) are forest yield growth (i.e., generation of fuelwood for energy needs), livestock production (i.e., generation of dried cattle dung (hereafter "dung cake") as a source of energy and as fertilizer for crop production), and agricultural yield dynamics (i.e., production of important crops such as teff, sorghum, millet, and wheat) (Figure 1). All these dynamic processes are essential livelihood sources for farm households. External factors that drive system dynamics are population growth, market prices of major crops, and policy (e.g., related to land tenure).

Drawing on the ecofeminism sustainability approach [28] and the gendered mental WEF nexus model, two hypotheses were tested using the ABM.

**Hypothesis 1 (H1).** *Because of fuelwood scarcity, reallocating labor of female-headed households from agricultural to other activities (e.g., fuelwood collection) will reduce the agricultural yield available for households due to the traditional gender division of labor.*

Regardless of gender, labor is a crucial crop production input, especially in rural areas of Africa. Thus, it is assumed that the reallocation of labor from crop production to fuelwood collection would reduce crop outputs (representing a trade-off). This premise also assumes that as households increase labor input for fuelwood collection due to increased scarcity of energy resources (fuelwood or dung cake) and, consequently, reduce labor inputs for agriculture, the resulting shift contributes to forest degradation [36–38].

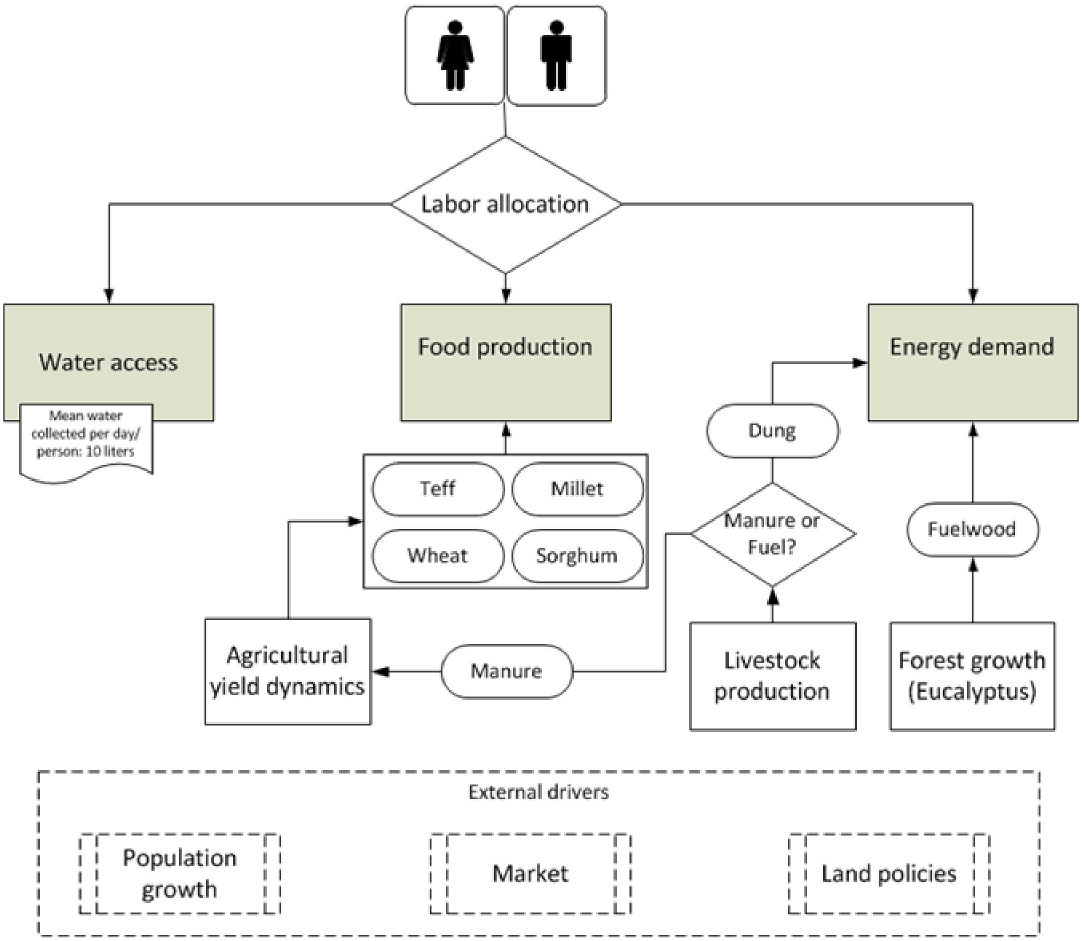


**Figure 1.** Household-level conceptual model based on a participatory approach (modified from [20]).

**Hypothesis 2 (H2).** *Access to modern energy sources (e.g., biogas), especially for female-headed households, will improve their agricultural production, socio-economic status, and quality of life (by reducing their workloads from fuelwood collection).*

Rural women are particularly impoverished with respect to time because their available time is constrained by responsibilities related to energy production and household chores [39]. Thus, increasing access to modern forms of bioenergy (e.g., biogas produced by biomass digesters) can increase time availability for women and allow them to engage in other productive activities (e.g., training and education), improve agricultural production while reducing pressure on forest resources (fuelwood), as well as enhance their quality of life. These two hypotheses using ABM simulation may provide insights into two of three aspects of ecofeminist theory.

## 2. Materials and Methods

### *2.1. Case Study and Data*

The rural highland of Ethiopia is the case study area. In sub-Saharan Africa, Ethiopia is the second most populated country, with approximately 120 million inhabitants (in 2021). The economy of Ethiopia has grown rapidly over the past 15 years, with a mean annual rate of 9.5%, which has helped reduce poverty in both rural and urban areas. However, the country remains one of the poorest in the world, and food security is a persistent challenge [40].

Agricultural production is vital to the Ethiopian economy, contributing about 41% of the GDP in 2015 [41]. The mean annual population growth over the 15 years between 2000 and 2016 was around 2.6% [40]. Consequently, the demand for water, energy, and food has been growing rapidly, magnifying trade-offs and externalities among associated resources. Moreover, population growth, overgrazing, drought, social unrest, and land tenure policies are perceived as the major drivers of WEF resource dynamics in Ethiopia [20,42]. Drought, productivity declines, loss of wildlife, and land degradation are negative impacts resulting from these drivers. Due to the extremely limited availability of arable land, cropland expansion has caused further land degradation. Thus, farmers compensate for associated problems by shifting to or integrating crop and livestock production. The study area includes the regional states of Amhara and Oromia, where triangulation exercises were conducted [20]. These regions constitute most of the Upper Nile Basin and are critical to the management of land and water resources in the entire basin.

The main crops grown in the study areas are sorghum (*Sorghum bicolor*), maize (*Zea mays*), teff (*Eragrostis tef*), wheat (*Triticum durum*), and millet (*Pennisetum glaucum*) (Table 1). There has been substantial growth in cereal production since 2000 in terms of area cultivated and yields; however, yields remain low by international standards, and overall production is highly susceptible to weather shocks, particularly drought [43]. Crop cultivation in Ethiopia is limited to only 13% of the country. The most preferred crops are teff and wheat, partly due to their relative profitability.

**Table 1.** Yields of the most common crops in Ethiopia (Source: Taffesse et al. [44]).

| Crop | National Mean Yield (t/ha) | On-Farm Yield (t/ha) |
|---|---|---|
| Teff | 1.17 | - |
| Wheat | 2.11 | 6.0–8.0 |
| Sorghum | 2.11 | 2.5–5.0 |
| Maize | 3.01 | 3.3 |
| Millet | 1.72 | 2.8–2.9 |

Land is commonly accessed by households based on inheritance or allocation by local leaders or chieftains. There are also farmers who rent land or occupy land without state permission. Livestock production is the dominant form of agricultural production in Ethiopia, and cattle are the most important livestock. From 1995–1996 to 2012–2013, the cattle population grew from 54.5 million to over 103.5 million, with a mean annual increment of 3.4 million [45]. Cattle are the most highly valued livestock in the study areas, although camels, goats, and sheep are abundant in some parts of the country [46]. The mean number of cattle per household is 5.6 in the study areas. On average, cows produce 10 calves during their lifetime. In the southern districts of Oromia, the mean number of cattle per household is 21.1 (±15.5), whereas, in other districts, household cattle herds range between 11 to 26 head [46]. Mean household cattle herd size in the country is decreasing, primarily due to the reduction of available grazing land resulting from cropland expansion. Drought and the lack of feed and water during the dry season are the main constraints on livestock production in the study areas. The dominant feed resources for cattle are natural grasslands, which exhibit considerable seasonal variation in forage availability and quality based on rainfall fluctuations [46]. The availability of water is better in areas where there are traditional wells and where there have been water development projects. Water sources include wells (*elas*), ponds, and boreholes.

Biogas is an alternative energy resource in rural Ethiopia. It is considered a means of negating the disproportionate use of available traditional sources of firewood, cattle dung, agricultural residues, and charcoal [47,48]. There are two household-scale biogas digesters being promoted by the National Biogas Programme Ethiopia (NBPE) in the rural areas of the country, a 4 $m^3$ and a 6 $m^3$ model. The advantages of using biogas relative to traditional biomass energy use include the following:

- Half of the time typically used for collecting fuelwood can be saved through biogas use [48], suggesting that households can save about 1 h per day of adult labor time with biogas;

- The 4 $m^3$ and 6 $m^3$ biogas digester models can potentially replace up to 2208 kg and 3319 kg of firewood per year, respectively;
- The 4 $m^3$ and 6 $m^3$ biogas digester models can potentially replace up to 6015 kg and 9021 kg of dung cake per year, respectively;
- Relative to the use of fuelwood for baking injera (a staple food item), the use of biogas stoves reduces energy consumption by up to 50%.

#### 2.1.1. Data Sources

Secondary data from the 2013/2014 Ethiopian Socioeconomic Survey conducted by the Central Statistics Agency of Ethiopia and the World Bank [49] were used to parameterize the gendered nexus ABM (Gen-ABM). The objective of the survey was to collect multi-panel household-level data with a focus on improving agricultural statistics and linkages between crop agriculture and other household income-generating activities (e.g., livestock production). The data cover all regional states and the capital, Addis Ababa. The survey included questions about household agricultural activities and other economic activities, human capital, access to services, and access to resources (e.g., energy). Data on water availability and consumption were not available. Of the 3744 total survey respondents, 74% (2700) corresponded to male-headed households and 26% (974) to female-headed households (see Annex S1 for descriptive statistics). The data were used to parameterize the model and compare gender differences in terms of household heads and household membership with respect to labor allocation and farm activities. The secondary data were analyzed using the statistical software STATA 17 [50]. Furthermore, the results of the six gender-disaggregated focus group discussions (FGDs) were also utilized, which involved 56 participants (divided evenly between female- and male-only groups) from three villages (two in Amhara and one in Oromia) conducted from August to December 2016 [20]. The conceptual framework in Figure 1 is one of the key results of the FDGs. The FGDs were useful for identifying gender-specific roles and related daily activities, as well as for triangulation and validation purposes (see Section 2.5 Validation).

### *2.2. Model*

The purpose of the Gen-ABM is to identify areas where trade-offs and synergies exist in the food–energy–land nexus system in response to the specific decisions of male- and female-headed households. The description of the model follows the 'Overview, Design concept, and Details plus Decision' (ODD + D) protocol. The model was programmed in NetLogo version 6.0 (http://ccl.northwestern.edu/netlogo/ (accessed on 19 February 2019)).

#### 2.2.1. Overview

*Agents, state, variables, and scales*: There are two types of agents in the model. Human agents are representations of individual farm households with social, natural, physical, human, and policy access (i.e., bioenergy interventions) state variables. The initial number of household agents simulated is 3744, of which 26% are female-headed households, and the rest are male-headed, according to CSA-LSMS-WB [49]. Landscape agents (i.e., congruent land patches) have state variables based on secondary data. The landscape agents are composed of a stylized environment developed in the NetLogo interface. Individual land patches represent 50 m × 50 m (2500 $m^2$) plots, and the entire model landscape represents 27,722 ha. The indicator variables for observing system interactions are crop yields and fuelwood and dung cake availability.

*Process overview and scheduling*: Each simulation time step represents one year. The main simulation loop (an annual production cycle) includes the following steps: (1) setting-up initial state of system variables, (2) updating agent and patch attributes, (3) adopting behavioral parameters (e.g., labor allocation), (4) making household energy choices, (5) making household soil fertility choices, (6) making household farming choices, (7) updating changes in agent and patch attributes, (8) creating new agents, and (9) translating annual changes.

2.2.2. Detail

*Dung productivity*: The data and parameters used for cattle dung production are summarized in Table 2. A livestock model was parameterized based on the secondary data (see Section 2.1.1). The model assumes a linear relationship with a population growth rate from FAOSTAT [51]. In this study, the cattle were the only focus.

**Table 2.** Sub-model parameter values for cattle dung and fertilizer.

| Variable | Estimated Mean | Source |
|---|---|---|
| Cattle dung production:<br>Cattle (kg/day/TLU [a]) | <br>3.3 | Haileslassie et al. [52] |
| Nutrient content of cattle dung:<br>Nitrogen (g N/kg)<br>Phosphorus (g P/kg)<br>Potassium (g K/kg) | <br>18.3<br>4.5<br>21.3 | <br>Lupwayi et al. [53]<br>Haileslassie et al. [54] |
| Organic fertilizer content:<br>Nitrogen (g N/kg/year)<br>Phosphorus (g P/kg/year)<br>Potassium (g K/kg/year) | <br>154<br>37<br>179 | Haileslassie et al. [52] |
| Cattle dung (kg):<br>Diammoniumphosphate (DAP) (kg) | <br>1 | Gwavuya et al. [48] |

Note: [a] Tropical livestock units (TLUs) were estimated using a conversion factor of 0.79/head for cattle.

*Forest growth*: The Gen-ABM model adopted the forest growth functions using the calculations made by Pukkala and Pohjonen [55,56] for *Eucalyptus globulus* Labill. in the central highlands of Ethiopia. Calculations are based on short rotation management (using a coppicing technique) without thinning treatments. The prediction variables included stem volume, biomass yield, and age [55]. Thirty percent is the default forest cover value used for the stylized landscape.

*Agricultural yield:* The logarithmic Cobb–Douglas production function [57] was used to calculate crop production (Table 3). The specific gender and crop data for each household head were used for the production function. Time spent for crop production by males and females is specified in each sub-model, suggesting that the type of crop produced is also gender specific. Thus, it was also expected that the resulting yields would be gender specific.

2.2.3. Design Concept

Some model components (i.e., stochasticity) were adopted from the existing gender ABM in Villamor and van Noordwijk [27] and Villamor et al. [26]. Household agents are considered bounded rational in the sense that they do not have global information and they do not have infinite computational power [58]. In terms of individual decision-making, the model follows the guiding questions developed by Müller et al. [59] (Table 4).

**Table 3.** Agricultural yield sub-models and parameters of the Gen-ABM.

| Model Description | Explanatory Variable | | Parameter | |
|---|---|---|---|---|
| | Variable | Initial Value | Parameter | Default Values |
| Yield—*teff*<br>Extended Cobb–Douglas yield function of teff (kg/m$^2$/year)<br>($R^2$ = 0.40;<br>$p$ < 0.000) | Farm plot area (m$^2$)<br>Agro-chemical input (kg/m$^2$/year)<br>Time spent by females (h/m$^2$/year)<br>Time spent by males (h/m$^2$/year) | CSA-LSMS-WB [49] | Elastic coefficient<br>Elastic coefficient<br>Elastic coefficient<br>Elastic coefficient | 0.356<br>0.298<br>–0.190<br>0.167 |
| Yield—*millet*<br>Extended Cobb–Douglas yield function of millet (kg/m$^2$/year)<br>($R^2$ = 0.38;<br>$p$ < 0.000) | Farm plot area (m$^2$)<br>Agro-chemical input (kg/m$^2$/year)<br>Time spent by males (h/m$^2$/year)<br>Time spent by females (h/m$^2$/year) | CSA-LSMS-WB [49] | Elastic coefficient<br>Elastic coefficient<br>Elastic coefficient<br>Elastic coefficient | 0.874<br>0.091<br>0.199<br>–0.017 |
| Yield—*wheat*<br>Extended Cobb–Douglas yield function of wheat (kg/m$^2$/year)<br>($R^2$ = 0.54;<br>$p$ < 0.000) | Farm plot area (m$^2$)<br>Agro-chemical input (kg/m$^2$/year)<br>Time spent by females (h/m$^2$/year) | CSA-LSMS-WB [49] | Elastic coefficient<br>Elastic coefficient<br>Elastic coefficient | 0.584<br>0.252<br>0.069 |
| Yield—*sorghum*<br>Extended Cobb–Douglas yield function of wheat (kg/m$^2$/year)<br>($R^2$ = 0.44;<br>$p$ < 0.01) | Farm plot area (m$^2$)<br>Agro-chemical input (kg/m$^2$/year) | CSA-LSMS-WB [49] | Elastic coefficient<br>Elastic coefficient | 0.589<br>0.219 |

**Table 4.** Decisions protocol description of the gendered nexus-ABM (Gen-ABM).

| Guiding Questions | Gendered Nexus-ABM |
|---|---|
| What are the subjects and objects of the decision-making? On which level of aggregation is decision-making modeled? Are multiple levels of decision-making included? | Two types of subjects are (1) male and (2) female household heads, who decide on the household energy source and fertilizer use on their farms; farm plots and livestock are objects; decisions made at the higher level (scenario) affect the decisions made at the lower level; no multiple levels included |
| What is the basic rationale behind agent decision-making in the model? Do agents pursue an explicit objective or have other success criteria? | This model follows bounded rationality (or condition-based) with limited information; there is no explicit objective |
| How do agents make their decisions? | The agents make decisions about whether or not to purchase or harvest crops (from the field) by calculating probabilities (Tables 5 and 6, respectively); preference coefficients were derived from regression analyses and integrated as decision algorithms |
| Do the agents adapt their behavior to changing endogenous and exogenous state variables? And if yes, how? | Yes, via the update-status sub-model as part of the process overview and scheduling |
| Do social norms or cultural values have a role in the decision-making process? | Yes, social norms are important |
| Do temporal aspects have a role in the decision-making process? | Yes |
| To what extent and how is uncertainty included in agent decision rules? | Uncertainty is included in the calculation of the choice for energy and fertilizer use (in the form of standard deviation) |

*Energy source choice*: The use of energy by households can be categorized into two major purposes: for household illumination and for cooking. Household energy use changes according to seasons (winter and summer). For model simplification, the study focused exclusively on energy use for cooking because households cook throughout the year, and household members spend relatively more time collecting energy resources for cooking [37,60]. The most significant portion (77%) of household energy is sourced by collecting fuelwood, followed by purchasing fuelwood (9%), collecting dung cake (5%), and collecting crop residues (3%).

In terms of gender differences between household heads, there were differences in the use of kerosene and fuelwood. Almost 50% more male-headed households than female headed-households used kerosene, whereas almost 50% more female-headed households than male-headed households used fuelwood. The factors affecting household energy choices are summarized in Table 5.

**Table 5.** Bi-logit model estimation of willingness to purchase fuel by households ($n$ = 2612).

| Variable | Coefficient (β) | 95% Confidence Interval | |
|---|---|---|---|
| (constant) | –2.135 *** | –2.534 | –1.737 |
| Labor availability (# of man-days) | 0.286 *** | 0.169 | 0.401 |
| Household total time spent harvesting (hours) | –0.001 *** | –0.002 | –0.001 |
| Time spent on agriculture by male household members (hours) | –0.025 *** | –0.034 | –0.016 |
| Number of cattle (#) | –0.164 *** | –0.223 | –0.105 |
| Value of assets (USD/year) | 0.001 ** | 0.999 | 1.000 |

Note: Likelihood ratio test (chi-square statistics) = 182.26; Pseudo $R^2$ = 0.1402; ** $p < 0.01$, *** $p < 0.001$.

A behavioral rule for shifting from a traditional energy resource (e.g., fuelwood and dung cake) to a renewable energy technology was developed. Based on FGD, the adoption of biogas by households depends on the number of cattle and labor availability, which is consistent with Table 5 and previous studies [61].

The two biogas digester models being promoted by NBPE (as previously described) were adapted as follows using a production rule-based approach (i.e., if [conditions]; then [execution]) based on FGD results and previous study of Berhe et al. [57]:

- If a household does not have enough labor for fuelwood or cattle dung collection, but has a minimum of four cattle and does not want to purchase kerosene; then install a 4 $m^3$ biogas digester;
- If a household does not have enough labor for fuelwood or cattle dung collection, but has a minimum of five cattle and does not want to purchase kerosene; then install a 6 $m^3$ biogas digester.

*Fertilizer choice*: Household agents have the choice to apply either chemical fertilizer or cattle manure. The factors affecting individual farmer decisions are presented in Table 6.

**Table 6.** Bi-logit model estimation of willingness to use chemical fertilizer ($n$ = 2612).

| Variable | Coefficient (β) | 95% Confidence Interval | |
|---|---|---|---|
| (constant) | –0.651 *** | –0.863 | –0.439 |
| Maize yield (kg) | 0.001 *** | 0.002 | 0.003 |
| Teff yield (kg) | 0.002 *** | 0.002 | 0.003 |
| Wheat yield (kg) | 0.004 *** | 0.002 | 0.004 |
| Millet yield (kg) | 0.002 *** | 0.001 | 0.002 |
| Barley yield (kg) | 0.002 *** | 0.001 | 0.002 |
| Household farm area ($m^2$) | 0.001 ** | 0.000 | 0.001 |
| Number of cattle (#) | –0.036 *** | –0.061 | –0.012 |
| Number of cattle lost (mortality) (#) | –0.168 *** | –0.289 | –0.048 |
| Total household time spent on harvest (hours) | 0.001 *** | 0.0004 | 0.0008 |
| Labor availability (# of man-days) | –0.096 *** | –0.167 | –0.024 |
| Value of assets (USD/year) | –0.651 ** | –0.863 | –0.439 |

Note: Likelihood ratio test (chi-square statistics) = 631.17; Pseudo $R^2$ = 0.1744; ** $p < 0.01$, *** $p < 0.001$.

### *2.3. Scenarios*

Since population growth is a major external stress on food–energy–land nexus resources [62], population growth and household labor allocation were used as parameters for the scenarios. The population growth rate of 2.5%, as reported by the World Bank [63], was used as the default value. For the household labor allocation scenario, the default labor combination was 40% of labor allocated for fuelwood collection, 40% of labor allocated for crop production, and 20% of labor allocated for water collection (40%–40%–20%) based on the sex-disaggregated FGD results [20,64]. Nevertheless, labor allocation varies for each household agent because the labor availability of each agent depends on the number of adult males and females as well as the number of hours (and then translated to the number of days) spent on the production of each crop. Furthermore, there are crops that are gender specific according to preferences (see Annex S4). The following labor allocation distributions with associated population growth scenarios in the simulations are tested.

(1) Population growth rate of 5% (high):
- (5%) 40–40–20 = with 40% of household labor for energy resource collection, 40% for crop production, and 20% for water collection;
- (5%) 30–50–20 = with 30% of household labor for energy resource collection, 50% for crop production, and 20% for water collection;
- (5%) 20–60–20 = with 20% of household labor for energy resource collection, 60% for crop production, and 20% for water collection.

(2) Population growth rate of 2.5% (normal, based on the 2016 growth rate):
- (2.5%) 40–40–20 = with 40% of household labor for energy resource collection, 40% for crop production, and 20% for water collection;
- (2.5%) 30–50–20 = with 30% of household labor for energy resource collection, 50% for crop production, and 20% for water collection;
- (2.5%) 20–60–20 = with 20% of household labor for energy resource collection, 60% for crop production, and 20% for water collection.

(3) Population growth rate of 1.0% (low):
- (1%) 40–40–20 = with 40% of household labor for energy resource collection, 40% for crop production, and 20% for water collection;
- (1%) 30–50–20 = with 30% of household labor for energy resource collection, 50% for crop production, and 20% for water collection;
- (1%) 20–60–20 = with 20% of household labor for energy resource collection, 60% for crop production, and 20% for water collection.

### 2.4. Run Set Up Summary

A total of three simulation runs were performed independently for each scenario. In each simulated scenario, the mean parameter values were considered. Each simulation run consisted of annual time steps over five years. Among the indicators used to assess the simulation results were effects on forestry yields in response to the agent's use of fertilizer and energy use (as an overall resource use pattern). For specific gender differences, crop yields, amounts of dung cake and fuelwood collected, and the type of fertilizer applied were compared.

### 2.5. Validation

Since the traditional empirical validation techniques are difficult to apply in ABM that represents a socio-ecological system [65], a stakeholder-centric validation was carried out, in which a conceptual framework was co-designed by actual stakeholders. According to Saam [35], stakeholders' judgments are an indispensable point of reference for validation. Once the conceptual model was co-developed [20,64], it was translated to ABM. The parameters used for the ABM, including the initial simulation results, were presented in one of the villages in Oromia during two gender-disaggregated FGDs conducted on 18–19 July 2017. The discussions revolved around (1) willingness to adopt biogas digesters, (2) how male and female household members use their time for different farming and livelihood activities, (3) planting of eucalyptus trees and associated fuelwood yields, and (4) crop yields. For detailed information about the co-development of the gendered mental model, see Villamor et al. [20].

## 3. Results

### *3.1. Overall Resource Use Pattern and Bioenergy Adoption*

The general simulation results are presented in Figure 2. As expected, the predicted total number of logged forestry (or 'tree') patches was higher under the high population growth scenario (Figure 2a) due to the dependency of most of the population on fuelwood as their primary household energy source. There was little difference in the predicted number of logged tree patches under the normal and low population growth rates, as well as under different labor allocation percentages.

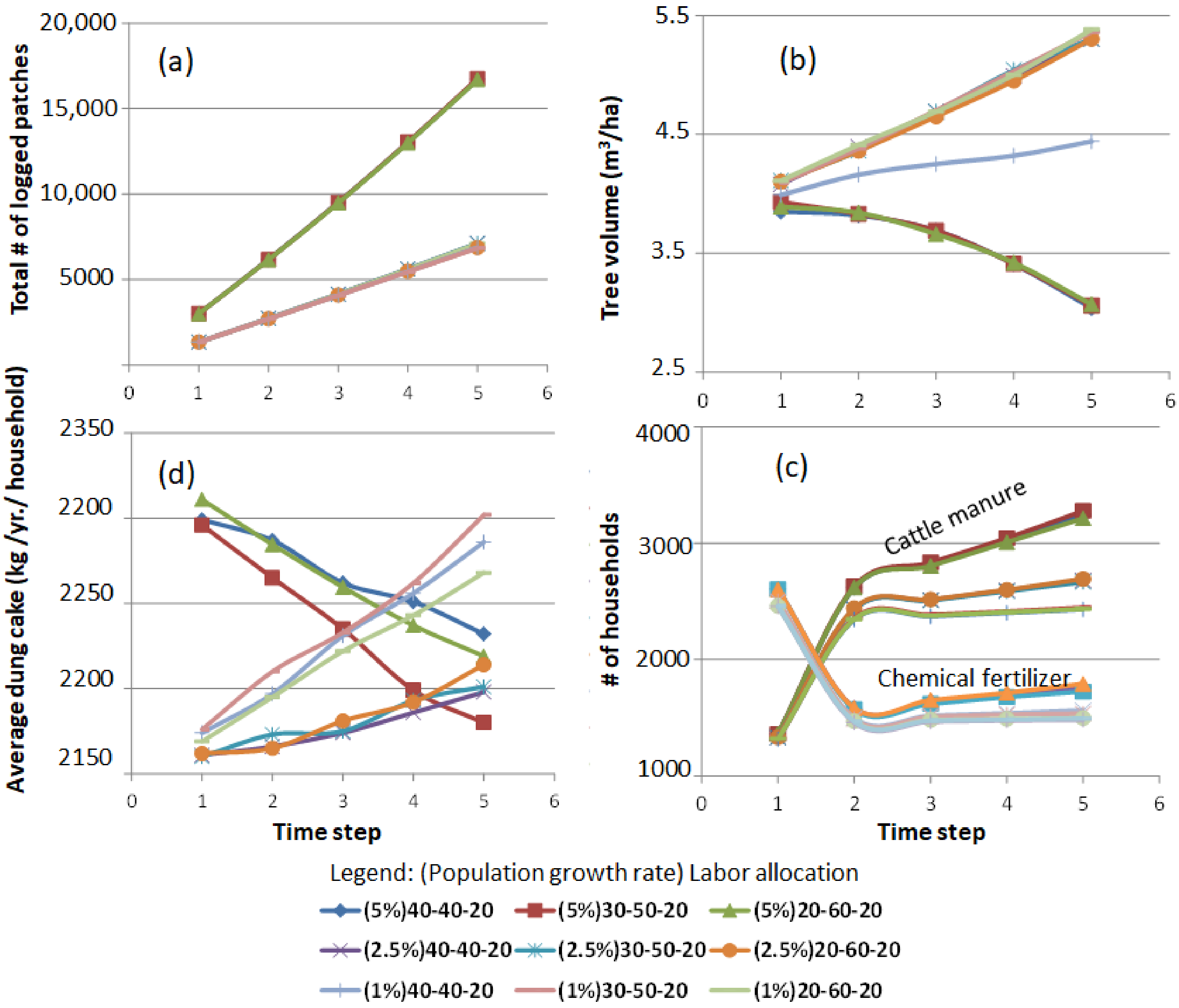


**Figure 2.** Patterns of logged tree patches (**a**), tree volume per hectare (**b**), number of households using organic (cattle dung) and chemical fertilizers (**c**), and mean amount of cattle dung collected (**d**) per household under different labor allocations and population growth scenarios.

Tree volume per hectare under the high population growth scenario was consistently predicted to have a decreasing trend, whereas there was an increasing trend under population growth scenarios of 2.5% and 1.0% (Figure 2b). There were no differences in tree volume among all three labor allocations under different population growth scenarios. In terms of cattle dung collection (Figure 2c), both the 2.5% and 1% population growth rate scenarios had a similar increasing pattern. In contrast, under the high population growth rate, the mean amount of cattle dung collected per household was predicted to decrease. There were only slight differences in predicted cattle dung collection among the different labor allocations, particularly under the high population growth scenario.

There was an increasing trend of cattle manure and chemical fertilizer use (Figure 2c). Although initially, there was a sharp decrease in the predicted number of households using chemical fertilizers, an increase was predicted after year two. Furthermore, there were no differences among the different labor allocations regarding the predicted use of cattle dung and chemical fertilizer. However, there was a greater number of households that applied manure than chemical fertilizer (Figure 2d).

In terms of the predicted adoption or installation of alternative bioenergy options, relatively few households shifted from traditional energy options (Figure 3), and most of those who adopted were male-headed households. The FGD results support this predicted ABM result. Accordingly, males, in general, have more access to external actors and, thus, have a greater awareness of energy alternatives than their female counterparts [64]. The highest number of households with biogas and a slightly increasing trend as labor allocated for energy decreased was predicted under the high population growth scenario (Figure 3b).

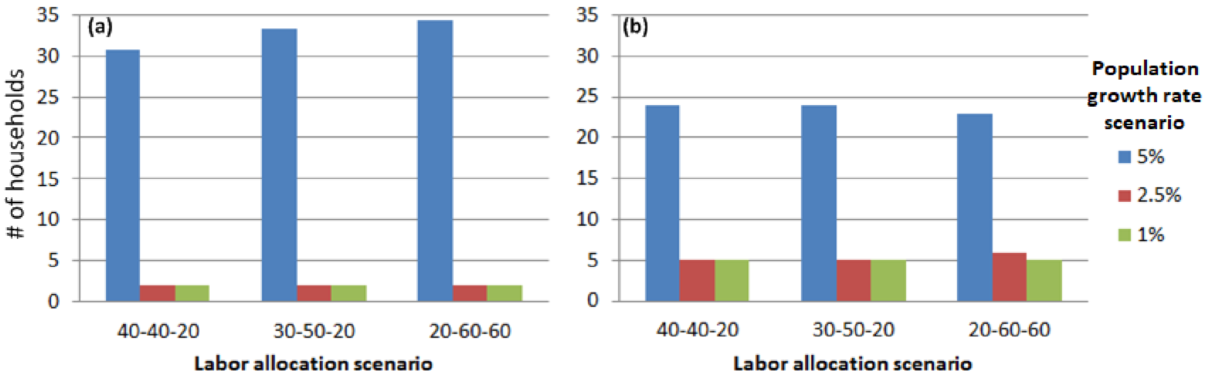


**Figure 3.** Adoption of biogas (**a**) and other bioenergy alternatives (**b**) under different labor allocations and population growth scenarios.

However, based on the validation exercise (see Section 2.5), some key stakeholders expressed their unwillingness to adopt or continue using biogas technology due to the additional work required to collect the water needed for the operation of the biogas digesters, which is mainly performed by female household members, as well as to mix the feedstock and water, which requires about 30 min each day. Furthermore, the inability to pay for the initial investment costs was identified as a factor preventing most households from adopting biogas technology.

### *3.2. Gender-Specific Differences*

#### 3.2.1. Energy Sources

More female-headed households were predicted to collect cattle dung than male-headed households by almost 20% (Figure 4a). Under scenarios of labor allocation compositions, no substantial differences in cattle dung collection were observed between gender. In contrast, the mean amount of cattle dung used per household was much greater in male-headed households than in their female-headed counterparts (Figure 4b). The relatively lower amount of cattle dung in female-headed households may be attributable to the projected number of livestock they owned (Annex S2). Male-headed households were predicted to have more cattle (5.26 TLU) than female-headed households (3.66 TLU).

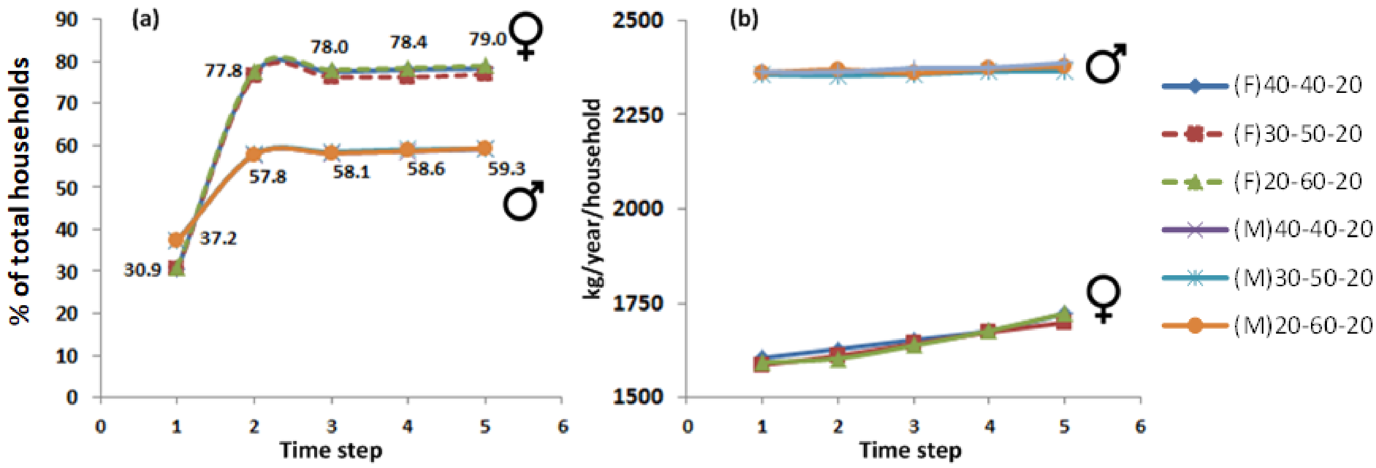


**Figure 4.** Percentages of households collecting cattle dung (**a**) and mean amounts of cattle dung collected (**b**) according to the gender of household heads by labor allocation under normal population growth (2.5%).

### 3.2.2. Crop Yields

Gender-specific differences were evident in household crop yields (Figure 5). As expected, male-headed households were predicted to produce more crops than female-headed households under all scenarios, with substantially greater yield differences in sorghum (Figure 5b) and millet (Figure 5c). The crop with the greatest production by both genders was wheat (Figure 5d). Our simulated yields were comparable to national averages reported by Taffesse et al. [44] but lower than on-farm averages (Table 2). These latter relationships may be attributable to less application of fertilizers. Crop yields were responsive to the amount of labor allocated to crop production by households. There was no substantial difference predicted between 50% and 60% of household labor allocation for crop production among crops and genders, except for sorghum produced by female-headed households (Figure 5). The simulated results suggest that crop yields of female-headed households, particularly of teff and wheat, could be comparable to (or even exceed) yields of male-headed households under a 40–40–20 labor allocation if labor allocated to energy collection is shifted to crop production by 10%.

### 3.2.3. Land Fertility: Fertilizer Use

The predicted percentages of households that applied cattle manure and chemical fertilizer are presented in Figure 6. A gradual increase in the use of manure was predicted for both household types (Figure 6a), as well as a gradual decrease in the use of chemical fertilizers (Figure 6b). More female-headed households were predicted to use manure relative to male-headed households, and less used chemical fertilizer relative to male-headed households (Figure 6a,b).

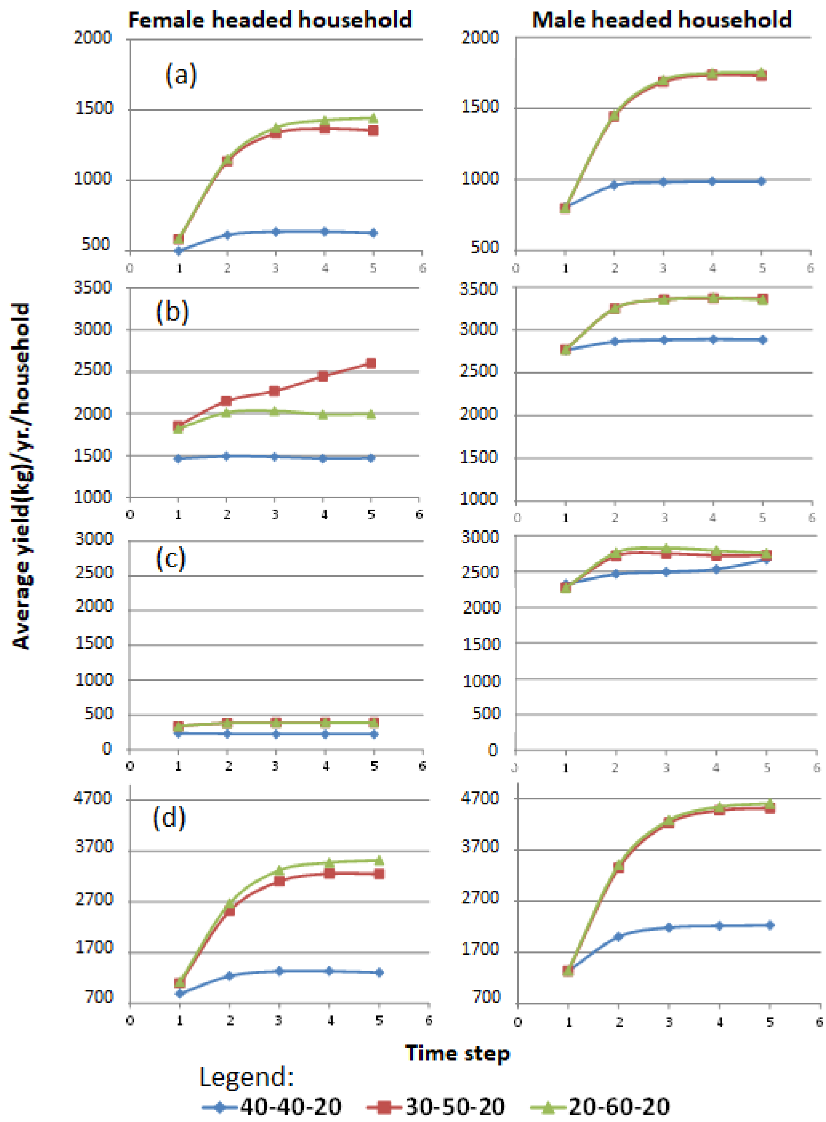


**Figure 5.** Average annual crop yields for teff (**a**), sorghum (**b**), millet (**c**), and wheat (**d**) by gender of household head under different labor allocations and normal population growth (2.5%).

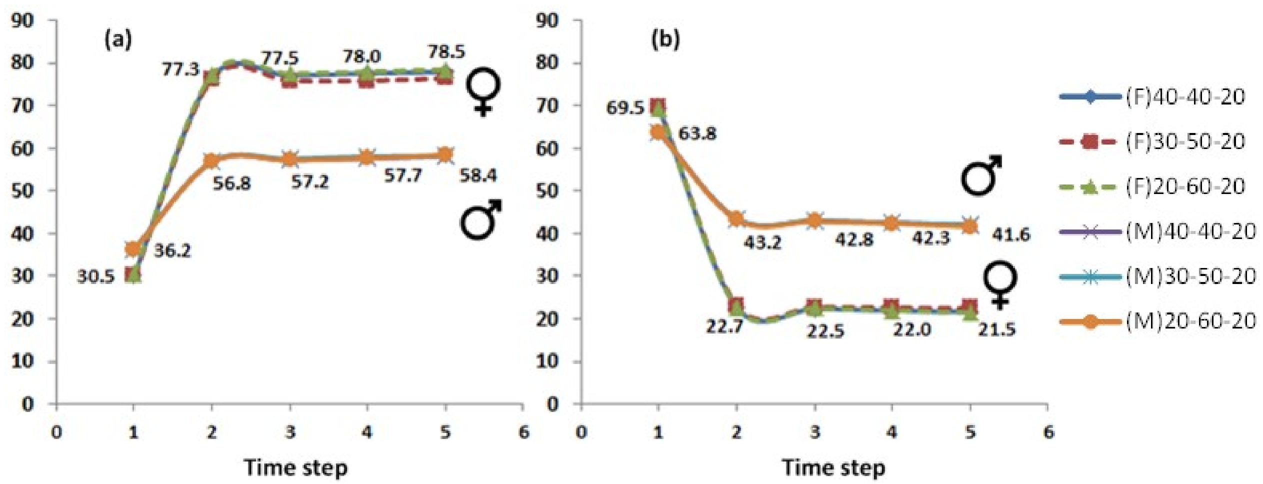


**Figure 6.** Annual percentages of households that applied manure (**a**) and chemical fertilizer (**b**) by gender of household head under different labor allocations and normal population growth (2.5%).

## 4. Discussion

### 4.1. How Does the Reallocation of Labor Brought by Modern Energy Options Affect Male-Headed and Female-Headed Households Differently?

Based on the simulation results, there was a low adoption of biogas from household agents. The majority of households that did were male-headed households. This result is consistent with the findings of Berhe et al. [61] in the Tigray region of northern Ethiopia, where the majority of households continue to depend on traditional energy sources. The findings of Mengistu et al. [66], also in northern Ethiopia, were consistent with our findings that male-headed households were more likely to adopt biogas than female-headed households. One possible factor contributing to this trend is that male-headed households have more access to external actors that promote energy technologies [20]. In contrast, Berhe et al. [61] and Kabir et al. [67] (in Bangladesh) found that female-headed households were more likely to adopt or have a positive association with the decision to adopt biogas energy use. These differences may be attributable to the different methods (e.g., econometric models) used, contextual differences among study areas, as well as available data. The low adoption of new rural energy sources suggests a further increase on reliance on traditional energy sources (particularly on forests, residues from agricultural areas, and from animal wastes).

With respect to whether to accept or reject Hypothesis 1 (H1: Because of fuelwood scarcity, reallocating labor of female-headed households from agricultural to other activities (e.g., fuelwood collection) will reduce the agricultural yield available for households due to traditional gender division of labor), there are two relevant aspects of the model results. The reallocation of labor from agriculture to fuelwood collection would be expected to result in a reduction of crop yields, specifically by reducing agricultural labor by 20%. In this aspect, H1 is accepted. However, a 10% difference did not have much effect on crop yields for either gender, with the exceptions of sorghum yields for female-headed households (Figure 5b) and millet yields for male-headed households after year five when millet yields were almost equal (Figure 5c). These findings suggest that labor differences by gender affect yields as well as the specific crop types. The reallocation of labor from agriculture to fuelwood collection may have a negative impact on forest productivity. In contrast, variation of labor allocation to crop production (Figure 2) would have little effect on forestry productivity.

Regarding Hypothesis 2 (H2: Access to modern energy sources (e.g., biogas), especially for female-headed households, will improve their agricultural production, socio-economic status, and quality of life (by reducing their workloads from fuelwood collection)), the introduction of technology to improve energy efficiency or alternative bioenergy use could potentially increase the household time available to engage in other productive activities. In this case, alternative energy is associated with an increase in food production (Figure 5); thus, H2 is accepted. However, whether this introduction will lead to greater leisure time (or quality of life) for women remains unanswered due to the low adoption. It should be noted that even with an alternative energy source intervention, such as biogas or kerosene subsidies, households are predicted to remain dependent on fuelwood and dung cake, which is consistent with the findings of Berhe et al. [61] that the majority of rural households continue to depend upon traditional energy sources despite biogas digester adoption. Whereas female-operated farms have less access to chemical fertilizers, as observed by Croppenstedt et al. [68], which may suggest that they use the available time to collect dung cake for fertilizer or household energy use.

### 4.2. Trade-Offs in Food–Energy–Land Nexus

Within the concept of WEF nexus trade-offs, the improvement or development of one sector (e.g., energy sector) is expected to have a deleterious effect on the resources available to the other two sectors. For the Ethiopian case, trade-offs would be expected due to competition for land between bioenergy and food production. To mitigate this trade-off, the introduction of modern bioenergy alternatives was seen as a potential intervention that could promote synergies among nexus resources, alleviate poverty [69], "decarbonize" energy production [70], and enhance soil fertility. However, the results of this study would suggest that most of the households would remain dependent on traditional energy sources, suggesting that these aims are unlikely to be realized based on the performance of existing interventions in the study areas. Furthermore, the scenario of population increase was associated with a substantial decrease in tree volume, suggesting further forest degradation. According to Guta [71], heavy reliance on biomass resources for household energy in Ethiopia is largely attributable to the lack of access to bioenergy alternatives, deep-rooted poverty, and limited willingness to make technological transitions. The gender-specific roles of household members and gender-specific preferences regarding energy options may contribute to these already skewed energy relationships to other WEF nexus resources.

Gender-specific roles may also be important considerations among households that have adopted small-scale biogas digesters. It was observed that the availability of women's labor did not change significantly with the adoption of biogas because their work responsibilities merely shifted to collecting water needed to operate the digesters [20]. According to one study in Ethiopia, in order to operate a biogas digester efficiently, the time required to access water should be no more than 30 min [72], which may result in more time spent collecting water [73], burdening further the women in the households who are responsible for fetching and transporting water. Trade-offs may arise between efficiency (in resource use) and social equity, especially in developing areas where gender-specific roles are part of the social norm. While most of the WEF nexus literature has focused on resource-use efficiency [74], labor differences between male and female household members can be an indicator of resource efficiency. Therefore, gender-based labor productivity comparisons are suggested for future investigation.

### *4.3. Post-Simulation Focus Groups (Validation)*

The FGD participants agreed with the key results of the ABM simulation and further provided contexts to support the results. For example, in the male-only focus group, the participants expressed their strong interest and willingness to adopt biogas. However, they also identified the two major barriers to adoption: (1) lack of financial capital to cover the cost of installation and (2) shortage of dung and water needed for the biogas plant. Male participants estimated that about 1 to 2 h per day is needed to collect water for the biogas operation. According to their experience, men are responsible for collecting water, whereas women are mostly responsible for collecting dung, mixing it with water, and feeding it into the biogas plant. They also agreed with the ABM result on fertilizer; accordingly, they estimated a decline of about 100 kg of use of chemical fertilizer as compared to the previous year when they used compost (derived from animal dung). In terms of crop yields, the estimated yields (particularly teff and wheat) are comparable with the results from ABM.

In the female-only focus group, the female participants also expressed strong interest and even described the many benefits of biogas (e.g., smokeless, clean, convenient to use, and a good substitute for kerosene). Regarding the barriers to adoption, they shared similarities with their male counterparts, with an additional barrier identified that biogas is laborious to install. They further described the tasks that women needed to perform to operate the biogas every day, such as 10 min to 1 h to collect water, 10 min to collect cattle dung, and 1 to 2 h for mixing dung and water before feeding into the biogas plant. In terms of fertilizer, the participants indicated that if they use biogas, they must buy chemical fertilizer to grow their crops. In terms of crop yields, the female participants were not able to estimate since harvesting is usually men's role.

### *4.4. Limitations and Further Modeling Improvements*

Water use is an important component of the WEF nexus; however, in this study, the importance of water is limited because most farm households are engaged in rain-fed agriculture. Thus, available data on water resources (i.e., consumption and availability) were inadequate (See Section 2.1.1).

Despite the limited available data to parameterize the female and male farmers' decision-making, the simulation results provide an initial step to understanding the potential implications of the gender-specific differences (also within the households) on the food–energy–land nexus. However, there is always room for improvement, such as making the Gen-ABM more spatially explicit, parameterization of human decisions on water resources (i.e., non-rational behavioral theories), testing economic and climate change-related scenarios, etc. Nevertheless, this study is a first step to making gender studies more dynamic and coupled with agroecosystems [28] and process-based, whereas the food–energy–land nexus is a bottom-up approach.

## 5. Summary and Conclusions

This paper investigates the gender dimensions of the food–energy–land nexus in rural Ethiopia using an agent-based model that was translated from a co-designed conceptual framework of the food–energy–land nexus. The ABM integrated two key decision-making processes by female-headed and male-headed households: energy and agricultural production (e.g., fertilizer choices and crop production scenarios), designed to simulate changes that are likely to affect food–energy–land nexus-related trade-offs. The results show that gender can affect food–energy–land nexus outcomes and that future development and technological changes will be influenced by such heterogeneous decision-making. Future trade-offs between energy resource production and forestry conditions are likely to be influenced by both population growth as well as the tendency of female-headed households to rely on the collection and utilization of fuelwood. Deforestation rates might increase if population growth rates increase. Biogas might be an option for mitigating the trade-offs associated with fuelwood collection and agricultural production, yet only a few households were predicted to adopt this energy alternative, and male-headed households were more likely to do so than female-headed households. The reallocation of labor from agriculture to other activities is likely to have negative impacts on agricultural production and, thus, adversely affect the food security of rural populations. Gender-specific labor allocation differences may be as important as specific differences in crop selection and other agricultural activities in terms of determining trade-off outcomes. Accordingly, promoting agricultural production development might increase rural employment and lead to the adoption of modern energy sources, reducing labor allocation for fuelwood and (cattle) dung cake collection. A similar pattern is expected if households adopt modern energy sources. Policy and other interventions that address food–energy–land nexus issues in rural areas should consider gender-specific decision-making to anticipate how these differences may influence related outcomes. For future research efforts, it will be important to identify how gender-specific differences among rural households can be addressed in policies designed to mitigate WEF nexus trade-offs.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12030585/s1. Annex S1: Descriptive statistics of household agents ($n$ = 3744); Annex S2: Land acquisition by gender ($n$ = 3453); Annex S3: Labor allocation for key activities by gender; Annex S4: Farming type by gender.

**Funding:** This research was financially supported by the German Federal Ministry for Economic Cooperation and Development (BMZ) under the research project: The Water-Energy-Food Nexus: Global, Basin and Local Case Studies of Resource Use Efficiency under Growing Natural Resource Scarcity (Project Number: 14.1432.5-001.00) and the CGIAR WLE research project "Bioenergy, Food Security and Poverty Reduction: Mitigating trade-offs and promoting synergies along the Water–Energy–Food Security Nexus" of the Center for Development Research (ZEF) at the University of Bonn.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** The studies involving human participants were reviewed and approved. As this this study was conducted in rural Ethiopia, a letter was obtained from the Center for Environment and Development Studies of Addis Ababa University and addressed to woredas where the study took place and got full acceptance from woreda administrations and participants in the focus group discussion. The patients/participants provided their written informed consent to participate in this study.

**Data Availability Statement:** Data available in a publicly accessible repository. The secondary data presented in this study are openly available in https://microdata.worldbank.org/index.php/catalog/2247 (accessed on 15 October 2022). with reference ID: ETH_2013_ESS_v03_M and doi: https://doi.org/10.48529/mccp-y123 (accessed on 15 October 2022).

**Acknowledgments:** The author greatly appreciates the valuable comments of Utkur Djanibekov, Alisher Mirzabaev, Claudia Ringler, Dawit Guta, Dean Meason, the Woreda administration representatives and the four anonymous reviewers.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

## References

1. Mirzabaev, A.; Guta, D.D.; Goedecke, J.; Gaur, V.; Börner, J.; Virchow, D.; Denich, M.; von Braun, J. *Bioenergy, Food Security and Poverty Reduction: Mitigating Tradeoffs and Promoting Synergies along the Water-Energy-Food Security Nexus*; ZEF Working Paper No. 135; Center for Develoment Research (ZEF): Bonn, Germany, 2014.
2. Gebreegziabher, Z.; Mekonnen, A.; Ferede, T.; Guta, F.; Levin, J.; Köhlin, G.; Alemu, T.; Bohlin, L. *The Distributive Effect and Food Security Implications of Biofuels Investment in Ethiopia: A CGE Analysis*; Routledge: Oxfordshire, UK, 2013.
3. Djanibekov, U.; Gaur, V. Nexus of energy use, agricultural production, employment and incomes among rural households in Uttar Pradesh, India. *Energy Policy* **2018**, *113*, 439–453. [CrossRef]
4. Endo, A.; Tsurita, I.; Burnett, K.; Orencio, P.M. A review of the current state of research on the water, energy, and food nexus. *J. Hydrol. Reg. Stud.* **2017**, *11*, 20–30. [CrossRef]
5. Bazilian, M.; Rogner, H.; Howells, M.; Hermann, S.; Arent, D.; Gielen, D.; Steduto, P.; Mueller, A.; Komor, P.; Tol, R.S. Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy* **2011**, *39*, 7896–7906. [CrossRef]
6. Howells, M.; Hermann, S.; Welsch, M.; Bazilian, M.; Segerström, R.; Alfstad, T.; Gielen, D.; Rogner, H.; Fischer, G.; Van Velthuizen, H. Integrated analysis of climate change, land-use, energy and water strategies. *Nat. Clim. Change* **2013**, *3*, 621–626. [CrossRef]
7. Allouche, J.; Middleton, C.; Gyawali, D. Technical veil, hidden politics: Interrogating the power linkages behind the nexus. *Water Altern.* **2015**, *8*, 610–626.
8. Ringler, C.; Bhaduri, A.; Lawford, R. The nexus across water, energy, land and food (WELF): Potential for improved resource use efficiency? *Curr. Opin. Environ. Sustain.* **2013**, *5*, 617–624. [CrossRef]
9. Bizikova, L.; Roy, D.; Swanson, D.; Venema, H.D.; McCandless, M. *The Water-Energy-Food Security Nexus: Towards a Practical Planning and Decision-Support Framework for Landscape Investment and Risk Management*; International Institute for Sustainable Development Winnipeg: Winnipeg, MB, USA, 2013.
10. Cairns, R.; Krzywoszynska, A. Anatomy of a buzzword: The emergence of 'the water-energy-food nexus' in UK natural resource debates. *Environ. Sci. Policy* **2016**, *64*, 164–170. [CrossRef]
11. Sijapati Basnett, B.; Elias, M.; Ihalainen, M.; Paez Valencia, A. *Gender Matters in Forest Landscape Restoration: A Framework for Design and Evaluation*; CIFOR: Bogor, Indonesia, 2017.
12. Habtezion, S. *Gender and Energy*; United Nations Development Programme: New York, NY, USA, 2012.
13. Arndt, C.; Benfica, R.; Thurlow, J. Gender implications of biofuels expansion in Africa: The case of Mozambique. *World Dev.* **2011**, *39*, 1649–1662. [CrossRef]
14. FAO. *State of Food and Agriculture 2010-11: Women in Agriculture-Closing the Gender Gap for Developent*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2011.
15. Mirzabaev, A.; Guta, D.; Goedecke, J.; Gaur, V.; Börner, J.; Virchow, D.; Denich, M.; von Braun, J. Bioenergy, food security and poverty reduction: Trade-offs and synergies along the water–energy–food security nexus. *Water Int.* **2015**, *40*, 772–790. [CrossRef]
16. Tiruye, G.A.; Besha, A.T.; Mekonnen, Y.S.; Benti, N.E.; Gebreslase, G.A.; Tufa, R.A. Opportunities and Challenges of Renewable Energy Production in Ethiopia. *Sustainability* **2021**, *13*, 10381. [CrossRef]
17. Daley, B. *Environmental Issues in Ethiopia and Links to the Ethiopian Economy*; Department of International Development: London, UK, 2015; p. 28. [CrossRef]
18. Karlberg, L.; Hoff, H.; Amsalu, T.; Andersson, K.; Binnington, T.; Flores-López, F.; de Bruin, A.; Gebrehiwot, S.G.; Gedif, B.; Johnson, O. Tackling complexity: Understanding the food-energy-environment nexus in Ethiopia's Lake tana sub-basin. *Water Altern.* **2015**, *8*, 710–734.
19. Djanibekov, U.; Finger, R.; Guta, D.D.; Gaur, V.; Mirzabaev, A. *A Generic Model for Analyzing Nexus Issues of Households' Bioenergy Use*; ZEF Discussion Papers on Development Policy No. 209; Center for Development Research (ZEF), University of Bonn: Bonn, Germany, 2016; p. 39.

20. Villamor, G.; Guta, D.; Mirzabaev, A. Gender Specific Differences of Smallholder Farm Households Perspective of Food-Energy-Land Nexus Frameworks in Ethiopia. *Front. Sustain. Food Syst.* **2020**, *4*, 491725. [CrossRef]
21. Tantoh, H.B.; McKay, T.T.; Donkor, F.E.; Simatele, M.D. Gender Roles, Implications for Water, Land, and Food Security in a Changing Climate: A Systematic Review. *Front. Sustain. Food Syst.* **2021**, *5*, 707835. [CrossRef]
22. Gotts, N.M.; van Voorn, G.A.K.; Polhill, J.G.; Jong, E.d.; Edmonds, B.; Hofstede, G.J.; Meyer, R. Agent-based modelling of socio-ecological systems: Models, projects and ontologies. *Ecol. Complex.* **2019**, *40*, 100728. [CrossRef]
23. Magliocca, N.R. Agent-based modeling for integrating human behavior into the food–energy–water nexus. *Land* **2020**, *9*, 519. [CrossRef]
24. Bonabeau, E. Agent-based modeling: Methods and techniques for simulating human systems. *Proc. Natl. Acad. Sci. USA* **2002**, *99*, 7280–7287. [CrossRef] [PubMed]
25. Taylor, R.; Besa, M.C.; Forrester, J. *Agent-Based Modelling: A Tool for Addressing the Complexity of Environment and Development Policy Issues*; JSTOR: New York, NY, USA, 2016.
26. Villamor, G.B.; Le, Q.B.; Djanibekov, U.; van Noordwijk, M.; Vlek, P.L. Biodiversity in rubber agroforests, carbon emissions, and rural livelihoods: An agent-based model of land-use dynamics in lowland Sumatra. *Environ. Model. Softw.* **2014**, *61*, 151–165. [CrossRef]
27. Villamor, G.B.; van Noordwijk, M. Gender specific land-use decisions and implications for ecosystem services in semi-matrilineal Sumatra. *Glob. Environ. Change* **2016**, *39*, 69–80. [CrossRef]
28. Meinzen-Dick, R.; Kovarik, C.; Quisumbing, A.R. Gender and sustainability. *Annu. Rev. Environ. Resour.* **2014**, *39*, 29–55. [CrossRef]
29. Buckingham, S. Ecofeminism in the twenty-first century. *Geogr. J.* **2004**, *170*, 146–154. [CrossRef]
30. Sheldon, M.V. So What Happened to Ecofeminism? *Ky. J. Anthropol. Sociol.* **2012**, 166.
31. Sachs, C. Reconsidering diversity in agriculture and food systems: An ecofeminist approach. *Agric. Hum. Values* **1992**, *9*, 4–10. [CrossRef]
32. Dah-gbeto, A.P.; Villamor, G.B. Gender-specific responses to climate variability in a semi-arid ecosystem in northern Benin. *Ambio* **2016**, *45*, 297–308. [CrossRef]
33. Etienne, M.; Du Toit, D.; Pollard, S. ARDI: A co-construction method for participatory modeling in natural resources management. *Ecol. Soc.* **2011**, *16*, 44. [CrossRef]
34. Villamor, G.B.; Griffith, D.L.; Kliskey, A.; Alessa, L. Contrasting stakeholder and scientist conceptual models of food-energy-water systems: A case study in Magic Valley, Southern Idaho. *Socio-Environ. Syst. Model.* **2020**, *2*, 16312. [CrossRef]
35. Saam, N.J. The Users' Judgements—The Stakeholder Approach to Simulation Validation. In *Computer Simulation Validation*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 405–431.
36. Mekonnen, A. The Impact of Natural Resource Scarcity on Agriculture in Ethiopia; Environment for Development Discussion Paper Series 15–13; Gothenburg, Sweden. 2015. Available online: https://media.rff.org/documents/EfD-DP-15-13.pdf (accessed on 15 January 2020).
37. Mohammed, K.A.; Kawo, K.N.; Robe, E. Evaluation of fuel wood consumption and its implication to forest degradation in Agarfa Wereda, South-Eastern Ethiopia. *Evaluation* **2020**, *62*, 19–33.
38. Teka, K.; Welday, Y.; Haftu, M. Analysis of household's energy consumption, forest degradation and plantation requirements in Eastern Tigray, Northern Ethiopia. *Afr. J. Ecol.* **2018**, *56*, 499–506. [CrossRef]
39. Blackden, C.M.; Wodon, Q. *Gender, Time Use, and Poverty in Sub-Saharan Africa*; World Bank Publications: Washington, DC, USA, 2006; Volume 73.
40. WB. Ethiopia Overview. Available online: https://www.worldbank.org/en/country/ethiopia/overview (accessed on 15 January 2020).
41. CIA. Ethiopia, Central Intelligence Agency the World Factbook. Available online: https://www.cia.gov/the-world-factbook/about/archives/2021/countries/ethiopia/#people-and-society (accessed on 10 January 2023).
42. Ariti, A.T.; van Vliet, J.; Verburg, P.H. Land-use and land-cover changes in the Central Rift Valley of Ethiopia: Assessment of perception and adaptation of stakeholders. *Appl. Geogr.* **2015**, *65*, 28–37. [CrossRef]
43. Bewket, W. Rainfall variability and crop production in Ethiopia: Case study in the Amhara region. In Proceedings of the 16th International Conference of Ethiopian Studies, Trondheim, Norway, 6 June 2009; pp. 823–836.
44. Taffesse, A.S.; Dorosh, P.A.; Gemessa, S.A. Crop production in Ethiopia: Regional patterns and trends. In *Food and Agriculture in Ethiopia: Progress and Policy Challenges*; Dorosh, P.A., Rashid, S., Eds.; University of Pennsylvania Press: Philadelphia, PA, USA, 2012; pp. 53–83.
45. Leta, S.; Mesele, F. Spatial analysis of cattle and shoat population in Ethiopia: Growth trend, distribution and market access. *SpringerPlus* **2014**, *3*, 310. [CrossRef]
46. Tolera, A.; Abebe, A. Livestock production in pastoral and agro-pastoral production systems of southern Ethiopia. *Livest. Res. Rural Dev.* **2007**, *19*, 4–7.
47. Amigun, B.; Von Blottnitz, H. Capital cost prediction for biogas installations in Africa: Lang factor approach. *Environ. Prog. Sustain. Energy Off. Publ. Am. Inst. Chem. Eng.* **2009**, *28*, 134–142. [CrossRef]
48. Gwavuya, S.; Abele, S.; Barfuss, I.; Zeller, M.; Müller, J. Household energy economics in rural Ethiopia: A cost-benefit analysis of biogas energy. *Renew. Energy* **2012**, *48*, 202–209. [CrossRef]

49. CSA-LSMS-WB. *Ethiopia Socioeconomic Survey 2013/2014*; Central Statistical Agency and Living Standards Measurement Study, World Bank: Washington, DC, USA, 2015.
50. StataCorp. *Stata Staistical Software: Release 15*; StataCorp LP: College Station, TX, USA, 2017.
51. FAOSTAT. Food and Agriculture Organization of the United Nations, Statistical Databases. 2015. Available online: http://faostat.fao.org (accessed on 19 February 2019).
52. Haileslassie, A.; Priess, J.; Veldkamp, E.; Teketay, D.; Lesschen, J.P. Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. *Agric. Ecosyst. Environ.* **2005**, *108*, 1–16. [CrossRef]
53. Lupwayi, N.; Girma, M.; Haque, I. Plant nutrient contents of cattle manures from small-scale farms and experimental stations in the Ethiopian highlands. *Agric. Ecosyst. Environ.* **2000**, *78*, 57–63. [CrossRef]
54. Haileslassie, A.; Priess, J.A.; Veldkamp, E.; Lesschen, J.P. Nutrient flows and balances at the field and farm scale: Exploring effects of land-use strategies an{d access to resources. *Agric. Syst.* **2007**, *94*, 459–470. [CrossRef]
55. Pukkala, T.; Pohjonen, V. *Yield Models for Ethiopian Highland Eucalypts*; UN: New York, NY, USA, 1989.
56. Pukkala, T.; Pohjonen, V. Use of linear programming in land use planning in the Ethiopian highlands. *Silva Fenn.* **1990**, *24*, 235–347. [CrossRef]
57. Cobb, C.W.; Douglas, P.H. A Theory of Production. *Am. Econ. Rev.* **1928**, *18*, 139–165.
58. Epstein, J.M. Agent-based computational models and generative social science. In *Generative Social Science: Studies in Agent-Based Computational Modeling*; Princeton University Press: Princeton, NJ, USA, 2012; pp. 4–46.
59. Müller, B.; Bohn, F.; Dreßler, G.; Groeneveld, J.; Klassert, C.; Martin, R.; Schlüter, M.; Schulze, J.; Weise, H.; Schwarz, N. Describing human decisions in agent-based models–ODD+ D, an extension of the ODD protocol. *Environ. Model. Softw.* **2013**, *48*, 37–48. [CrossRef]
60. Dresen, E.; DeVries, B.; Herold, M.; Verchot, L.; Müller, R. Fuelwood savings and carbon emission reductions by the use of improved cooking stoves in an Afromontane Forest, Ethiopia. *Land* **2014**, *3*, 1137–1157. [CrossRef]
61. Berhe, M.; Hoag, D.; Tesfay, G.; Keske, C. Factors influencing the adoption of biogas digesters in rural Ethiopia. *Energy Sustain. Soc.* **2017**, *7*, 716. [CrossRef]
62. Molajou, A.; Pouladi, P.; Afshar, A. Incorporating social system into water-food-energy nexus. *Water Resour. Manag.* **2021**, *35*, 4561–4580. [CrossRef]
63. WB. Population Growth Rate. Available online: https://data.worldbank.org/indicator/SP.POP.TOTL?locations=ET (accessed on 29 October 2017).
64. Villamor, G.B.; Guta, D.D.; Djanibekov, U.; Mirzabaev, A. *Gender Specific Perspectives among Smallholder Farm Households on Water-Energy-Food Security Nexus Issues in Ethiopia*; Center for Development Research, University of Bonn: Bonn, Germany, 2018.
65. Polhill, G.; Salt, D. The importance of ontological structure: Why validation by 'fit-to-data'is insufficient. In *Simulating Social Complexity*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 141–172.
66. Mengistu, M.G.; Simane, B.; Eshete, G.; Workneh, T.S. Factors affecting households' decisions in biogas technology adoption, the case of Ofla and Mecha Districts, northern Ethiopia. *Renew. Energy* **2016**, *93*, 215–227. [CrossRef]
67. Kabir, H.; Yegbemey, R.N.; Bauer, S. Factors determinant of biogas adoption in Bangladesh. *Renew. Sustain. Energy Rev.* **2013**, *28*, 881–889. [CrossRef]
68. Croppenstedt, A.; Goldstein, M.; Rosas, N. Gender and agriculture: Inefficiencies, segregation, and low productivity traps. *World Bank Res. Obs.* **2013**, *28*, 79–109. [CrossRef]
69. Cushion, E.; Whiteman, A.; Dieterle, G. *Bioenergy Development: Issues and Impacts for Poverty and Natural Resource Management*; World Bank Publications: Washington, DC, USA, 2009.
70. Pacala, S.; Socolow, R. Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science* **2004**, *305*, 968–972. [CrossRef] [PubMed]
71. Guta, D.D. Effect of fuelwood scarcity and socio-economic factors on household bio-based energy use and energy substitution in rural Ethiopia. *Energy Policy* **2014**, *75*, 217–227. [CrossRef]
72. Eshete, G.; Sonder, K.; ter Heegde, F. *Report on the Feasibility Study of a National Programme for Domestic biogas in Ethiopia*; SNV Netherlands Development Organization: Addis Ababa, Ethiopia, 2006.
73. Bansal, V.; Tumwesige, V.; Smith, J.U. Water for small-scale biogas digesters in Sub-Saharan Africa. *GCB Bioenergy* **2017**, *9*, 339–357. [CrossRef]
74. Salam, P.A.; Shrestha, S.; Pandey, V.P.; Anal, A.K. *Water-Energy-Food Nexus: Principles and Practices*; John Wiley & Sons: Hoboken, NJ, USA, 2017.