Appendix ODD

The model used in this dissertation is described following ODD (Overview, Design concepts, and Details) protocol (Grimm & Railsback, 2012; Grimm et al., 2010).

1. Purpose

The purpose of this agent-based model is to simulate the behaviors of small farming households in the Amazon estuary region and evaluate their resilience to external shocks with the presence of several government cash transfer programs.

The model is implemented with three decision making mechanisms (Max Leisure, Max Profit, and Subsistence First) as individual ensembles to demonstrate the range of possible livelihood outcomes and to compare the influence of demographic and socio-economic factors. The model is used to quantify the resilience of rural livelihoods in the face of external pressure such as price oscillation and climatic events. Specifically, we adopt the definition and properties of "development resilience" to frame the model output, in order to (1) identify the alternative states in the resilience landscape, (2) determine the negative influence from each shock, and (3) explore interventions to move households out of poverty trap or be more resilient. This is a pioneering effort to demonstrate the resilience dynamics by the simulation of an agent-based model, which extends the theoretical exploration and provides valuable policy implications.

2. Entities, state variables and scales

The two primary entities of this model are the household agent and the landscape. Each of them constitutes a list of core entities. One time step (tick) in the model is a single year.

Based on the decision making method, the *household agent* attempts to maximize its utility of capital (Max Profit), leisure time after subsistence is met (Max Leisure), and grow subsistence crops and maximize capital (Subsistence First). *Capital* is in fixed monetary unit since we don't consider inflation-adjustment in the model. The household agent uses capital to purchase seeds, manage soil, and cover the subsistence and other cost for family members. The household agent contains a list of *family members* (*person* agent) as their core entity. A person is described by his or her age, gender, and education. The *Labour* is derived from the age and gender of each member (Da Silva & Kageyama, 1983) and summarized into a total labour to the household agent. A male adult is considered as one labour unit, and teenagers and elders are bring a fraction of one unit, which depends on their age. A female labour unit is half of the male unit who contains same attributes. School-attending teenagers and pension-beneficiaries do not count as available labour for the household.

A person can age, die, and reproduce, resulting in a demographic change in the household agent. The number and demographic structure of family members in each household agent is populated at the initialization stage of the model and it follows a weighted distribution that can be adjusted based on scenario settings. The probability of death and reproduction for a person is based on the data of Abaetetuba derived from the Brazilian Institute of Geography and Statistics (Portuguese abbreviation: IBGE)[1]. However, there is no farm succession module in this model yet. The school attendance rate depends on the per capita capital in the household: if the per capita capital is beyond the poverty line, there is a slightly higher probability for children from this household to attend school compared to a household with a per capita capital below the poverty line. We use the percentage of school attendance from empirical studies as a proxy for

[1] http://www.ibge.gov.br/home/mapa_site/mapa_site.php#populacao

the probability. The process of the demography module is shown below Table 1 Major stages and steps in each stageTable 1).

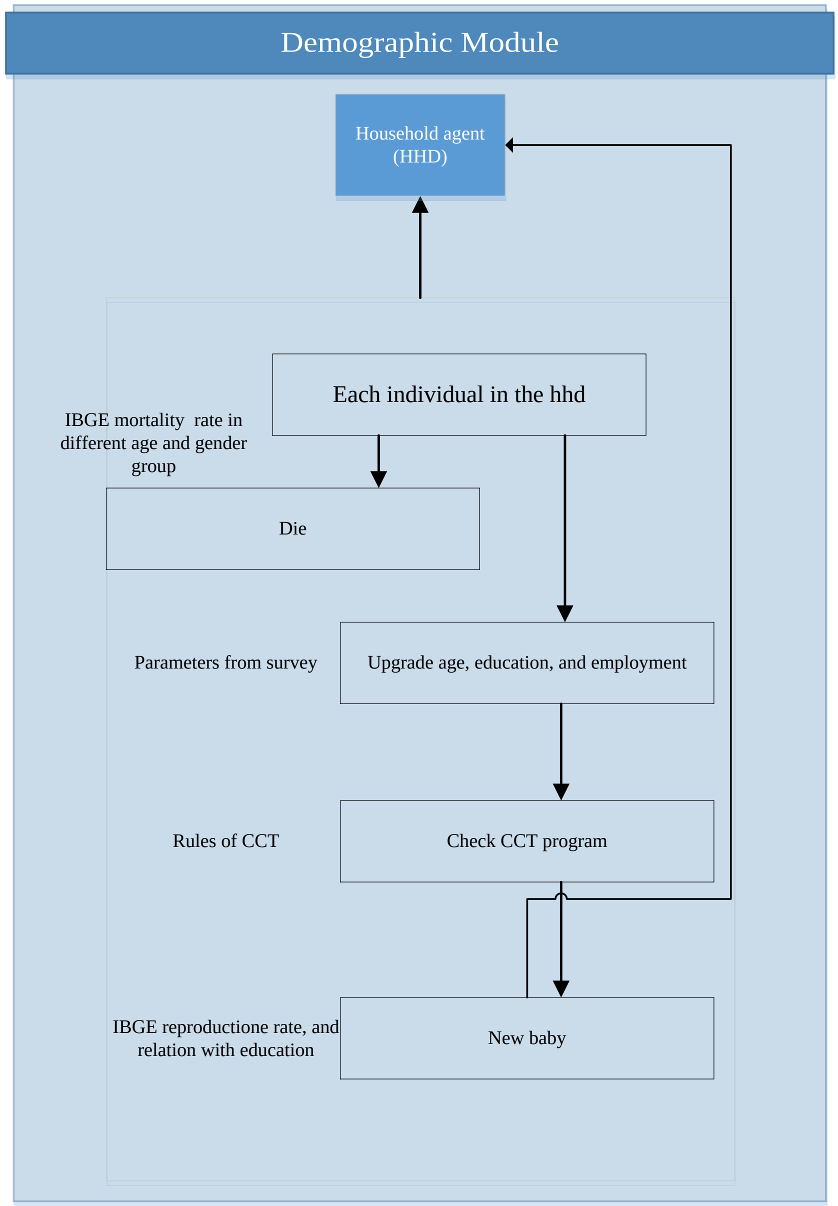

Figure 1 Model flow through the demography module

The age of a person is updated every year. The education is also updated every year if the kid attends school. Subsistence and other cost are calculated based on age and gender, and are updated every year. Capital is renewed at the end of each year: counting revenue from all activities and cash transfer program, and deducting the subsistence requirement.

The landscape is a 612 × 600 grid of 15 m ×15 m cells. It is a semi-theoretical landscape representing a binary land types: water and land. This landscape was recycled from a previous project of Paricuba, the region of which shares a high resemblance of Abaetetuba. The water region was masked off a Landsat TM/ETM image. Each household agent has a *property*, which is stored as a list of (x, y) coordinates on a 15 m-resolution raster grid. The household itself is stored as a (x, y) coordinates and does not occupy any grid cell. Each land *cell* is implemented as an agent in Repast Simphony. Based on the distance to water, land cells are classified as floodplain (varzea) or upland (terra firme). Cells are scheduled for land cover and soil fertility transition as agent and can be allocated to one of the four land uses: forest, intense acai, house gardens, and fallow. These land uses produce: timber[2], acai, and manioc[3]. The price of the three products refers to the market prices of goods.

Each land cell has the following attributes stored: land cover density (fuzzy variables), years since initial planting (age, as an integer), soil fertility (a fuzzy variable), and yield of each good (in kg) that is different for floodplain and upland (i.e., acai has a much higher yield on floodplain than upland when manioc is the opposite). Land cover transitions and resulting yields are derived from Brondizio (2004) and is scaled to a linear relation with the distance to water. The maintenance of land cells of the year is stored as a Boolean variable, which also affects the yield. The idea of this maintenance is a simplification of farming practices: whether a list of actions (e.g., weeding for manioc, or thinning for acai) has been performed or omitted.

[2] Because we didn't observe on-going deforestation in the Amazon delta, in this paper, we set the timber price extreme low to a point that farmers will never exact any goods from the forest or clear forest for timber. Therefore, the actual land use products are only acai and manioc.
[3] Manioc represents a collection of goods that can be extracted from house garden.

The economy of the model is represented by market agent and employer agent. *Market agent* sets the prices for all commodities, which are conceptualized and operated as exogenous factors in our model. The price of each commodity is stored as an array for the length of simulation and is delivered to household agents at the beginning of every year. Having said that, the amount of goods that household agents produce does not affect the price of the commodity—household agents are simply price takers, which is a reasonable assumption since the overall acai outcome from Amazon delta plays no significant role in the world market. This design of market agent provides us freedom to stimulate the system with different price shocks for resilience testing.

The *employer agent* is located in nearby city of Belém and offers rural household agents off-farm job opportunities in the city. The agent sends a limited number of jobs, which is updated every year, to the household agents. Household agents are sorted (from highest to lowest) by the probability of employment which is calculated based on a function of average education of female members and the education of the husband. The probability function is empirically derived from a database that was collected in the year of 2012. Job opportunity is sent to household agents in the ascending order of probability which is then compared with a random number to determine whether or not this household can actually get the job. It is assumed that households, in order to get an off-farm job, have to compete with a larger community instead of the households within the model, and households with better education normally have a higher chance to get an off-farm job. If a household agent is capable of receiving a job offer, the most eligible family member (based on age, gender, and education) will be sent out to take this offer.

Policy in our model is represented by two types of cash transfer programs. The first program is pension, which offers a minimum wage to all the elder members. The other program is Bolsa Familia that is given to households with a per capita income lower than the gate value of the policy. Once receiving Bolsa Familia, children in the households will have a full attendance to school. Thresholds for pension (age and minimum wage) and Bolsa Familia (per capita income and amount) are stored as constant numbers in the model that can be adjusted by modellers.

3. Process overview and scheduling

The model operates on an annual base and is divided into major stages of cultivation and harvesting that are scheduled using Repast Simphony's priority based scheduler. A typical time step is listed in Table 1.

Table 1 Major stages and steps in each stage

Stage	Steps and scheduling
Setup	• land cell maintenance flags are reset • policy is renewed for the year • market prices, climate, and employment of the year is read from the file • each person's demography is updated (age, death, reproduction, education)
Broadcast	• employment offers are sent • market prices are broadcast
Planning	• households accept or reject the job offer • households allocate cultivation resources
Cultivation	• households perform cultivation

	• off-farm job labour moves to city
Biophysical	• land cover transitions • yields are calculated based on land use, soil fertility, and practices
Harvest	• households perform harvest • revenues are calculated
Retrospect	• all household attributes are updated and recorded for the next decisions

The setup stage sets the maintenance for land cover transition model (i.e., *isMaintained* flag set to be false). The policy and economy are also set at this stage. The model reads the external file to learn the amount of the Bolsa Familia and Pension program for this year, as well as the price for every commodity and number of jobs offered. Household agents update every person's demographic status: everyone age, some may reproduce or die, and kids attend school or help at home.

The setup stage is followed by the *Broadcast* stage, where market prices and job offers are broadcast to all household agents. Household agents are sorted based on education and then receive the job offer orderly with the assumption that employment is offered from big cities like Belém to these rural communities, and is more likely to be obtained by households with higher education.

In the *Planning* stage, households, no matter what decision making strategy they are using, traverse their resources and feasible actions. Employment is first evaluated and compared with average crop revenue, for households to decide to accept or reject the offer. After the employment decision is made, the household agent inventories for land use and management options. For each land cell, if the labour and capital are not constrains, household agents can choose one action from the following: (1) change the land use; (2) change the land use management: intensify, maintain, or abandon current crops. This is to give household agents an opportunity to make comprehensive decisions based on a full inventory or their resources and constraints, which also mimic the real decision making stage before the planting period.

The *Biophysical* stage is where land cover transitions occur. The transition is a mixed effect from natural processes and land use and management actions during the Cultivation stage. Yields are calculated as a result of these processes.

The decisions that are made during the Planning stage will all be executed during the *Cultivation* stage. Besides those already made decisions, households can decide whether or not to call back the member who is working off-site for the *Harvesting* stage. At the Cultivating stage, the cost of seeding and planting is taken away from the household capital. At the Harvesting stage, the revenue from selling crops can be collected. The feasibility of all planned actions during Planning stage is verified at this stage to avoid any error.

The last stage is the *Retrospect* stage in which household agents update all the properties and statistics for their future consideration. The system also writes the updated attributes into the database for this year.

4. Design Concepts

A few key concepts have been extensively discussed and raised awareness for the design of ABM (Grimm & Railsback, 2012; Polhill, Parker, Brown, & Grimm, 2008). Here we summarize the following concepts of our model, including emergence, adaptation, objectives, prediction, sensing, interaction, stochasticity, and collectives.

4.1 Emergence

Emergence is a standing out feature of agent-based model in contrast to many traditional dynamic models since no global equilibrium is needed. Simply speaking, emergence is the aggregated pattern from individual behaviors at a lower level. Many times this emergent pattern is surprising to modellers. Depending on what research questions this model is used to answer, the emergent patterns are different.

We used the model to explore resilience concept and assess the factors and shocks on the resilience of household livelihoods, which leads to a few emergent patterns as well. The first surprising finding is only eight out of 27 state combinations that we observed from the simulation results. This proves the theoretical concept of "basin of attraction"--entering a certain state of the livelihood system might drive households lock-in such state and households experience difficulty to walk out of it. The other emergence from model results is that raising household initial capital may not increase household resilience unless the raise is above a certain level. This result, nevertheless, gives an uncommon policy implication that in order to increase resilience the capital boost has to be significant otherwise it will not be effective.

4.2 Adaptation

Households do not change decision making strategy over the simulation. One household implements a single strategy in one model run.

4.3 Objectives

Three decision making strategies are implemented as three ensemble members. In the setting of this model, households have subsistence requirement of both acai and manioc based on the demographic structure of the family, while acai has higher market value and manioc is much more labour intensive. The Max Profit household agents seek to optimize the monetary profits based on their labour and capital resources and constraints. Therefore Max Profit household actors who live on várzea usually manage acai plots and not manioc. The Max Leisure households, instead of optimizing the profit, prefer having leisure time once they produce enough to meet their subsistence requirement. However, the Subsistence First households optimize neither monetary profits nor leisure time. Instead, they first conduct activities that fulfill their domestic needs of both acai and manioc. Once this demand is secured, they go after market value, which is acai planting and management.

4.4 Prediction

When household agents make crop decisions, there are two variables, crop price and yield, that are not certain and need prediction. Crop price is implemented as an external factor in the model and yield is a function of land cover transition and climate variable. Household agents use the average price of the past three years as the price for this year when making cropping decisions. We also manipulate the climate variable to create a drastic dynamic for crop yield. In a similar way to predicting for crop price, agents also use the three year average as the yield prediction for this year. The three year window is chosen based on a field experiment that is done by Brondizio & Moran (2008).

4.5 Sensing

All agents have identical and perfect knowledge of their properties. Perfect knowledge means that they know the age, the land cover density, and soil fertility of each cell accurately. The broadcasting of crop price also reaches all agents at the same time. However, the sensing of non-farm job opportunities is in an order that depends on education level, which means that agents with higher education will have a better and earlier sense of the job opportunity.

Agents predict the price of this year based on the previous three years when making cropping decisions. However, they are not able to know the future price with certainty until later in the year during harvest season when they will know the value of their harvest based on this year's market price.

4.6 Interactions

Interactions between agents occur in three forms: message-passing between household agents, multi-site household communication, and the competition between household agents for available jobs.

The message-passing between household agents is prior to the Planning stage and during the execution stages. It is programmed as a public broadcast to all agents which simulates the information dissemination. Messages can also be sent from farming households to their connected off-site agents to recall for agricultural work; on the other direction, off-site agents will send half of their salary to the farming households to support subsistence or agricultural preparations. Between different household agents, they need to compete for the available off-farming jobs.

4.7 Stochasticity

The original MARIA uses a Poisson process to assign the non-farm job opportunities and a uniform distribution for wage. We changed this process and wage expectation to a probability function of household agents' education level that is derived from the empirical data. The probability calculated from the function is compared to a randomly generated number in the model, to determine whether this agent will get the job.

The stochasticity also happens during the model setup stage when a weighted distribution is used to populate households with different demographic structures, education for each member, and the initial capital. For instance, the baseline scenario for initial capital is that 25 % households in 1000-4000, 50 % will be having a capital within the range of 4000-7000, the rest will be assigning in 7000-10,000. The overall distribution is set up in a mixed form of regularity and randomness, which ensures a fixed number of households in a certain range but the exact value of capital is stochastically assigned. When we want to have a scenario with more households with a large capital, the weight on larger capital ranges can be set up higher.

During the simulation of one model run, the reproduction and death of a family member is also implemented by a probability compared to a randomly generated number. This stochasticity may change a household demographic structure significantly and is not scheduled at the beginning of the model but during the model run.

4.8 Collectives

A household in this model is treated as an explicit agent and a single decision making unit with its own property, capital and other resources. They do not form any social or kin groups.

However, the off-site households and farming households are connected with economic and labour links, and the resources of the two households are maintained as one collective unit.

5. Initialization

The landscape is initialized as floodplain forest near the water and upland that is further away from the water cells. The demographic and capital resources of household agents are compliant with weighted distributions. The distribution of the baseline scenario aligns with empirical pattern we found in a household survey.

6. Input data

This model uses the following input data: the scenario file, the basic parameters, the decision making method, and the landscape (Table 2).

Table 2 Model input files and their functions

Input file	Explanation	Function
1. Scenario Input	defines the scenario (price, climate, job offers, etc…) and convert plain text file into the model	to set up scenarios
2. Basic Data	contains basic parameters and distribution weights used in model set up	to define the initial characteristics of the agents
3. Decision Making	defines the decision making method that agents use in this model run	to allocate the decision making strategy that agents use
4. Theoretical Landscape	represents the water cells, floodplain, and upland.	to initialize the environment that agents interact with

7. Submodels

In this section, we report the three decision making strategies that are implemented in this model, which are Max Profit, Max Leisure, and Subsistence First. They are all complied by a mixed-integer linear programming algorithm, the *lp_solve* library version 5.5.2.0. Every decision making strategy, although it uses the same algorithm, has a specific goal to optimize. However the general structure of decision variables and the coefficient are the same across different strategies. There are four decision actions that agents allocate their resources on, which are: expanding new land uses, maintenance of existing plots, acceptance of employment opportunities, and the recall of off-farming family member to the agricultural activities. Agents first send out the most eligible family member for the job offer (if there is one) and allocate the remaining resources on land uses.

The coefficients of the decision variables include crop prices, crop yields (expected yield for Planning stage and known yield for Harvesting stage), and costs, which are represented respectively by *p*, *y*, and *c*. Off-farm wages are represented by *w*. The agent's current resources (i.e., labour, capital, and land) are also the variables in the linear program definition. The available land for new land use expansion is old growth forest or fallow land that can be converted, and the plots for maintenance are existing land cells of acai or manioc.

7.1 Max Profit decision making

Agents adopting Max Profit strategy optimize the market value of different crops considering their resources and constraints. The revenue of each available land use action is to multiply the average expected profit (the price and average expected yield minus cost) by the number of action is taken (number of land cells), which can be represented by the following formula align with off-farm revenue:

$$\max \begin{Bmatrix} (p_{acai} y_{acai} - c_{n\_acai}) n_{acai} + (p_{garden} y_{garden} - c_{n\_garden}) n_{garden} + \\ (p_{acai} y_{acai} - c_{m\_acai}) m_{acai} + (p_{garden} y_{garden} - c_{m\_garden}) m_{garden} + \\ \sum_j \bar{r}_j w_j \end{Bmatrix}$$

subj. to

$$l_{n\_acai}n_{acai} + l_{n\_garden}n_{garden} + l_{m\_acai}m_{acai} + l_{m\_garden}m_{garden} + \sum_j \bar{r}_j l_j \leq Labour$$

$$c_{n\_acai}n_{acai} + c_{n\_garden}n_{garden} + c_{m\_acai}m_{acai} + c_{m\_garden}m_{garden} \leq Capital$$

$$n_{acai} + n_{garden} \leq AvailableLand$$

The employed family member can be recalled to the household and is represented by a Boolean variable $\bar{r}_j$. In the land use section, the number of new plots of acai and manioc gardens is represented by integers n_{acai} and n_{garden} respectively, and the number of existing acai and manioc gardens is represented by m_{acai} and m_{garden}. The labour is represented as *l*, and *c* is cost.

Above is the formula that agents use for planning the land uses. A similar linear program is used for the harvest stage, except there is no difference for labour requirement for new cells, maintained cells, and non-maintained cells. Resources are allocated towards the extraction of crop yields from existing land use cells. Employed family member can be recalled to help out harvest if their wage is not as substantial as the revenue from agricultural products. Other constraints are trivial and are omitted here for brevity (e.g., the upper bound of available land cells).

7.2 Max Leisure decision making

Agents using the Max Leisure strategy are implemented similarly as Max Profit, with different goals and constraints, shown as following:

$$\min\ l_{n\_acai}n_{n\_acai} + l_{n\_manioc}n_{n\_manioc} + l_{m\_acai}n_{n\_acai} + l_{m\_garden}n_{m\_garden} + l_j$$

subj. to

$$
\begin{aligned}
&((p_{acai}y_{acai} - c_{n\_acai})n_{acai} + (p_{garden}y_{garden} - c_{n\_garden})n_{garden} + \\
&(p_{acai}y_{acai} - c_{m\_acai})m_{acai} + (p_{garden}y_{garden} - c_{m\_garden})m_{garden} + \\
&\sum_j \bar{r}_j w_j + CashTrans) \geq MonetarySubsistence
\end{aligned}
$$

$$
c_{n\_acai}n_{acai} + c_{n\_garden}n_{garden} + c_{m\_acai}m_{acai} + c_{m\_garden}m_{garden} \leq Capital
$$

$$
n_{acai} + n_{garden} \leq AvailableLand
$$

The narratives of this strategy is that agents allocate their resources on different land uses to make just enough for subsistence needs in monetary units. Their goal is to use as little labour as possible. This is still a utility maximization but with an extreme favored weight on leisure time. Notice that cash transfer income plays a significant role here in this decision making, since it counts as part of income to meet the subsistence requirement.

7.3 Subsistence First decision making

The agents who use the Subsistence First strategy follow this formula. They still try to optimize the profit from growing different crops, however, they are also subject to grow both acai and manioc enough to domestic consumption first. Note here the constraint is the quantity of acai and manioc, instead of a monetary unit like in Max Profit or Max Leisure.

$$
\max \begin{aligned}
&(p_{acai}y_{acai} - c_{n\_acai})n_{acai} + (p_{garden}y_{garden} - c_{n\_garden})n_{garden} + \\
&(p_{acai}y_{acai} - c_{m\_acai})m_{acai} + (p_{garden}y_{garden} - c_{m\_garden})m_{garden} + \\
&\sum_j \bar{r}_j w_j
\end{aligned}
$$

subj. to

$$
\begin{aligned}
&(n_{acai} + m_{acai})y_{acai} \geq acaiSubsistence \\
&(n_{garden} + m_{garden})y_{garden} \geq maniocSubsistence
\end{aligned}
$$

$$c_{n\_acai} n_{acai} + c_{n\_garden} n_{garden} + c_{m\_acai} m_{acai} + c_{m\_garden} m_{garden} \le Capital$$

$$n_{acai} + n_{garden} \le AvailableLand$$

7.4 Production function

A production function expresses the systematic relation of the quantity of output with the quantity of input. The assumption in agriculture is that the crop yield responds to labour and capital use (e.g., fertilizer, herbicide, pesticide, irrigation). In our case, it is the relation between output of acai/manioc yield, labour use (*l*), and monetary cost (*c*) per crop on a per cell basis, as well as the maintenance of the land cell. The Cobb-Douglas function has been used as the production function in the ABM, a typical case of which is in MP-MAS that uses empirical Cobb-Douglas production function as the economic component (Berger & Schreinemachers, 2009; Schreinemachers & Berger, 2006; Schreinemachers, 2005). Due to a lack of empirical data, we simplified the form of the production function in our model. The basic assumption of the production module in our model is that there is a fixed labour and capital cost for each crop in a per cell basis, which produces a fixed yield subject to the cell history and physical property. In addition, we also include the relation between crop yield and maintenance of a cell using a fixed amount of labour and capital input. The production function of crops in our model is specified as the following form:

$$Y_c = f(l, c, \bar{m}) * cv$$
$$\bar{m} = flag(l_m, c_m)$$

Where *l*, *c* are fixed labour and capital input for each cell, $\bar{m}$ is the Boolean variable to indicate if this cell is maintained, cv represents the climate variable that is used only in Chapter

Five for the climate scenario. The yield function here is actually a constant value, to be specific the function can be written as:

$$Y_c = a * \bar{m} + b$$

a and b are constant, meaning if the cell is maintained, the yield will be a+b, if not, it will only be b. The management of the plots in reality includes a list of actions such as weeding, extracting, which is hard to quantify as a labour input. In the future, we can try to represent the relation between yield and this maintenance work in a more accurate mathematical form.

In the employment sector, the wage function depends on a few variables, the relation of which is derived from a database. We use a linear regression to estimate the relation between size of salary and these variables, the form of which is:

$$w = \beta_i \cdot v_i + d$$ **Error! Reference source not found.**

Where y is the wage of a household, V_i is the *i*th variable, and d is the constant value. Data that are operated in this linear regression include only households that have employment, in this case, 277 households who have employment. Variables that we found significant for the wage amount are: husband education and husband age.

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