Land Use Optimization in the Thu Cuc Catchment in Northern Vietnam

Application of LUPAS

by

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MSc. Thesis

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Application of LUPAS

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Preface and Acknowledgement

This report closes my time as a student at Wageningen University. It also finishes a period in which I worked on the MSc. thesis resulting in this report. It presents the outcome of a land use optimization model which was applied to a mountainous watershed in Northern Vietnam.

Most of all I thank Bui Tan Yen for the time we worked together in both Vietnam and in the Netherlands. Your PhD created for me a thesis opportunity. During my time in Vietnam it was a great pleasure to go to the office to work with you. It turned out that I was also warmly welcomed by your direct and indirect colleagues. Many questions were asked and more answers were provided, in both ways.

However I visited the Thu Cuc catchment only once, it turned out to be a place where a foreigner is warmly welcomed. The visit did not only provide me the essential scientific information but also showed me a glimpse of the habits and traditions of this remote area in the mountainous area of Northern Vietnam. During the trip to and from the watershed, it also became clear to me which important changes Vietnam is undergoing. During the next few years, the Vietnamese agricultural sector is most likely to undergo further changes. These changes can already be observed in the direct surrounding of Hanoi where rice field are transformed into modern, luxurious residential areas.

My daily life, which mostly took place in Vietnam’s capital Hanoi, raised many questions about the behaviour of the Hanoians and Vietnamese in general. Fortunately, colleagues provided me most of the time with answers during the tea breaks. It was also in Hanoi that I celebrated Christmas, my birthday, New Year and the lost football final of the South East Asia Cup. In all of these events the Vietnamese people showed to be great hosts for a foreigner.

Back in the Netherlands my supervisors Saskia Visser and Marrit van den Berg were valuable sources for comments on the drafts of my report. The difference in scientific fields provided me with the essential information.

Laure, during my study, first thesis and especially this last thesis you have been of great support for me. It was superb that you were in Hanoi for one month and to share daily life in this magnificent city.

Erik Slingerland

Wageningen, June 2010
Abstract

Due to an increase in food demand and decrease in available agricultural land, steep agricultural areas in Northern Vietnam are likely to be used more intensive. The use of these marginal lands makes them more vulnerable to degrade. The objective of this study was to explore the optimal land use practices and their limitations in this context for the Thu Cuc watershed, located in the mountainous area of Northern Vietnam.

The LUPAS system was used as framework to reach this objective. The land evaluation tool LUSET was adapted and used to estimate suitability classes for the cultivation of crops. This data, together with the results of a household survey were used in a multiple goal linear programming (MGLP) model to explore the boundaries of the watersheds agricultural capacity. Using this MGLP model, three different scenarios were analyzed; 1) maximizing watershed income, 2) maximizing rice production and 3) minimizing potential erosion risk. In order to analyze these scenarios, different situations regarding sharing of resources and market access were modelled.

The outcome of these simulations shows that capital is the main constraint within the watershed. If no resources are shared the requirements of the villages can only be fulfilled by external capital. Sharing resources between villages increase the capacity of the Thu Cuc watershed. Potential erosion risk of the agricultural fields is lower when farmers do not share resources outside their village, but this results in a more intensified use of the available land. The model results showed that land which is currently used for agriculture has a higher potential or might require lower external input.
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>LP</td>
<td>Linear Programming</td>
</tr>
<tr>
<td>LU</td>
<td>Land Unit</td>
</tr>
<tr>
<td>LUC</td>
<td>Land Unit Code</td>
</tr>
<tr>
<td>LUPAS</td>
<td>Land Use Planning and Analysis System</td>
</tr>
<tr>
<td>LUSET</td>
<td>Land Use Evaluation Tool</td>
</tr>
<tr>
<td>LUT</td>
<td>Land Use Type</td>
</tr>
<tr>
<td>MGLP</td>
<td>Multiple Goal Linear Programming</td>
</tr>
<tr>
<td>USLE</td>
<td>Universal Soil Loss Equation</td>
</tr>
<tr>
<td>VND</td>
<td>Vietnam Dong, Vietnam’s national currency</td>
</tr>
</tbody>
</table>
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1. **Introduction**

1.1. Land use intensification

The growing population and increasing urbanization in South and South-East Asia requires an increase in productivity of the agricultural land. Due to economic development the demand for other agricultural products like meat will increase as well (Podwojewski et al., 2008; Roetter et al., 2005; van Ittersum et al., 2004). As a result, pressure on the marginal areas such as sloping lands is increasing (Podwojewski et al., 2008). The intensified use of sloping lands makes them more vulnerable to degradation by water erosion. Soil erosion causes the removal of fertile top soil, resulting in nutrient losses and eventually yield decline (Lal, 1998). The extent over which these degrading processes occur vary over space and time. This degradation process might be controlled by correct resource management. Management of the available resources in a sustainable manner to reduce the pressure on these resources might reduce degradation. Resource management however is complex and has multiple objectives (Walker, 2002). Furthermore land use decisions are often taken on local level whereas the administrative level at which policies are designed is represented by the province (Roetter et al., 2005). The different scales make the correct development and implementation of sustainable policies complex.

1.2. Problem definition

Sustainability and sustainable land use was put on the worldwide political and agricultural agenda in the late 1980s. Land use policies and agricultural research had to address the integrated character of the unsustainability. Two different methodologies in evaluating sustainability of an agricultural system are farming system research (FSR) and land evaluation (LE) (van Ittersum et al., 2004). The aim of the first methodology is to evaluate the possibility to increase productivity while analyzing the constraints and potentials of the existing farming system. This often takes place at the local level. The latter methodology on the other hand aims to assess the suitability of land for human use, which takes place at regional level.

More general, different model types to analyze land use change exist; prescriptive, descriptive and explanatory models all require different inputs and generate different outputs regarding the way they can be used. Prescriptive models do not analyze the driving factors behind changes but generate possibilities regarding the use of resources, within defined boundaries, taking into account the limits indicated by the stakeholders. Descriptive models on the other hand show the effect of certain interventions. An explanatory model tries to explain the underlying mechanisms of the changes (Castella et al., 2007). In order to come up with a land use plan a prescriptive model can be used to explore possibilities, and complementary a descriptive model can be used to analyze the effects of policies taking the results of the prescriptive model into account (Roetter et al., 2005).

Land use planning is complex; it involves multiple stakeholders with different objectives. South-East Asia experiences a need for more diversified products together with a reduced environmental impact (Roetter et al., 2007). This creates conflicts between land use objectives and the use of resources. To be able to analyze this complex interconnection between different stakeholders, an integrated approach towards land use optimization is required. Regarding the involvement of local people different modeling approaches are available for the analysis of land use change. A bottom-up approach in which the local stakeholders and their knowledge are involved in the prediction of land use change, are mostly used in order to understand certain changes in land use. By analyzing the often complex interactions between the different stakeholders historical land use changes are understood. (Castella et al., 2005).

Besides the difference in objectives, stakeholders in land use management act at different spatial scales. They can act at a small, local scale or at a larger regional or national scale. In order
to integrate these different scales a methodology is required that evaluates the system at these
different levels and creates a link. During explorative studies it has been proven that linear
optimization programs are useful tools to establish future land use options (López-Ridaura et al.,
2005). This method of analyzing makes it possible to find a range of land use options while
optimizing several goals at different level. Multi-scale analysis however is very susceptible to
overestimating land use system or inaccurately representing the goals of different stakeholders
(Laborte, 2007). For these reasons an analysis at different spatial scales will increase the correct
analysis of possible land use plans.

Analyzing and optimizing a land use plan requires thus an approach in which the possibilities
of the resources are analyzed and understood. Furthermore an integrated approach regarding the
interaction and involvement of the inputs and outputs forms the base of a decent analysis
(opportunities, constraints and trade-offs) of possible land use optimization. By understanding the
constraints of a land use plan and their relation to other constrains, makes it possible to explore
the possibilities of a land use system.

The System Research Network for Ecoregional Land Use Planning in Tropical Asia (SysNet)
developed the Land Use Planning and Analysis System (LUPAS) (Laborte et al., 2001; Roetter et
al., 2005). Multiple goal linear programming (MGLP) forms the core of LUPAS. It has been
shown that LUPAS is highly future orientated and it creates a possibility to explore new strategies
and explore the boundaries of natural recourse use options (van Ittersum et al., 2004). While
some models are more people-orientated LUPAS analyses the potential of the land and other
relevant resources (Castella et al., 2007), it can thus be seen as a top-down model approach.

1.3. Objectives

The aim of this study was to explore optimal land use practices and their limitations in the Thu
Cuc watershed in Northern Vietnam using the LUPAS system.

The following objectives were formulated:
1. Perform a land evaluation (resource availability, possible yields and in- and output);
2. Construct simple scenarios;
3. Create and run a land use optimization model using Multiple Goal Linear
   Programming.

1.4. Context of research

This MSc research took place in cooperation with the PhD research of B.T. Yen in which a
toolbox for land use analysis in Vietnam is developed. By determining optimal land use options
taking into account the constraints of the natural resources and the capacities of the farmers, the
adaptation of the optimal situation is not guaranteed. For this a much wider framework is required
and local knowledge needs to be implemented in the modeling approach. The aims of the PhD
project are thus to understand the agro-ecological and socio-economic interactions, try to come to
a common agreement on a solution between different levels of stakeholders and to stimulate the
dialogue between different stakeholders (Yen, 2007). This MSc research focuses on the link
between the agro-ecological and socio-economic interactions. The link will be made using
information from the land evaluation and the farmers in the catchment.
2. Materials and Methods

2.1. Study site

The study site is located in the Thu Cuc catchment, Tan Son district, Phu Tho province, located about 100km to the northwest of the capital Hanoi (Figure 1). The catchment has a total area of 1700ha which is divided over 2 sub-catchments. The elevation ranges from 140 to 940m asl. One fifth of the catchment is flat land while the remaining part is sloping land. Within the watershed the nearly 400 households are divided over three villages.

![Figure 1. Topographic representation of Thu Cuc watershed](image)

The climate is humid tropical and average monthly temperature varies between 15°C in winter time to 30°C during the summer. The total annual rainfall is 1500mm and is concentrated in the rainy season which last from June till October (Figure 2). The natural and social situation in the Thu Cuc catchment is, according to its characteristics, representative for the sloping land in northern Vietnam (Yen, 2007).

![Figure 2. Average monthly rainfall and air temperature](image)
The terrain data was obtained from a 30x30m DEM (Figure 3) (Global mapper). Using ArcMap this data was converted in a slope (%) map.

Figure 3. Digital Elevation Model of Thu Cuc watershed

The purpose of this thesis is to apply the LUPAS system to a typical steep sloping watershed with a characteristic variety in ethnic groups. Since this catchment is representative for steep lands in the northern part of Vietnam with its high variety in ethnic groups, it makes is suitable to apply this land use optimization model. Furthermore the increase in population in this part of Vietnam results that the pressure on the resources in the most steepest parts increase and makes them more vulnerable to degrade (Podwojewski et al., 2008). It are also these parts where the region’s poorest makes their living. Due to this intensification of marginal lands and households with limited resources, it makes these areas suitable for land use optimization.

2.2. Household survey

Information regarding the socio-economic situation and farming practices applied within the watershed was collected during a household survey which was conducted prior to this research. In order to establish a representative view of the watershed three types of farms were established; high, medium and low level in terms of available capital and technique investment. This division was made by the head of each of the three villages. In total 100 households were visited during the survey. In the villages Ray, Que and Con respectively 20, 47 and 33 households were visited. The household survey was used to obtain general information of the households and get insight in; non agricultural activities, cropping calendar, and the input/output of annual and perennial crops, forestry, livestock and aquaculture.

2.3. Soil survey

Prior to this research a soil survey was carried out in the Thu Cuc watershed, which resulted in a spatial representation of the soil within the watershed (Figure 4). The soil survey was performed to give insight in the physical and chemical properties of the soil. The FAO taxonomy was used to classify the soil based on the physical properties and soil depth (Figure 4). The topographical information from the watershed was used to select the sample sites. At each site a vertical profile was created by the use of a hand drill with a diameter of 3cm. Samples to a depth of 100cm were
taken. The soil fertility samples were taken at 5 locations, at a distance of 50m in a circular pattern around the core-site. This was done to overcome the problem of locally heavily weathered top soil.

The soil data was converted into a spatial representation using ArcGIS. This map was then converted into a raster format using the same grid size and position as the DEM. Each soil characteristic was then converted into a table.

![Figure 4. Soil map of Thu Cuc watershed](image)

2.4. LUPAS

LUPAS is applied on a system with clear boundaries. It uses the input of activities in the system together with the constraints which are present in the system such as labour, capital and land availability. This data is used as input in the core of LUPAS, the interactive multiple goal linear programming model. This model explores the possible solutions using the input and defined constraints. The results of this model are used to represent solutions in spatial form using maps. Output data is also used to define the use of input values and the limiting factors of the defined constraints. A schematic overview of the LUPAS system is given in Figure 5.
2.5. Land evaluation

In order to evaluate the possibilities of the agricultural land, the model LUSET (CGIAR-CSI; Yen et al., 2006) was used. It consists of two input-modules, a crop requirement and a land unit info module, and a calculation module. For the different land units (LU) the suitability to grow pre-defined crops is calculated using the characteristics of the land units and the crop requirements. The prescriptive approach of the LUSET model is presented in Figure 6. The output of LUSET consists of a table in which for each LU/crop/season combination a suitability class is assigned. This suitability class is also given for the three seasons which are use in the watersheds agricultural system.

Crop requirements
The calculation of LUSET begins with the assignment of parameters to the crop requirements for the crops used for the suitability analysis. These requirements are divided into four groups; landscape and soil characteristics, rainfall, temperature and irrigation conditions (Table 1). Predefined crop requirements (Sys et al., 1993) were used to generate these input tables for the selected crops. For each parameter the limits for 3 suitability classes were defined. Crops that according to the household survey are currently used in the watershed, were included, namely; Irrigated rice, Upland Rice, Maize, Soybean, Groundnut, Sweet potato, Vegetables, Cassava and Tea.
Table 1. Input LUSET

<table>
<thead>
<tr>
<th>Input value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landscape/soil characteristics</td>
<td></td>
</tr>
<tr>
<td>Slope (classification, 6 classes)</td>
<td>DEM</td>
</tr>
<tr>
<td>Soil depth (cm)</td>
<td>Soil map</td>
</tr>
<tr>
<td>Soil texture (Soil taxonomy, 12 classes)</td>
<td>Soil map</td>
</tr>
<tr>
<td>Cation information (CEC + BC)</td>
<td>Soil map</td>
</tr>
<tr>
<td>pH</td>
<td>Soil map</td>
</tr>
<tr>
<td>Base saturation (%)</td>
<td>Soil map</td>
</tr>
<tr>
<td>Organic carbon (%)</td>
<td>Soil map</td>
</tr>
<tr>
<td>Drainage (classification, 4 classes)</td>
<td>Soil map</td>
</tr>
<tr>
<td>Rainfall</td>
<td></td>
</tr>
<tr>
<td>Average monthly rainfall</td>
<td>Weather stations</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>Average monthly temperature</td>
<td>Weather stations</td>
</tr>
<tr>
<td>Irrigation</td>
<td></td>
</tr>
<tr>
<td>Access to irrigation water</td>
<td>Land use map</td>
</tr>
</tbody>
</table>

Land unit info

To evaluate the suitability of each land unit in relation to the different crops requirements, the same values defined in the crop requirements are given in the land unit info component. The sources of the data used in the land unit info component are shown in Table 1. The required climate data consisted of the temperature and the rainfall, both monthly average values. Since no local measurements were recorded an interpolated value of two weather stations (Phù Yên and Phú Hộ) was used. These stations are located 25 km to the west (Phù Yên) and 40 km to the northeast (Phú Hộ). Recordings from 2000 till 2008 were used to calculate these simple average values. The values for temperature and rainfall were both considered homogeneous throughout the watershed, no local variations were used.

The chemical characteristic were obtained from the soil survey and used as input for LUSET (paragraph 2.3). Regarding the physical properties, the soil depth and soil taxonomy (FAO) were used (Table 1).

Calculation module

Regarding the annual crops which were selected, an additional parameter is required. For these crops the sowing months needs to be included in LUSET. For these crops runs were performed for each calendar month in order to select the optimum sowing month. Some crops might be grown in different seasons, for these crops different suitability factors had to be calculated for each season.

The pixels from the DEM were used to assign land unit codes (LUC) to each pixel. The LUC was used in LUSET and in a later stage in the Land Use Optimization model. These LUC are numbers (1, 2, ..., n) assigned to the individual pixels of the watershed and used to link the input and output of the different models to a pixel in relation to it spatial position in the watershed. Microsoft Excel was used to generate a table in which all the input values of the LUSET model are assigned to the respective LUC.

To create a more robust result LUSET was adapted. Using the crop requirements and the soil characteristics, the suitability of the each land unit regarding the available conditions can be calculated. To come to a suitability class per crop, the suitability classes which are assigned to the...
individual crop requirements had to be combined. Different methods have been described regarding this combining (Sys et al., 1991). In general there are two approaches:

1. Limitation approach
2. Parametric approach

The limitation approach only evaluates the limiting crop requirements. Sys et al. (1991) describes two types of limitation calculations; taking the lowest value of all characteristics, or the limitation can be calculated using the number and severity of the limitations.

The parametric approach can be divided in four types of calculations:

1. Average
2. Exponent
3. Storie
4. Square root

Average method

\[
I = \frac{A + B + C + \ldots}{n}
\]  
Equation 1

Exponent method

\[
I = \sqrt[n]{A \cdot B \cdot C \cdot \ldots}
\]  
Equation 2

Storie method

\[
I = A \cdot \frac{B}{100} \cdot \frac{C}{100} \cdot \ldots
\]  
Equation 3

Square root method

\[
I = R_{\text{min}} \cdot \sqrt{\frac{A}{100} \cdot \frac{B}{100} \cdot \ldots}
\]  
Equation 4

In which \(I\): overall suitability, \(A, B, \ldots\): suitability factors of the individual characteristics and \(R_{\text{min}}\): lowest rating (Table 1).

The input values of the four methods to calculate the suitability are based on the limits provided by the crop requirements. Each land unit receives a suitability factor according to its value for each characteristic. This results in a suitability ranging from S1, S2, S3 to N (Table 2).

<table>
<thead>
<tr>
<th>Suitability class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Suitable</td>
</tr>
<tr>
<td>S2</td>
<td>Moderately suitable</td>
</tr>
<tr>
<td>S3</td>
<td>Marginally suitable</td>
</tr>
<tr>
<td>N</td>
<td>Unsuitable</td>
</tr>
</tbody>
</table>

Table 2. Description suitability classes

Since the importance of different characteristics varies for each crop, a weight factor for each characteristic was introduced in this adapted version. This varies from 1 to 3, in which 1 is more important then 3. Sys et al. (1991) described the use of weighted factors by assigning a smaller suitability range to characteristics with a lower rank (3). This principle is shown in Table 3.
Materials and Methods

Table 3. Suitability classes in combination with weight factors

<table>
<thead>
<tr>
<th>Suitability</th>
<th>Weight value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>S1</td>
<td>90</td>
</tr>
<tr>
<td>S2</td>
<td>60</td>
</tr>
<tr>
<td>S3</td>
<td>40</td>
</tr>
<tr>
<td>N</td>
<td>0</td>
</tr>
</tbody>
</table>

The suitability class and the weight factor are combined which results in a value ranging from 0 to 100. This is the suitability assigned to each characteristic. Using the exponent method (Equation 1), an overall suitability value is obtained which then is transformed into a suitability class ranging from S1, S2, S3 to N (Table 4). The exponential method was chosen above the other methods since it deals with the reduction in yield when one of the crops requirements is less suitable.

Table 4. Overall suitability factor

<table>
<thead>
<tr>
<th>Final rating</th>
<th>Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>S1</td>
</tr>
<tr>
<td>60</td>
<td>S2</td>
</tr>
<tr>
<td>40</td>
<td>S3</td>
</tr>
<tr>
<td>0</td>
<td>N</td>
</tr>
</tbody>
</table>

In relation to the previous version of LUSET the values which link the suitability classes to the weight factors (Table 3) has been included in the calculation. Due to these intermediate values the overall suitability gave a more robust result.

The soil data as described in paragraph 2.3 was converted to spatial representation using ArcGIS. The shape file in which the soil characteristics were shown was converted to Raster files which matched the DEM file of the watershed. The DEM raster was converted to a slope map. In this way the physical and chemical characteristics could be converted to a table format.

When performing the land evaluation only the LU assigned to agricultural use (irrigated rice and cash crops) were included, which resulted in a total of 4252 pixels representing an area of 383ha divided over the three villages. A map representing the current land use was used to select the area in which the actual land evaluation would take place. Since no data is available regarding the costs to change land from non-agricultural land to agricultural land all LU which were not used for agricultural purposes were excluded.

2.6. Potential erosion risk

To account for land degradation under the new land uses, the potential soil loss was calculated with the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). The USLE was developed to calculate the mean annual soil loss on an agricultural field.

\[
E = R \cdot K \cdot LS \cdot C \cdot P
\]

In which E is the mean annual soil loss (t ha\(^{-1}\) y\(^{-1}\)), R the rainfall erosivity factor (MJ mm h\(^{-1}\) ha\(^{-1}\) month\(^{-1}\)), K the soil erodibility factor, L slope length factor, S the slope steepness factor, C the crop management factor and P the erosion-control practice factor. The USLE provides a prediction of annual soil loss. However for the temporal resolution of the MGLP model seasonal soil loss is required. Using additional equations the USLE was adapted to yield potential seasonal erosion risk in a tropical region.
Materials and Methods

Rainfall erosivity factor
\[ R = 0.5673 \cdot P - 8.31 \]  
Equation 5

In which \( P \) is the average monthly rainfall (mm) (Phien and Siem, 1998).

Soil erodibility factor
\[ K = 1.333 \cdot 10^{-4} + 2.459 \cdot 10^{-5} \cdot Mn \]  
Equation 6

\[ Mn = si(si + sa) \]

In which \( si \): fraction of silt, \( sa \): fraction of sand (Mulengera and Payton, 1999).

Slope factor
\[ LS = \left( \frac{L}{72.6} \right)^m \cdot 65.41 \cdot \sin^2 S + 4.56 \cdot \sin S + 0.056 \]  
Equation 7

In which \( L \): slope length, \( S \): slope steepness. \( M \) varies between 0.5, 0.4, 0.3 and 0.2 for slopes of respectively >5%, 3.5-4.5%, 1-3% and <1% (Ha, 2009).

Management factor
The management factor was calculated using
\[ P = P_c \cdot P_s \cdot P_t \]  
Equation 8

In which \( P \): the management factor, \( P_c \): the contouring factor, \( P_s \): strip cropping factor and \( P_t \): terrace sedimentation factor. \( P_c \) varies between 0.5 and 0.9 for slope of 1 degree till slope of more than 25 degrees. Since the MGLP model has a temporal time span of 1 year, \( P_s \) was kept constant at 1 for all cases. \( P_t \) has a value of 0.2 when terraces are applied and a value of 1 when no terraces are applied (Schwab et al., 1993).

Seasonal erosion
For each land unit/crop/season combination and for the fallow period the potential soil erosion was calculated. Besides the predefined crops, the potential soil erosion was also calculated as the land unit is left fallow. The potential erosion values (ton/ha) were converted into an erosion risk classes (Table 5). These erosion risk classes were added to the input-file of the MGLP.

Table 5. Potential erosion risk classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Lower boundary (ton/ha)</th>
<th>Upper boundary (ton/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>4</td>
<td>120</td>
<td>180</td>
</tr>
<tr>
<td>5</td>
<td>180</td>
<td>240</td>
</tr>
</tbody>
</table>

When assigning a crops or fallow to a land unit in each of the three seasons the corresponding potential erosion risk value is assigned to this land unit. The potential erosion risk for the three villages and Thu Cuc watershed is calculated by summing up all values for the three seasons and land units belonging to the specific village.
2.7. Land use optimization

Within a land use optimization process, complex linkage between resources, constraints and objectives are present. This complexity brings the need for a structured approach. This was done by using Multiple Goal Linear Programming (MGLP), with the program GAMS (General Algebraic Modeling System, version 22.5). This program uses sets, parameters, variables and equations to come to, in this case, a possible land use map. Sets are units on which variables and parameters depend. Sets can be land units, crops, seasons etc. The input data is converted into parameters and used to generate the output which is stored in variables. Using equations the parameters are converted into variables, furthermore they defined the constraints of the model. To solve the equations one variable is selected to be maximized or minimized within the limits of the constraints.

Each variable and parameter depends on a number of sets and might be linked to fewer sets in order to generate (less) output values which give insight, using aggregation, in the results of the model. For example, the costs related to the used crops can be shown in relation to each land unit but can also be related to the villages present in the area. The former situation will result in a less usable result while the latter will show a more easily understandable situation since it only shows the results for the villages using the aggregated land units.

GAMS was used to identify the linkage between the land units and the different crops that can be grown according to the outcome of LUSET. A schematic overview of the Land Use Planning is given in Figure 7. The crops, household, land unit and livestock data refers to the ‘input’ and ‘constraint’ module of the LUPAS system. The right-hand side of the figure shows the different output of the LUPAS system.

![Figure 7: Structure of Land Use Planning (MGLP)](image)

The sets which are defined in this model are shown in Table 6. The crops which are grown in the watershed are converted to products since rice and maize are divided over several breeds. On the land units different rice breeds can be grown but for consumption or market products no difference is made for these breeds and are summed as Rice.
Table 6. Description of sets

<table>
<thead>
<tr>
<th>Set</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lu</td>
<td>Land Unit</td>
<td>1 - 4252</td>
</tr>
<tr>
<td>v</td>
<td>Village name</td>
<td>Con, Que, Ray</td>
</tr>
<tr>
<td>c</td>
<td>Crop name</td>
<td>13 crops</td>
</tr>
<tr>
<td>s</td>
<td>Cropping Season</td>
<td>Spring, Summer, Winter</td>
</tr>
<tr>
<td>t</td>
<td>Technology level</td>
<td>Low, High</td>
</tr>
<tr>
<td>a</td>
<td>Animal type</td>
<td>5 animals</td>
</tr>
<tr>
<td>p</td>
<td>Type of product</td>
<td>9 products</td>
</tr>
<tr>
<td>e</td>
<td>Suitability of lu</td>
<td>S1, S2, S3 and N</td>
</tr>
</tbody>
</table>

The model as used in this research consists of two parts regarding the equations. The first group of equations defines the calculation of the objective using the input-parameters. The second group delineates the constraints given to the model to come to the solution.

In total three scenarios were created to be implemented in the GAMS code. In The scenarios are as follows:

1. Maximizing watershed income;
2. Maximizing rice production;

In the first scenario the summed income of the three villages is maximized. The second scenario refers to the situation in which the summed amount of rice produced by the three villages is maximized. This only includes the rice cultivated within the watershed boundaries and does not include the rice that was bought at a market. The third scenario minimizes the potential erosion risk is minimized.

In the following part a mathematical representation of the equations used in GAMS are shown. These equations show the situation as in scenario 1. The abbreviations shown in subscript refer to the sets on which the parameters or variables depend(Table 6). The sets above the summation sign indicate over which set the variables or parameters are grouped. The GAMS code of this scenario is given in appendix 1.

**Income**

1. Watershed income is total income of all villages (watershed)
   \[
   \text{Income watershed} = \sum_v \text{Income}_{(v)}
   \]

2. Income of a village is total of income from Cultivation and Livestock (village)
   \[
   \text{Income villages} = \sum_{v,t,c} \text{Income}_{(v,at)}
   \]

3. Income from cultivation of each village (village)
   \[
   \text{Income}_{(v,\text{cultivation})} = \sum_i (\text{Market Product}_{(v,c)} \times \text{Market Price}_{(c)} - \text{Total Costs}_{(c,t)})
   \]

**Agricultural products**

4. Crop production (village - crop)
   \[
   \text{Production}_{(v,c)} = \sum_{lu} \sum_{t} \sum_{s} (\text{AreaUsed}(lu,v,c,s,t) \times \text{Yield}(c,s,t))
   \]

5. Available crop production for selling after self consuming (village - crop)
Materials and Methods

\[ Market\ Production_{(v,c)} = Production(v,c) - Consumption_{Tab}(v,c) \]

**Labour**
6. Required labour Agriculture (crop - season)

\[ Labour\ Requirement_{Agriculture_{(c,s)}} = \sum_1^l \sum_1^c \sum_1^n (Lab Re qTab_{(c,s)}, AreaUsed_{(h,v,c,s,t)}) \]

7. Required labour Livestock (village - season)

\[ Labour\ Requirement_{Livestock} = \sum_1^v (Lab Re qTab_{(v,u)} * NoAnimals_{(v,u)}) \]

8. Upper bound of labour used for agriculture (village - season)

\[ Lab Re qAgri_{(v,s)} + LabreqLstck_{(v,s)} \leq LabAvailTab_{(v,s)} \]

**Capital**
9. Constraint for the use of capital (village - season)

\[ \sum_1^v \sum_1^c \sum_1^l (AreaUsed_{(h,v,c,s,t)} * Costs_{(c,s,t)}) \leq CapitalAvailable_{(v,s)} \]

**Agricultural land**
10. Constraint for the use of land (land unit - village - season)

\[ \sum_1^h \sum_1^c \sum_1^l AreaUsed_{(h,v,c,s,t)} \leq \sum_1^h AreaAvailable_{(h,v)} \]

Each scenario was analyzed using four different situations; these situations were selected in order to get an overview of the behavior of the watershed when varying constraints. The first presents a situation in which each village is forced to grow enough food to sustain itself without sharing resources with the other villages and without having market access to buy products. The second situation allows the villages to buy products. Within this scenario some constraints are made about rice and maize that should be grown within the village. Within the watershed the goal of the communities was to sustain their own rice and maize demand. For this reason, rice and maize cannot be bought on the market, though it is possible to sell rice on the market. The third situation allows the villages to share resources while reaching the product demands. In the last situation the sharing of resources is combined with the access to a market where products can be bought.

In order to come to scenario 2 the income per village should be lowered with the costs made by buying products at market. Furthermore the production of crops has to be complemented with the crops bought at the market. Scenario 3 can be implemented by using the same adaptation as for scenario 2. Besides this the labour, capital and food requirements and availability should be summed over the village in order to get a watershed total instead of village totals.

The model only focuses on the land use regarding the crops, for completeness the in- and output related to the livestock is assumed to remain at the current situation. This results in constant values for labour, food and capital requirement. After identifying the suitability of the selected crops for each land unit per season, the expected yield are calculated regarding the limitations that are calculated in the LUSET model. Using this method, the four possible classes of the suitability factors are directly linked with a yield reduction factor. These yield reduction factors were established using field experiments in the watershed. These field experiments took place prior to this MSc. research.

The input data used as parameters in GAMS are defined in Table 7. Since the land units used in GAMS are based on the DEM grid, each land unit has a fixed area of 0.09ha (30x30m²). Input values obtained from the household survey are mainly based on the median values. Using this approach the extreme high and extreme low values did not influence the eventual input values.
Table 7. Input data GAMS

<table>
<thead>
<tr>
<th>Type</th>
<th>Input</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land units</td>
<td>Area</td>
<td>DEM</td>
</tr>
<tr>
<td></td>
<td>Suitability factor of crops</td>
<td>LUSET</td>
</tr>
<tr>
<td>Crops</td>
<td>Yields</td>
<td>Field experiments in Thu Cuc Watershed</td>
</tr>
<tr>
<td></td>
<td>Market prices</td>
<td>Household survey</td>
</tr>
<tr>
<td></td>
<td>Costs</td>
<td>Household survey</td>
</tr>
<tr>
<td></td>
<td>Labor requirements</td>
<td>Household survey</td>
</tr>
<tr>
<td>Livestock</td>
<td>Number of animals</td>
<td>Household survey</td>
</tr>
<tr>
<td></td>
<td>Labor requirements</td>
<td>Household survey</td>
</tr>
<tr>
<td></td>
<td>Fodder requirements</td>
<td>Household survey</td>
</tr>
<tr>
<td>Households</td>
<td>Labor availability</td>
<td>Household survey</td>
</tr>
<tr>
<td></td>
<td>Available capital</td>
<td>Household survey</td>
</tr>
<tr>
<td></td>
<td>Food requirements</td>
<td>Household survey</td>
</tr>
</tbody>
</table>

2.8. Analysis of MGLP results

Tradeoff curves show the relationship between two factors in a land use system. Tradeoffs are based on the assumption that if goods are scarce, obtaining one good requires the decrease of another good. Tradeoff curves are two-dimensional representations of the trade-off between two indicators. These tradeoffs are used to analyze the sustainability of the agricultural production system, by quantifying the relationships between the bio-physical processes and economical behavior of farmers (Stoorvogel et al., 2004). In order to produce tradeoff curves which represent the complex interaction between these processes, key interactions need to be selected. For the three scenarios the same combinations of indicators are selected.
3. Results and Discussion

3.1. Household survey

A survey was conducted over 100 households within the watershed. The people living within the watershed are divided over three villages. The average household varies from 5.0 to 5.9 for Que and Ray respectively. The amount of labour force per household varies between 3.0 and 3.3 for Con and Ray respectively (Table 8). The three villages are mainly located along the streams present in the watershed. The Con village is located in the South-east area of the watershed close to the outlet of the watershed.

| Village | Age | Household members | Population (2007) | Available labour/household | Education \(^1\)
|---------|-----|-------------------|-------------------|---------------------------|-----------------
| Con     | 42.4 | 5.2               | 743               | 3.0                       | 12.1            |
|         | (7.6) | (1.1)             | (1.1)             | (1.5)                     |
| Que     | 38.1 | 5.0               | 890               | 3.1                       | 11.6            |
|         | (9.5) | (1.7)             | (1.1)             | (2.2)                     |
| Ray     | 42.2 | 5.9               | 230               | 3.3                       | 9.1             |
|         | (10.9)| (1.7)             | (1.6)             | (2.6)                     |

\(^1\) Age at which final education was received
\(^2\) Standard deviation between brackets

The analysis of the crop calendar is shown in Table 9. In all villages three seasons were observed with sowing months in February, June and October. These three seasons were used to evaluate the outcome of the suitability calculations of LUSET. The data of the household survey show that the crops cultivated in spring are, using average values, in all cases sown in February. The summer crops show a more wide variety in starting date. Especially the rainfed rice is sown one month before the start of the summer season. The winter crops are based on only 1 observation per crop. Except 1 crop, which is sown in August, all other crops are sown in October. Crops which are sown in the same season do not show a high variety in sowing moment. This might be caused by the low temporal resolution of the household survey data, in theory the sowing month might vary 1 month without indicating it as different months.

<table>
<thead>
<tr>
<th>Products</th>
<th>Count</th>
<th>Early sowing</th>
<th>Late sowing</th>
<th>Average sowing</th>
<th>Most sowing</th>
<th>Early harvest</th>
<th>Late harvest</th>
<th>Average harvest</th>
<th>Most harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cassava</td>
<td>13</td>
<td>1</td>
<td>3</td>
<td>2.0</td>
<td>2</td>
<td>10</td>
<td>12</td>
<td>11.0</td>
<td>11</td>
</tr>
<tr>
<td>Sp maize</td>
<td>26</td>
<td>1</td>
<td>3</td>
<td>2.0</td>
<td>2</td>
<td>0</td>
<td>6</td>
<td>4.8</td>
<td>5</td>
</tr>
<tr>
<td>Sp peanut</td>
<td>6</td>
<td>1</td>
<td>2</td>
<td>1.7</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>4.2</td>
<td>4</td>
</tr>
<tr>
<td>Sp rice</td>
<td>27</td>
<td>1</td>
<td>3</td>
<td>1.8</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>4.9</td>
<td>5</td>
</tr>
<tr>
<td>Sp soybean</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1.5</td>
<td>-</td>
<td>4</td>
<td>4</td>
<td>4.0</td>
<td>4</td>
</tr>
<tr>
<td>Sm maize</td>
<td>17</td>
<td>6</td>
<td>8</td>
<td>6.9</td>
<td>6</td>
<td>9</td>
<td>11</td>
<td>9.9</td>
<td>9</td>
</tr>
<tr>
<td>Sm rainfed rice</td>
<td>6</td>
<td>4</td>
<td>6</td>
<td>5.2</td>
<td>5</td>
<td>9</td>
<td>10</td>
<td>9.5</td>
<td>9</td>
</tr>
<tr>
<td>Sm rice</td>
<td>30</td>
<td>5</td>
<td>7</td>
<td>6.2</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>9.2</td>
<td>9</td>
</tr>
<tr>
<td>Sm soybean</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>6.2</td>
<td>6</td>
<td>8</td>
<td>9</td>
<td>8.2</td>
<td>8</td>
</tr>
<tr>
<td>Wn cabbage</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>10.0</td>
<td>10</td>
<td>12</td>
<td>12</td>
<td>12.0</td>
<td>12</td>
</tr>
<tr>
<td>Wn maize</td>
<td>1</td>
<td>8</td>
<td>8</td>
<td>8.0</td>
<td>-</td>
<td>11</td>
<td>11</td>
<td>11.0</td>
<td>-</td>
</tr>
<tr>
<td>Wn silage maize</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>10.0</td>
<td>-</td>
<td>12</td>
<td>12</td>
<td>12.0</td>
<td>-</td>
</tr>
<tr>
<td>Wn sweet potato</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>10.0</td>
<td>-</td>
<td>12</td>
<td>12</td>
<td>12.0</td>
<td>-</td>
</tr>
<tr>
<td>Wn Vegetables</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>10.0</td>
<td>-</td>
<td>12</td>
<td>12</td>
<td>12.0</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^1\)=January to 12=December
Results and Discussion

In the household survey 27 different land use types (LUTs) (variations in crop/3 seasons combination) were found regarding the annual crops. Most of the LUT consists of the cultivation of a crop in spring and summer (Table 10). In the cropping patterns in 2000, a total of 37 land use types were observed. On some field Agro-forestry or intercropping is applied. This great number of LUT suggests that there is no need for farmers to use a limited number of LUT. Because of this, LUT were not used in the Land Use Optimizations model, instead the number and combination of crops per Land Unit (LU) were let free.

Table 10. Land used in crop rotation (% of agricultural LU)

<table>
<thead>
<tr>
<th>Cropping pattern</th>
<th>Con 2008</th>
<th>Que 2008</th>
<th>Ray 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-0-0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0-1-0</td>
<td>15</td>
<td>16</td>
<td>41</td>
</tr>
<tr>
<td>1-1-0</td>
<td>81</td>
<td>80</td>
<td>46</td>
</tr>
<tr>
<td>1-1-1</td>
<td>3</td>
<td>4</td>
<td>13</td>
</tr>
</tbody>
</table>

The code refers to the land used (1), or not used (0) in Spring-Summer-Winter

The cropping pattern data from the household survey was analyzed to get insight in the changes over time regarding the occupation of the LU. It was observed that in the villages Con and Que a gradual shift from summer to spring-summer occurred over the period from 2000 to 2008. The cropping pattern of the Ray village showed an increase in the land use with a recent shift from summer to spring-summer and spring-summer-winter (Table 11). A more intensified use of the available agricultural land is experienced in the past decade. This strengthens the need to manage the available agricultural land in a sustainable way.

Table 11. Land occupation per cropping pattern (%) during 4 periods

<table>
<thead>
<tr>
<th>Seasons</th>
<th>Ray</th>
<th>Con '00-'05-'08</th>
<th>Que '00-'05-'08</th>
<th>Ray '00-'05-'08</th>
</tr>
</thead>
<tbody>
<tr>
<td>sp-sm-wn</td>
<td></td>
<td>'00-'05-'08</td>
<td>'00-'05-'08</td>
<td>'00-'05-'08</td>
</tr>
<tr>
<td>1-0-0</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0-1-0</td>
<td></td>
<td>36</td>
<td>37</td>
<td>16</td>
</tr>
<tr>
<td>1-1-0</td>
<td></td>
<td>64</td>
<td>62</td>
<td>79</td>
</tr>
<tr>
<td>1-1-1</td>
<td></td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

The code refers to the land used (1), or not used (0) in Spring-Summer-Winter
The land within the Thu Cuc watershed was divided over the three villages (Figure 8) and assigned to one of the villages. The land use data shows the division of land and land use between the three villages (Table 12). Land that is used for agricultural purposes is assumed to be available for cultivation. The costs of the preparing or converting land with other than agricultural use were unknown. Land assigned to agricultural use in the land use map 2007 was further used in the land use optimization process. For the three villages of Con, Que and Ray, 31%, 13% and 22% respectively, of their total land is available for agriculture.

<table>
<thead>
<tr>
<th>Table 12. Land use types per village (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Dense forest</td>
</tr>
<tr>
<td>Young forest</td>
</tr>
<tr>
<td>Shrubs</td>
</tr>
<tr>
<td>Irrigated rice</td>
</tr>
<tr>
<td>Cash crops</td>
</tr>
<tr>
<td>Bare lands</td>
</tr>
<tr>
<td>Water surface</td>
</tr>
<tr>
<td>Resident areas</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

1 the area as defined as irrigated rice and cash crops are used in the land use optimization model

3.2. Capital and yields

Using the land use map of 2007, the amount of land used to cultivate crops per season was calculated. The information provided during the household survey resulted in average costs to cultivate crops. These costs include seeds, fertilizers and pesticides. After multiplying this area with the total costs for cultivation, the external input requirements for the three villages was calculated (Table 13). External input which is used prior to sowing and during the crops development becomes available after harvesting when the products are partially sold. The
external input calculated for the summer season was used as the available capital in each of the three seasons.

Table 13. External input requirement based on 2007 land use data (million VND)

<table>
<thead>
<tr>
<th>Village</th>
<th>Spring</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con</td>
<td>160.60</td>
<td>111.60</td>
<td>4.90</td>
</tr>
<tr>
<td>Que</td>
<td>169.20</td>
<td>114.20</td>
<td>4.90</td>
</tr>
<tr>
<td>Ray</td>
<td>23.80</td>
<td>10.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

In general the farmers in Con village purchase more external input per area in their land (Table 14). This suggests that the external input used for the different villages should follow this differentiation. Within the three villages a similar differentiation in external input was observed. It is not within the purpose of the land use optimization model to take this into account. The external inputs are assumed to be constant within the watershed.

Table 14. External input crops based on household survey (1,000VND/ha)

<table>
<thead>
<tr>
<th>Product</th>
<th>Spring</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Con</td>
<td>Que</td>
<td>Ray</td>
</tr>
<tr>
<td>Cassava</td>
<td>26</td>
<td>108</td>
<td>126</td>
</tr>
<tr>
<td>Maize</td>
<td>1,858</td>
<td>1,360</td>
<td>1,372</td>
</tr>
<tr>
<td>Peanut</td>
<td>3,212</td>
<td>2,560</td>
<td>1,917</td>
</tr>
<tr>
<td>Rice</td>
<td>1,015</td>
<td>980</td>
<td>887</td>
</tr>
<tr>
<td>Soybean</td>
<td>944</td>
<td>542</td>
<td>1,000</td>
</tr>
<tr>
<td>Vegetables</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The average yields for the annual crops are shown in Table 15. These figures are not compensated for the difference in invested capital (Table 14). Combining the results of the external inputs which is purchased for the crops and the obtained yields suggest a high capital/yield rate for Con. This might be explained by the need of Ray to deal with land with a lower suitability for most crops. The yield of a crop depend on several factors related to, among other things, the soil (Sys et al., 1991). It was however not possible to explain the differences in yield. For the three villages equal yield were applied when similar soil properties, climate and external input are used.

Table 15. Average yield based on household survey (kg/ha)

<table>
<thead>
<tr>
<th>Product</th>
<th>Spring</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Con</td>
<td>Que</td>
<td>Ray</td>
</tr>
<tr>
<td>Cassava</td>
<td>12,803</td>
<td>15,205</td>
<td>13,934</td>
</tr>
<tr>
<td>Maize</td>
<td>4,077</td>
<td>3,530</td>
<td>4,130</td>
</tr>
<tr>
<td>Peanut</td>
<td>2,670</td>
<td>905</td>
<td>972</td>
</tr>
<tr>
<td>Rice</td>
<td>3,833</td>
<td>3,783</td>
<td>4,314</td>
</tr>
<tr>
<td>Soybean</td>
<td>997</td>
<td>1,111</td>
<td>4,167</td>
</tr>
<tr>
<td>Vegetables</td>
<td>16,898</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

3.3. Land evaluation - LUSET

The output of the adapted version of LUSET was first used to get an overview of the changes in suitability for the different crops and the land units (LU). As shown in Figure 9 the suitability of the land for maize changes over the three different seasons. During the spring season the LU show a higher suitability for the cultivation of maize the winter season however is unsuitable but shows some regions which are highly suitable. This is mainly caused by the lower suitability of the land units regarding the precipitation. Land units with a high suitability for the soil and terrain
characteristics are able to compensate the lower suitability in precipitation while the marginal lands shift from marginally suitable land to unsuitable land.

Upland rice (Table 16) shows a higher suitability in June. In total 68% of the LU has a suitability class 1 or 2. The villages however show a different pattern. Con has 86% of its LU in this same suitability range while Ray only has 49% of its LU in these two highest classes. The amount of LU which are not suitable to grow upland rice are for the whole year as well as the individual seasons higher in ray then in Con. This difference in suitability is observed in more crop like sweet potato (Table 17). The villages Con and Que has 42% and 37% of their land with a suitability class S1 while Ray only has 5%.

Table 16. Suitability of LU (% of agricultural land) for Upland Rice

<table>
<thead>
<tr>
<th>Suitability class</th>
<th>Con Feb</th>
<th>Jun</th>
<th>Oct</th>
<th>Que Feb</th>
<th>Jun</th>
<th>Oct</th>
<th>Ray Feb</th>
<th>Jun</th>
<th>Oct</th>
<th>Thu Cuc Feb</th>
<th>Jun</th>
<th>Oct</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17</td>
<td>48</td>
<td>0</td>
<td>29</td>
<td>41</td>
<td>0</td>
<td>5</td>
<td>10</td>
<td>0</td>
<td>16</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>38</td>
<td>21</td>
<td>1</td>
<td>12</td>
<td>30</td>
<td>0</td>
<td>39</td>
<td>5</td>
<td>3</td>
<td>32</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>76</td>
<td>12</td>
<td>0</td>
<td>52</td>
<td>29</td>
<td>0</td>
<td>93</td>
<td>49</td>
<td>0</td>
<td>75</td>
<td>26</td>
<td>0</td>
</tr>
<tr>
<td>Not Suitable</td>
<td>2</td>
<td>2</td>
<td>79</td>
<td>18</td>
<td>18</td>
<td>70</td>
<td>3</td>
<td>3</td>
<td>95</td>
<td>6</td>
<td>6</td>
<td>81</td>
</tr>
</tbody>
</table>

*The results of LUSET use the same sowing months as the household survey showed (spring-Feb, summer-Jun and winter-Oct)*
Table 17. Suitability of LU (% of agricultural land) for Sweet potato

<table>
<thead>
<tr>
<th>Suitability class</th>
<th>Con Que Ray Thu Cuc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Feb</td>
</tr>
<tr>
<td>1</td>
<td>42</td>
</tr>
<tr>
<td>2</td>
<td>38</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>Not Suitable</td>
<td>4</td>
</tr>
</tbody>
</table>

The results of LUSET use the same sowing months as the household survey showed (spring-Feb, summer-Jun and winter-Oct)

The output of the adapted version of LUSET contains the suitability of each land unit in relation to different crops. These suitability factors were converted into potential yield to get insight in the sowing month which will result in the highest yield. The crops can be divided in 1-peak crops and 2-peak crops. The 1-peak type can result in a case where the crops give high yield in only one season. Some crops have a similar suitability in two of the three seasons while the third season is less suitable or unsuitable (e.g. irrigated rice in Figure 10). Regarding the 2-peak crops the peaks might have a difference in height (Soybean) or similar heights (Sweet potato).

The length of a peak differs for several crops. The relevance of this peak width is the possibility to move the sowing moment of the crop forward or backward without changing the potential yield. This gives the opportunity to spread the sowing of the crops (labour use) over several labour periods. Due to calculation capacity problems within GAMS this variation was not implemented in the eventual land use optimization model.

![Suitability classes per season](image)

Figure 10. Percentage of LU with suitability class 'S1' for the Thu Cuc watershed

3.4. Land Use Optimization Model Interface

The multiple goal linear programming segment of the LUPAS system requires a great amount of iterations in order to come to possible solutions. For convenient and speed sake a excel interface was made (Annex 2). By means of pull down menu’s the required GAMS model can be selected as well as the solver type. For each calculation round the values for labour, capital availability and consumption requirements are used according to the entered value; constraint (real value), non constraint (extreme high/low value) or a fraction of the real value. The required values of the three parameters are transferred to an .inc-file and loaded into the GAMS model. The other model input (sets and parameter values) are loaded from a general input-file at the start of each run using the GAMS gdx-converter. In order to keep an overview of the model results, the status of the model and solver are tested at the end of each run. Besides the objective value a number of eight variables are transferred to excel and displayed.
An additional module can be used to create a trade-off curve between two free selectable variables. Tradeoff values can be converted using a graph or table representation. Due to post-selection of model run results the values are normally transferred to a table. Due to capacity issues of the computer, some land units were aggregated to reduce the matrix size within the GAMS solver. To convert land use options to a non-aggregated solution, a converter was integrated in the interface. The results of the different runs can be converted into spatial data. Output files have an ArcGIS-format.

3.5. Land Use Optimization Model Analysis

Population size varies between the three villages, as well as the available land. The combination of the required amount of products and the possible yields, using moderately suitable land, gives an indication about the agricultural position within the Thu Cuc watershed (Table 18). The villages of Con Que and Ray have available agricultural land of respectively 191, 90 and 102ha. This land is available during three seasons, which makes it possible to cultivate the required amount of crops as defined in the input parameters of the MGLP.

Table 18. Required land (ha) to produce crops on LU with moderate suitability

<table>
<thead>
<tr>
<th>Tech1 Village</th>
<th>Rice</th>
<th>Maize</th>
<th>Soybean</th>
<th>Groundnut</th>
<th>Sweet Potato</th>
<th>Vegetables</th>
<th>Cassava</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hi Que</td>
<td>42.0</td>
<td>69.6</td>
<td>-</td>
<td>1.78</td>
<td>0.09</td>
<td>58.42</td>
<td>7.68</td>
</tr>
<tr>
<td>Hi Con</td>
<td>35.1</td>
<td>27.3</td>
<td>-</td>
<td>1.55</td>
<td>0.13</td>
<td>23.55</td>
<td>3.09</td>
</tr>
<tr>
<td>Hi Ray</td>
<td>10.9</td>
<td>6.43</td>
<td>-</td>
<td>0.09</td>
<td>0.17</td>
<td>5.68</td>
<td>0.75</td>
</tr>
<tr>
<td>Lo Que</td>
<td>60.1</td>
<td>113.7</td>
<td>-</td>
<td>5.88</td>
<td>2.00</td>
<td>252.31</td>
<td>22.11</td>
</tr>
<tr>
<td>Lo Con</td>
<td>50.2</td>
<td>44.6</td>
<td>-</td>
<td>5.15</td>
<td>2.92</td>
<td>101.68</td>
<td>8.91</td>
</tr>
<tr>
<td>Lo Ray</td>
<td>15.6</td>
<td>10.51</td>
<td>-</td>
<td>0.29</td>
<td>3.95</td>
<td>24.52</td>
<td>2.15</td>
</tr>
</tbody>
</table>

1 High and low technology refers to the amount of fertilizer and pesticides used.

The analysis of the model outputs, using the initial values of the household survey, was used as an indication to show the feasibility of the used input. Using actual values for labour, capital, land availability and product requirements showed that only one model situation resulted in a feasible solution. Sharing resources and crops in combination with market access to buy products, lead to a feasible solution. By releasing the input for labour and capital up to the level where they are not constrained, the available land becomes constrained. This available land does not have a potential yield high enough to grow the required amount of crops. With the access to a market it is possible to shift the cultivation to more profitable crops and use the obtained capital to buy crops. Within the watershed it is as suggested by the MGLP model not possible to cultivate the required amount of crops which followed from the household survey.

With values for labour, capital and agricultural land based on the present situation, the required amount of crops was increased and varied over the different combinations between the crops while the required amount of rice and maize were kept constant. In all three villages the combinations in which vegetables or cassava is involved leads to infeasible model runs. The cassava is limited by the available agricultural land while the vegetables are limited by the available capital. The amount of sweet potato and ground nuts are relatively small and thus more feasible. Requiring smaller amounts of vegetables or cassava, the demand could be satisfied within the villages1 capital and agricultural land.

The input values regarding vegetables and cassava are mainly based on fodder requirements (Table 19). Observations in the watershed suggest that vegetables used for animal consumption are, besides on agricultural land as used in the model, also cultivated on smaller parcels of land which has been assigned to other land uses then agricultural land. The original values as used in the input-file appear to be overestimated for the agricultural land used in the MGLP. The
available LU are underestimated since in reality crops are being cultivated outside the LU which are included in the model input.

Table 19. Animal and human consumption based on household survey (ton/year)

<table>
<thead>
<tr>
<th>Product</th>
<th>Animal consumption</th>
<th>Human consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Que</td>
<td>Con</td>
</tr>
<tr>
<td>Rice</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Maize</td>
<td>292</td>
<td>115</td>
</tr>
<tr>
<td>Vegetables</td>
<td>1,314</td>
<td>529</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Cassava</td>
<td>230</td>
<td>93</td>
</tr>
</tbody>
</table>

The results from the MGLP model show that, if no market access is available where products can be bought, the exact amount of required products is cultivated in each village. When there is access to a market the village of Que cultivates 10 times more groundnuts (Table 20). This product is sold at a market and the capital from this action is used to buy the products. Con and Que spend respectively 371 and 921 million VND to buy products at a market. Ray did not buy crops at a market. Con however, does not produce more crops than required for consumption but uses available capital. This confirms the better financial position of Con within the watershed.

Table 20. Agriculture products produced with/without access to market (Ton/year)

<table>
<thead>
<tr>
<th></th>
<th>Rice</th>
<th>Maize</th>
<th>Soybean</th>
<th>Ground Nuts</th>
<th>Sweet potato</th>
<th>Vegetables</th>
</tr>
</thead>
<tbody>
<tr>
<td>No access to market</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Con</td>
<td>117</td>
<td>100</td>
<td>56</td>
<td>5</td>
<td>69</td>
<td>4,543</td>
</tr>
<tr>
<td>Que</td>
<td>140</td>
<td>200</td>
<td>45</td>
<td>6</td>
<td>14</td>
<td>1,315</td>
</tr>
<tr>
<td>Access to market</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Con</td>
<td>117</td>
<td>100</td>
<td>56</td>
<td>5</td>
<td>69</td>
<td>4,543</td>
</tr>
<tr>
<td>Que</td>
<td>140</td>
<td>200</td>
<td>46</td>
<td>66</td>
<td>14</td>
<td>1,008</td>
</tr>
</tbody>
</table>

When adjusting the input values of both labour and capital availability the results show that labour in none of the situations regarding market access and labour/product sharing is more constraining than the available land. In Con village the lack of available land in order to cultivate the required amount of crops are meet by the use of capital. When the available capital approaches the actual values the Con village does not have sufficient amount of capital in order to buy products at the market.

3.6. Scenario - Maximizing watershed income

Combining the results of a selection of runs of the MGLP model provides the tradeoffs between watershed income and rice production (Figure 11). The watershed income decreases with food production when resources and products are shared. The watershed income is mainly based on the income of Con while Que produces the lowest income. When labour and products are shared to meet the requirements, a shift in land use is made from Que village to the other two villages. This shift is justified by the less suitable land of Que, by sharing the capital and labour of this village the more suitable land of mostly Con is used. The tradeoffs for sharing of resources with or without market access matches which indicate that sharing resources does not benefit from additional access to a market.
As described before has the sharing of labour and products a strong influence on the land which is used. The results show that sharing resources induces a shift from land belonging to Que to the other two villages (Table 21). Combining this with access to a market shows a slight shift from Con to Que. This indicates the lower suitability of the LU belonging to Que while more profitable crops have higher suitability classes in Que.

Table 21. Agricultural land used during different model situations

<table>
<thead>
<tr>
<th>Village</th>
<th>Market</th>
<th>Share</th>
<th>Share+ Market</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con</td>
<td>179</td>
<td>367</td>
<td>322</td>
</tr>
<tr>
<td>Que</td>
<td>232</td>
<td>127</td>
<td>151</td>
</tr>
<tr>
<td>Ray</td>
<td>85</td>
<td>106</td>
<td>104</td>
</tr>
</tbody>
</table>

The available labour does not become a constraint during the initial analysis of the model. When releasing the demands the available land is no longer constraint and both labour and capital become constraint. In comparison to the situation without market access and no sharing of resources, the implementation of these two parameters individually results in a higher income (Figure 12). In order to maximize the watershed income, sharing of resources is essential to overcome the marginal suitability of land units for several crops. The land units of Con with a higher suitability for Rice and Maize are used to cultivate these crops, partially to fulfill the crops requirements of Que and Ray. Marginally suitable land for the cultivation of Rice and Maize in the latter two villages is then used to cultivate more profitable crops to increase the watershed income.
The costs which are made to produce the agricultural product are an indicator for the efficiency of the available capital. When maximizing the total income of the watershed the cultivated products are, besides the rice and maize, mainly cash crops which can be sold at a market. The results show that the watershed income increases in relation to the investment costs when market access is present and resources are shared.

To fulfill the need for specific crops, more suitable land for each crop is used when sharing resources between villages. The villages do not meet their own requirements for all crops but by sharing or buying at a market their goals are reached. The external input is lower when resources are shared since crops can be cultivated using more suitable land (Figure 13). The tradeoff for the situation in which resources are shared with market access shows the effect of using the LU for the most profitable crop without the limitation of the LU belonging to a certain village.

The tradeoffs which include the potential erosion risk show an erratic pattern. This is clearly observed in the tradeoff with watershed income (Figure 14). The situation with shared resources and market access shows a higher erosion risk while the market access and the base situation have a lower erosion risk. The higher erosion risk is caused by the shift to more profitable crops which induce the erosion risk. Furthermore the access to a market, which has the highest erosion...
risk, creates the opportunity to cultivate less but more profitable crops which leaves a higher percentage of land fallow.

![Tradeoff Watershed income & Potential erosion risk](image)

**Figure 14. Tradeoff between Watershed income and Potential erosion risk**

### 3.7. Scenario - Maximizing watershed rice production

When maximizing the rice production of the Thu Cuc watershed the results show that maize production decreases when income increases (Figure 15). From this tradeoff curve it can be observed that only the sharing of labour and products with and without the access to a market results in a feasible solution of the MGLP model to fulfill the need to produce the 433.8 ton of maize required in the Thu Cuc watershed. The access to a market results in a lower watershed income when the maize demand reaches the required amount. Sharing resources result in a maize production which is 41% higher than the situation in which products can be bought at a market. This shows that especially for maize it is more efficient to buy the product at a market instead of producing it within the watershed.

![Tradeoff Watershed income & Maize production](image)

**Figure 15. Tradeoff between Watershed income and Maize production**

The tradeoff between watershed income and rice production indicates that maximizing the rice production results in a rice production which remains nearly constant while the watershed income
might increase with 50% (Figure 16). Since rice production is maximized and no secondary objective was formulated the tradeoff curves of the different situations are closer as in the scenario where watershed income is maximized. Resources which are not used to capacity are not used to reach an additional goal.

The tradeoff between the available labour and the watershed income shows the effect of the access to a market when sharing resources (Figure 17). Furthermore it shows the limited effect of the additional labour to the watershed income. This clearly shows that labour is, within the watershed as a whole, not constrained. The tradeoff between labour and rice production shows a similar result. The amount of produced rice shows a slight increase when increasing the available labour.

The costs of agriculture are higher when rice is being maximized compared with maximizing watershed income. When similar constraints are applied to the model, more LU are assigned to rice instead of more profitable crops. This was observed in the four model varieties regarding sharing resources and market access.

During the process of reducing the product requirements, the minimum product requirements are meet and maximum amount of rice is produced. In all cases the available capital becomes
constrained except during the winter season. During the winter season no rice can be cultivated which results in the land becoming constrained to maximize rice. Since no secondary objective was defined this constraint results in the under efficiency of the resources (including available land) while coming to a feasible solution.

The tradeoff between rice production and used capital is shown in Figure 18. If more capital is available more rice can be produced. The available capital which represents the base situation is 708 million VND. Available capital reaches a point at which available land to produce rice is becoming constraint. The amount of available capital at which available land becomes constrained varies between the four situations.

![Figure 18. Tradeoff between Rice production and Required input](image)

The potential erosion risk shows an erratic relation with different output variables (e.g. watershed rice production in Figure 19). Changing the cropping pattern causes the value assigned to each land unit to shift between potential erosion risk classes. Sharing resources creates a higher erosion risk; rice is cultivated on more profitable LU which create a higher erosion risk.

![Figure 19. Tradeoff between Rice production and Potential erosion risk](image)
3.8. Scenario - Minimizing erosion

The input data of the potential erosion risk was based on six classes using the outcome of the USLE equation. The use of these classes reduces the precision of the potential erosion risk. Minimizing the erosion risk indicate that within this objective, several land use options are possible with the same erosion risk value. The MGLP model was adjusted by assigning the minimum potential erosion risk, obtained in the initial model runs, to the upper boundary of the potential erosion risk, and then maximizing watershed income. Using this approach the constant value of the erosion risk is respected while the watersheds possibilities are maximized. The tradeoff of the potential erosion risk and both watershed income and rice production shows a constant erosion risk while the watershed income and rice production increases. All situations showed a potential erosion risk of 1,151 units. This suggests that the potential erosion risk as presented in this study does not give a good indication.

The tradeoff between watershed income and watershed rice production shows a similar result as the scenario where watershed income is maximized. Differences are found in the amount of rice which is cultivated; it is higher when erosion is minimized. A tradeoff took place between produced rice and potential erosion risk. Due to the cultivation of rice the soil remains less fallow. Maize and cash crops are cultivated on more sensitive LU to reduce fallow on these lands.

The potential erosion rate shows for each model situation a constant risk value. While lowering the constraints regarding the food demand, income and rice production decreases. The production of cash crops (all crops except Rice and Maize) increased however when the production values reaches its actual value (Figure 21). The villages of Que and Ray cultivate the exact amount of required products while the Con village cultivates a higher amount of cash crops. Sharing resources and market access results in a low constant amount of cash crops which are produced. A higher amount of maize is produced within the Con village, caused by the high suitability of its LU for the production of maize.
Model simulations show that the available capital is the constraining factor for all villages in the three seasons. Sharing of resources results in a shift from LU which are used to produce the crops, more LU in the Ray village are used during all three seasons and in Con during the winter season. This shift meets the difference in land suitability regarding the cultivation of more profitable crops. This shift of profitable crops is compensated by the shift of rice cultivation to Con village.

3.9. Model performance

The tradeoff analyses of the three scenarios show that the situations in which resources are shared with and without a market to buy products, give similar results. While the access to a market shows lower results. This strengthens the results which indicate that available capital and, to a lower extent, available agricultural land is constraining resources within the watershed. When more constrained, the results of the model runs show the constraining effect of capital. The situation in which resources are shared shows that available resources are used more efficiently. Capital which is used as external input to produce crops is assigned to land units with a higher suitability class.

The potential erosion risk component in the land use optimization model shows erratic results. These results are observed in the model results of the two scenarios in which watershed income and watershed rice production are maximized. This suggests that the threshold values of the erosion classes or the number of classes are not suitable for this purpose.

Resources which are used and crops which are produced are related to the LU on which they are cultivated. It is thus not possible to analyze the contribution of each village to the used resources. Besides this, no data is available regarding the amount of land used to cultivate the crops in the current situation. For this reason, current land use could not be compared with the land use which follows from the MGLP model.
Conclusions and Recommendations

The purpose of this study was to explore the optimal land use practices and its limitations.... This was done by using a land evaluation model LUSET in order to establish potential yield values taking into consideration the soil conditions and climatic data. Together with the results of a household survey, the input data for the land use optimization model was created. The LUPAS system was used as framework to perform the land use optimization process.

The adapted version of LUSET shows that implementing weight factors for each input parameter give a robust output. Although the results of the suitability analysis were not compared to the reality, this version of LUSET follows in a more accurate way the land use analysis method described by Sys et al. (1991). The Con and Que villages have a higher amount of suitable land for the crops included in the land use evaluation. The land units in the three villages show a difference in suitability for different crops. This resulted in small possibilities for the villages to fulfil their own requirements.

The land use optimization model used input regarding demands and external input to represent the boundaries of the socio-economic and agricultural capacity of the Thu Cuc watershed. During the model runs the opportunities and limitation of the villages and watershed showed similarities. The requirements as defined by the villages are too high to be met by the three villages individually due to capital constraints. It is however possible to share the resources within the watershed which will bring benefits to all villages in the form of reduced capital input and self subsistence.

The available labour does not turn out to be a constraining resource. Its availability in combination with the chosen labour period does not limit the MGLP model to come to a feasible solution. Reducing the labour availability within the watershed showed a limited reduction in watershed income when resources are shared. Other resources in the watershed compensate the reduced labour availability by shifting to less labour intensive crop/LU combinations. This indicates that the watershed has a higher potential regarding agricultural production when resources are shared among the villages. In the scenarios where “Watershed income” and “Rice production” were maximized came to a higher result than the present situation. Due to the larger variety in available resources, the objectives of the villages can be met without using the marginal lands.

The potential erosion risk, as presented in this report, showed that when minimizing erosion there is no difference between the situations with or without sharing resources and market access. The tradeoff curves in which the potential erosion risk is included shows an irregular pattern. Because of this, it was not possible to fully analyze the effect of the scenarios on potential erosion. However the scenarios in which “Watershed income” and “Rice production” were maximized showed that potential erosion risk increases, on the other hand minimizing this potential erosion risk did not demonstrate a difference in this parameter. The potential erosion risk may provide more realistic values when actual erosion values are used instead of classes. This, however, requires a larger calculation capacity to solve the MGLP model. More classes and different distribution in threshold values will probably yield in less irregular results.

The output of the MGLP model is a mathematical representation of a possible solution using the input of the model. Although several input parameters have a spatial association, there are a limited amount of conditions which fully link this spatial data to the output. Since the outcome of a model simulation leads often to equal results for different LU, the model will assign the crop to the LU with the lowest sequence number. More variables should be included to make the spatial values of the input data appear in the output data.

Three scenarios were analyzed using different situations within the watershed regarding sharing of resources and access to a market. Further analysis of the resources will contribute to a more precise understanding of the watersheds opportunities. Resources might be divided in agricultural land, labour and capital. Furthermore, the results of the MGLP model show that when the villages are
sharing resources the income of one or two villages is negative. To be able to analyze the effect of sharing the resources, it would be valuable to calculate a fictive village income in which their contribution in the total resources is converted to income. The model results as calculated by the present model assigns the income of sold products to the village in which the products were cultivated.

Scale issues were dealt with in a limited manner; watershed and villages were the two scales considered. An additional scale which implements the household decisions is the farm-level. This however requires additional input data which is not available. Outcome of the MGLP model should be considered as an analysis of the capacity and boundaries of the Thu Cuc watershed and not as a final result of the land use optimization process. The MGLP model represents a static situation in which a limited amount of decisions at farmer level are included. Furthermore these decisions are static and do not adapt when circumstances within the decision framework change. The output of the MGLP model could be used in an Agent Based Model in order to include human decision making (Jepsen et al., 2006; Le et al., 2008).
References


Appendix 1 - GAMS code Scenario 1

$TITLE      Land use optimization Thu Cuc watershed
$ONTEXT
Author: E.C. Slingerland
Date: 21-03-2010
Project: MSc. thesis
Land Degradation and Development group, Wageningen University
Wageningen, the Netherlands
$OFFTEXT

*Set input and output directory to store data
$if not set outdir $set outdir Output
$if not set indir $set indir Input
$call 'if not exist %outdir%
ul mkdir %outdir%
' $call 'if not exist %indir%
ul mkdir %Indir%'
$eolcom #

* ---------------------------------------------------------------------------
* IMPORT DATA FROM .xls FILE
* ---------------------------------------------------------------------------

$call GDXXRW @%Indir%\Xls2GdxInput.txt
$gdxin %Indir%\InputData.gdx

* ---------------------------------------------------------------------------
* set declarations and definitions. Members of Set are in .xls file
* ---------------------------------------------------------------------------

SETS
  lu(*)           Land Unit (1 - n)
  v(*)            Village name (Con. Que. Ray)
  c(*)            Crop name (16 crops)
  s(*)            Croping Season (Spring. Summer. Winter crops)
  t(*)            Technology level (High. Low)
  a(*)            Animal type
  p(*)            Type of product (Rice.Maize....)
  e(*)            Suitability 1.2.3.0

$load lu v c s t p a e

*Definition of types of crops
  Ca(c) Annual crops    /RiceD1, RiceD3,RiceH1,UpRice
                 GmaizeH1,GmaizeH2, Soyb, GrNut
                 Spo, Veg/

  Cp(c) perennial crops /Cas,Tea,Fru,Cin,Tmb,Bbo,Plm /

*Definition of products and crops
  pc(p,c) Subset other products  /pRice.RiceD1, pRice.RiceD3,
pRice.RiceH1 ,pRice.UpRice, pMaize.GmaizeH1,pMaize.GmaizeH2,
(PARAMETERS
* CULTIVATION
   CombiCST(c,s,t) CrossTab of crops and seasons
   LuArea(lu,v) Area of a land unit
* Input
   CostTab(c,s,t) Fertilizer use
   CapAvailTab(v,s) Capital available
   LabReqTab(c,s,t) Labour requirement of land use types
   LabWageTab Price of hiring labor
* Output
   YieldTab0(c,s,t,e) Crop yields
   YieldTab(lu,c,s,t) Crop yields for LUs
   Suit(lu,c,s) Suitability classes
   PriceTab(p) Price of agricultural product
   LabAvailTab(v,s) Available labor of a village
   ErosTab(lu,c,s) Erosion classes
* LIVESTOCK
   LFoodReqTab(v,a,p,t) Food requirement of animal
   LLabReqTab(a,s) Labour requirement of animal
   LCostTab(v,a,t) Cost requirement of animal
   nAnimalsTab(a,v) Number of animals
;

$load CombiCST, LuArea, CostTab, LabReqTab, LabWageTab
$load YieldTab0, Suit, PriceTab, LLabReqTab, nAnimalsTab, ErosTab, Goal
$gdxin

YieldTab(lu,c,s,t)$((Suit(lu,c,s)=1)) = YieldTab0(c,s,t,'1');
YieldTab(lu,c,s,t)$((Suit(lu,c,s)=2)) = YieldTab0(c,s,t,'2');
YieldTab(lu,c,s,t)$((Suit(lu,c,s)=3)) = YieldTab0(c,s,t,'3');

* Variable definitions
*------------------------------------------------------------------------------
**VARIABLES**

- **W**  
  Objective
- **wIncome**  
  Waterched income
- **vIncome(v)**  
  Village income
- **IncomeC(v)**  
  Income from Cultivation
- **IncomeF(v)**  
  Income from Forestry
- **IncomeL(v)**  
  Income from Livestock
- **IncomeA(v)**  
  Income from Aquaculture
- **Cost(v,c,s,t)**  
  Cost of production
- **TotCost(v,c,t)**  
  Total yearly cost crops
- **LabCost(v)**  
  Cost to hire labour
- **VLabUsed(v,s)**  
  Labour use per village
- **LabUsedC(v,s)**  
  Labour use crops
- **LabUsedL(v,s)**  
  Labour use livestock
- **ProductC(v,p,s)**  
  Quantity of cultivation products
- **AreaUsedLU(lu,v,c,s,t)**  
  Area of a land unit used to grow a crop
- **Erosion(lu,s)**
- **ErosionS(s)**
- **ErosionT**

;  
* Most variables will always be positive.  

**POSITIVE VARIABLE**

- **Cost**
- **AreaUsedLU**
- **ProductRice(v,p,s)**

;  

**FREE VARIABLE**

- **TotCost**, **LabCost**, **wIncome**, **vIncome**, **IncomeC**, **W**

;  

* equation declarations (description of the equations).  
* The actual equations are in the next section.  
*-----------------------------------------------------------------------------

**EQUATIONS**

*General

- **e_Objective**  
  Objective function
- **e_VlIncome**  
  Income of each village

* Cultivation

- **e_IncomeC**  
  Income from cultivation
- **e_ProductC**  
  Market production (Without consumption)
- **e_LabUsedC**
- **e_AreaCp**  
  Control stable area of perennial crops
- **e_TotCostC**

* Livestock

- **e_IncomeL**  
  Income from livestock
* **e_MProductL**  
  Market production
* **e_TotCostL**  
  Total yearly cost of livestock
- **e_LabUsedL**

* Forestry
* Income from forestry

* Income from Aquaculture

*CONSTRAINTS

  c_LabLimit    Labour limit
  c_AreaLimit   Land area limit
  c_CapLimit    Capital limit
  c_ProductC
  c_SuitLimit

;

* EQUATION definitions. The actual model equations.
* ================================================================= ==================================

*General

e_Objective$(Goal=1),..
  W  =e=  sum(v,VIncome(v));
e_Objective2$(Goal=2),..
  W  =e=  sum((v,s),ProductC(v,'pRice',s))

e_VIncome(v),..
  VIncome(v)  =e=  IncomeC(v)+ IncomeF(v)+IncomeL(v)+IncomeA(v);

*Cultivation

e_IncomeC(v),..
  IncomeC(v)=e=  SUM(p,(SUM(s,ProductC(v,p,s)) - ConsptTab(v,p)) * PriceTab(p)) - SUM((c,t),TotCostC(v,c,t));

e_TotCostC(v,c,t),..
  TotCostC(v,c,t) =e=  sum(s,sum(lu$((LuArea(lu,v)>0)), AreaUsedLU(lu,v,c,s,t)*CostTab(c,s,t)));

e_ProductC(v,p,s),..
  ProductC(v,p,s) =e=  sum(c$(Pc(p,c)),sum((lu,t)$((LuArea(lu,v)>0)), AreaUsedLU(lu,v,c,s,t)*YieldTab(lu,c,s,t,t)));

e_AreaFal(lu,v,"fal",s,"lo"),..
  AreaUsedLU(lu,v,"fal",s,"lo")=e=  LuArea(lu,v)- sum((Ca,t)$((CombiCST(Ca,s,t)=1),AreaUsedLU(lu,v,Ca,s,t)) - sum((Cp,t)$((CombiCST(Cp,s,t)=1),AreaUsedLU(lu,v,Cp,s,t));

e_AreaCp(lu,v,Cp,s,t),..
  AreaUsedLU(lu,v,Cp,s,t)$((LuArea(lu,v)>0)=e=  AreaUsedLU(lu,v,Cp,'Sp',t);

e_LabUsedC(v,s),..
  LabUsedC(v,s) =e= sum((c,t),LabReqTab(c,s,t)*sum(lu$((LuArea(lu,v)>0), AreaUsedLU(lu,v,c,s,t)));

*Livestock
Appendix 1 GAMS code Scenario 1

```
*IncomeL(v),
  IncomeL(v)=e= 0;

*LabUsedL(v,s),
  LabUsedL(v,s)=e=sum(a,LLabReqTab(a,s)*nAnimalsTab(a,v));

*IncomeF(v),
  IncomeF(v)=e= 0;

*IncomeA(v),
  IncomeA(v)=e= 0;

*Erosion
  Erosion(lu,s),
    Erosion(lu,s) =e= SUM((v,t),AreaUsedLU(lu,v,c,s,t)) * ErosTab (lu,c,s));

  ErosionS(s),
    ErosionS(s) =e= SUM((lu),erosion(lu,s));

  ErosionT,
    ErosionT =g= SUM((lu),erosion(lu,s));

* CONSTRAINTS

  sum((c,t)$((LuArea(lu,v)>0),AreaUsedLU(lu,v,c,s,t)) =L= LuArea(lu,v);

  LabUsedC(v,s) + LabUsedL(v,s)=L= LabAvailTab(v, s);#+ LabHire(v,s);

  sum((c,t),sum(lu$((LuArea(lu,v)>0)and (CombiCST (c,s,t)=1)),
    AreaUsedLU(lu,v,c,s,t)*CostTab(c,s ,t)))=L=CapAvailTab(v,s);

  sum(s,ProductC(v,p,s))=G= ConsptTab(v,p);

  AreaUsedLU(lu,v,c,s,t)$((suit(lu,c,s)=0)=e= 0;

OPTION ITERlim =30000;  #Default iteration limit (Iterlim)= 1000
OPTION RESlim = 10000;  #Default time limit(ResLim)  = 1000 seconds

* model statements

MODEL ThuCucModel /ALL/;

*SOLVE ThuCucModel USING LP MAXIMIZING W;
```
Appendix 2 - Model interface

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Role 1</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Current User</td>
<td>User Guide</td>
<td>User Guide</td>
</tr>
<tr>
<td>Role 2</td>
<td>No</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Current User</td>
<td>User Guide</td>
<td>User Guide</td>
</tr>
<tr>
<td>Role 3</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Current User</td>
<td>User Guide</td>
<td>User Guide</td>
</tr>
</tbody>
</table>

Legend:
- **Yes** indicates the feature is available.
- **No** indicates the feature is not available.
- **Current User** refers to the user currently using the interface.
- **User Guide** refers to the availability of user guides for the interface.

Note: The table above provides a summary of the model interface features for different roles or names. The features include has an interface, interface use, user, user guide, Q & A, V & V, simulation, calculation, output values, output use, current user, and user guide. The table is designed to help users understand the capabilities and requirements of the model interface for various roles or names.