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November 2011

Report 417

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Preface

The challenge African agriculture faces is to develop food systems that are economically viable and socially acceptable, contribute to food security, have a favourable greenhouse gas (GHG) balance and that are adapted to future climate conditions. Various technological and policy options are on the shelf to develop food systems, but integrated and evidence-based assessment approaches are lacking to evaluate such options in terms of their contribution to the adaptation of agriculture to climate change, food security and GHG mitigation objectives. The effectiveness and efficiency of technologies and policies in achieving desired contributions to these objectives could be greatly enhanced if they could be *ex-ante* assessed at farm level. This is the level where technologies have to be implemented and where policies ultimately need to exert their effect. Interventions, whether these are technical in nature or policies, can be better targeted if their potential impacts can be anticipated.

This report presents the results from a modelling approach for rain fed farm household systems in the Central Rift Valley of Ethiopia to assess the possible effects of intensification of cereal-based cropping systems to farm income, mitigation of GHG emissions and other household indicators.

The research has been carried out as part of two related projects. First, it is part of the Netherlands policy support research project on 'sustainable agricultural strategies in a climate change context in Ethiopia (BO-009-107)', which has been funded by the Netherlands Ministry of Economic Affairs, Agriculture and Innovation. Second, the work contributed to the Knowledge Base Program 'Global food security: scarcity and transition', and more specifically the project 'Development pathways for global agriculture in the Green Blue environment'.

We thank Amare Haile of the Horn of Africa Regional Environment Centre in Ziway for collecting empirical data used in our modelling approach.

Abstract

Increasingly, agricultural technologies and policies are designed to contribute to the triple goals of food security, adaptation to the anticipated negative effects of climate change and the mitigation of greenhouse gasses (GHG). The effectiveness and efficiency of such technologies and policies in achieving desired contributions could be greatly enhanced if they could be *ex-ante* assessed. This report describes a bio-economic farm household approach for the Central Rift Valley of Ethiopia to identify the potential contribution of rain fed cropping systems and associated production techniques to farm income, mitigation of GHG emissions and other household indicators. We use existing models and tools which have been updated to represent prevailing conditions in the Central Rift Valley and modified to incorporate GHG emissions associated with cropping systems. We distinguish five crops (i.e. maize, wheat, barley, sorghum and teff) each with three production techniques, one representing current production techniques ('business-as-usual') and associated crop yields, and two alternative production techniques with higher yields and correspondingly higher input levels. Estimated GHG emissions from cropping systems relate to nitrogen applications and fuel used in mechanised field operations. Although the results should be interpreted with care as data needs to be verified and important aspects (e.g. livestock) of rain fed farming systems in the Central Rift Valley are not considered, model results suggest that farm income can be increased considerably given the household resource base and the alternative production techniques assessed. However, any improvement in household income is associated with an increase in GHG emission expressed per hectare as well as kg product. This is largely due to the low to zero input rain fed cropping systems prevailing in the Central Rift Valley. These results suggest that improving food security and mitigating GHG emission are difficult to achieve simultaneously in sub-Saharan Africa in situations where food insecurity prevails and external inputs are required to increase crop productivity. The results also indicate at the importance of labour in developing climate smart technologies. Any intervention aimed at improving income, adaptation or mitigation should give due attention to labour availability at household level.

1. Introduction

Africa faces multiple challenges related to reducing food insecurity, degrading ecosystems and adapting to climate change. With its strong dependency on the natural resources base African agriculture is particularly vulnerable to climate change. Yet, for Africa with food insecure conditions, agricultural growth remains fundamental to alleviate poverty and promote economic growth. Investments in agriculture and agricultural development will have to address the potential impacts of climate change. However, agriculture is also a major source of greenhouse gasses (GHG) contributing to global warming (Houghton and Goodale, 2004). The challenge agriculture faces is to develop climate smart systems that are economically viable and socially acceptable, contribute to food security, have a favourable GHG balance and that are adapted to future climate conditions. The term 'triple win' has been coined to achieve the challenge of sustainable development, adaptation of agriculture to climate change, and the reduction of GHG emissions by agriculture.

The farm household is the pivot in agricultural development: Possibilities and constraints from both the external socio-economic and institutional environment, as well as the available natural resource base determine the pace and direction of change in farm household systems and hence, overall agricultural development. Bio-economic farm household approaches can be used to assess the contribution of agricultural systems to socio-economic and environmental development objectives (e.g. Wossink *et al.*, 1992). Recently, bio-economic farm models have been developed to evaluate *ex-post* or to assess *ex-ante* the impact of policy and technology on agriculture, farm economics and the environment (e.g. Janssen *et al.*, 2010). Bio-economic farm models are quantified representations of actual farm households and offer the possibility to analyse the performance of households under given conditions and to simulate the impact of new technologies, changes in farm endowments, prices or policies (Van den Berg*et al.*, 2007).

Here, we present a bio-economic farm household approach for the Central Rift Valley of Ethiopia to identify the potential contribution of the intensification of rain fed cropping systems and associated production techniques to economic development of farm households and mitigation of GHG emissions. Focus of the application is on identifying possible synergies and trade-offs among the various desired objectives underlying the concept of 'triple win', i.e. farm income and GHG mitigation. The presented approach is based on the farm household model developed by Van den Berg *et al.* (2007), which has been updated with characteristics of farm households and cropping systems prevailing in the Central Rift Valley and further modified to include N_2O emissions associated with external nitrogen inputs, and CO_2 emissions associated with the use of fuel for mechanised field operations. At this stage the impacts of climate change are not yet included in the analysis. Using scenarios the study illustrates the potentials of the approach and the type of information that can be generated. The application focuses on the potential impact of cropping systems on household income, GHG emissions and other farm household indicators.

In Chapter 2 the used material and methods are described, including the scenarios. Chapter 3 presents the results and Chapter 4 the discussion and the general conclusions.

2. Material and methodology

2.1 Overview of approach

The bio-economic farm household approach used in this study consists broadly of two existing analytical tools, i.e. (i) the expert-based tool TechnoGIN, which allows to quantify inputs and outputs of current and prospective cropping systems (Ponsioen *et al.*, 2006), (ii) a mathematical programming model of stylized farm household systems (Van den Berg *et al.*, 2007). The farm household model maximizes income from cropping systems, subject to the availability of land, family and hired labour, capital and market prices of inputs and outputs. Inputs and outputs of cropping systems including well-defined production techniques are generated by TechnoGIN, which stands for Technical coefficient Generator for Ilocos Norte, which is a region in the Philippines for which the tool was originaly developed (Ponsioen *et al.*, 2003). TechnoGIN is a generic expert tool for integrating different types of biophysical and socio-economic information related to crop production. Based on this information and agro-ecologically sound calculation rules TechnoGIN quantifies inputs and outputs of well-defined cropping systems both in physical and monetary terms.

Both tools, i.e. the farm household model and TechnoGIN have been modified to allow representation of the conditions prevailing in the Central Rift Valley. In our analysis we focus on rain fed production systems as they are the predominant systems in the Central Rift Valley and most vulnerable to climate change.

2.2 Farm household model

Major resource constraints of the farm household relate to land, labour and capital. Both labour and capital availability are calculated on a monthly basis in the model to identify peak demands for both resources, which often limit the adoption of new technologies in sub-Saharan Africa (Anderson, 1992). See Table 1 for the major characteristics of the typical farm household, which have been derived from various farm surveys conducted recently in the Central Rift Valley (e.g. Tesfaye Shiferaw, 2008; Mengistu Assefa, 2008). Since farm characteristics vary across the Central Rift Valley we use scenarios to show the effect of variable land holding size. We do not assume livestock systems in this version of the model, except for the use of oxen in crop production and the availability of manure for fertilising crops. There are no costs associated to the use of family labour in the model. However, we assume that hiring of labour is possible at a wage rate of 20 Birr per day, the current agricultural wage rate (1 USD=13.51 Birr; price level mid 2010). We introduce a maximum for the number of days hired labour per month, which is set arbitrarily to 23 days per month corresponding with 25% of the family labour input at a 2 ha farm with access to current production techniques only. In this version of the model capital availability is not restricted as information was lacking on the current capital availability of farm households in the area and their acces to credit. Capital needs of farm households can be used for ex-post evaluation of the model outcomes in stead of using capital availability as an *ex-ante* characteristic of a farm household.

Table 1. Typical resource base of farm households in the Central Rift Valley used as standard characteristics in the farm household model.

Farm household characteristic	Value
Land holding	2 ha
Family size	3.8 persons (adult equivalents)
Household labour availability	2 persons
Number of working days available per month per person	18 days
Maximum number of hired labour per month	23 days
Minimum cereal needs per household member (adult equivalent)	150 kg

The farm household model is programmed in the General Algebraic Modeling System (GAMS; Rosenthal, 2011) . See Appendix I for the model code.

2.3 Cropping systems

We describe cropping systems in terms of discrete sets of combinations of inputs and outputs, also called technical coefficients (Chambers, 1988; Hengsdijk *et al.*, 2002). These coefficients are generated using location-specific information from farm surveys (Scholten, 2007; Tesfaye Shiferaw, 2008; Mengistu Assefa, 2008), Farm Handbooks (Mohammed Abdulwahab, 1988), general agronomy knowledge, physical data (climate and soil) and the dedicated collection of input prices at local agrochemical stores. These information sources are used to quantify current crop yields and related labour requirements and labour calendars, and fertiliser and biocide use. In addition, TechnoGIN estimates the associated environmental impact of cropping systems in terms of nitrogen losses (e.g. nitrogen leaching and N_2O emissions associated with the use of external nitrogen inputs) using simple transfer functions of which many are based on Smaling *et al.* (1993).

In our analysis we include five rain fed crops, i.e. teff, maize, wheat, barley and sorghum, which are major crops for food self-sufficiency. We distinguish different production techniques for each of these crops. The first production technique (TAC) represents the current practice of low to zero external inputs ('business-as-usual'). Generally, these techniques deplete soil nutrient stocks as less external nutrients are supplied than harvested with grains and residues and lost from the system, for example due to leaching (Haileslassie *et al.*, 2007). Subsequently, the TBF and TCF production techniques represent higher crop yields (i.e. twice the yield of TAC) and associated higher input levels. The input levels of these new production techniques have been defined based on the target-oriented approach (Hengsdijk and Van Ittersum, 2002), which entails that first a target yield level is determined and subsequently the optimal combination of inputs to realize this yield. We used TechnoGIN to quantify the input levels of TBF and TCF. We used twice the current crop yields as target yields for TBF and TCF as these levels are obtained by the best farmers in the Central Rift Valley (Table 2). Research across Ethiopia showed that doubling of yields of legume crops is feasible within a few years after introducing the proper technologies through new innovation platforms (Tsedeke Abate *et al.*, 2011). Calculated nutrient (nitrogen and phosphorus) requirements of the TBF and TCF cropping systems need to be satisfied in the farm household model by different (combinations of) fertilizers and manure depending on associated costs of both inputs and resource constraints at household level. TBF and TCF differ in the use of labour, i.e. TCF includes the use of mechanised field operations for field preparation, sowing and harvesting, in contrast with TBF which is based on manual and oxen labour input only, just as TAC. Mechanisation of some field operations such as field preparation and combine harvesting is happening at a small scale in the area but is not yet common practice for the large majority of farmers (Eshete *et al.*, 2007). See Table 2 for selected inputs and outputs of the assessed cropping systems in this study. Note that production costs more than double while yields double, due to various non-linear relationships in inputs and outputs. See Appendix II for all input and output coefficients of cropping systems generated with TechnoGIN and which have been assessed in the farm household model. TechnoGIN also has been used to generate inputs and outputs of haricot bean and pepper, and also the farm household model is able to assess these crops. However, we decided to exclude them in the results considering the nature of both crops, i.e. they are (mainly) used for cash production, sometimes even produced for export (haricot beans) with high input levels and management requirements, for which the associated data is uncertain.

Table 2. Selected inputs and outputs of assessed production techniques (TAC and TCF) for five crops, and the used output prices of grains used in this study. Costs do not include costs for (hired) labour and nutrients. See Appendix II for the files with all inputs and outputs of cropping systems assessed in this study.

Crop:	Production technique TAC		Production technique TCF		
	Yield (kg/ha)	Costs (Birr/ha)	Yield (kg/ha)	Costs (Birr/ha)	Output price (Birr/kg)
Maize	2000	652	4000	1962	3.2
Teff	1000	706	2000	2516	6.9
Wheat	2500	1225	5000	2785	5.4
Barley	2000	1060	4000	2620	4.9
Sorghum	1200	354	2400	2014	4.2

Calculated GHG emissions are associated with external nitrogen applications (nitrogen in fertilizers and manure) and fuel (diesel) in the case of mechanized field operations (only in production technique TCF). We use default methods of the Intergovernmental Panel on Climate Change (IPCC) to calculate N_2O-N emissions, i.e. 1.25% of the applied external nitrogen (IPCC, 2001). Subsequently, the N_2O emission is converted into CO_2 equivalents using a global warming potential multiplication factor of 296 while accounting for the nitrogen mass in N_2O. Fuel is converted into CO_2 equivalents by multiplication with a factor of 2.98. Farm income is the difference between the financial returns obtained with selling crop products (only grains) and the associated costs including costs for hired labour and nutrients, which are both determined in the optimization model.

2.4 Scenarios

We calculate two different scenarios to illustrate the potentials of the approach and the type of information that can be generated. The scenarios indicate at the potential impact of production techniques and land holding enlargement on household income, GHG emissions and other farm household indicators.

2.4.1 Scenario 1: Reducing GHG emissions

In the first scenario, the GHG emissions are stepwise reduced from the optimal situation with the highest farm household income that can be obtained given prevailing prices, available production technique and household characteristics. In this way the relationship between GHG emissions and household income can be assessed. Farm household characteristics are shown in Table 1 and farmers can choose from all three production techniques in this scenario, i.e. TAC, TBF and TCF.

2.4.2 Scenario 2: Enlargement of the land holding

In scenario 2 the land holding size of the farm is increased with steps of 0.5 ha from 1 to 7.5 ha to assess the effect on household income and GHG emissions. The farm household characteristics are the same as shown in Table 1 except for the land holding size. Hence, the effect of both smaller and larger land holdings than the standard situation (2 ha) on income, GHG emission and other indicators are simulated in this scenario. We run the scenario for two situations, i.e. in the first situation only the current production technique TAC is available, while in the second situation all three available production techniques can be selected by the farm household.

2.4.3 Study area

The Central Rift Valley (about 1 million ha), part of the greater African Rift Valley, is situated 150 km south-west of Addis Ababa and bounded in the east and west by highlands, with altitudes of more than 3000 m above mean sea level. The valley floor is at about 1500 m and receives about 700 mm per year, of which about 70% precipitates in the main rainy season (*Meher*) between June and October (Jansen *et al.*, 2007). Associated with the low and unreliable rainfall, the productivity of rain fed farming – the predominant livelihood of the majority of the population – is generally low. Part of the population depends structurally on aid through the Productive Safety Net Programme, indicating the extreme poverty and food insecurity.

3. Results

In the following the results of the model simulations are presented. Results are indicative only and values should be interpreted with care as imported aspects of current farming systems in the Central Rift Valley, such as livestock, are neglected in this model application, while used physical and socio-economic information needs to be further verified and updated. Therefore, relative changes in model outcomes are more important than absolute changes among scenarios.

3.1 Scenario 1: Reducing GHG emissions

Figure 1a shows the relationship between farm household income and GHG emissions. In the optimal situation, farm income is nearly 39,000 Birr with an associated farm level GHG emission of more than 1,400 kg CO_2 eq. In the optimal solution both wheat and maize with TBF production technique are selected.

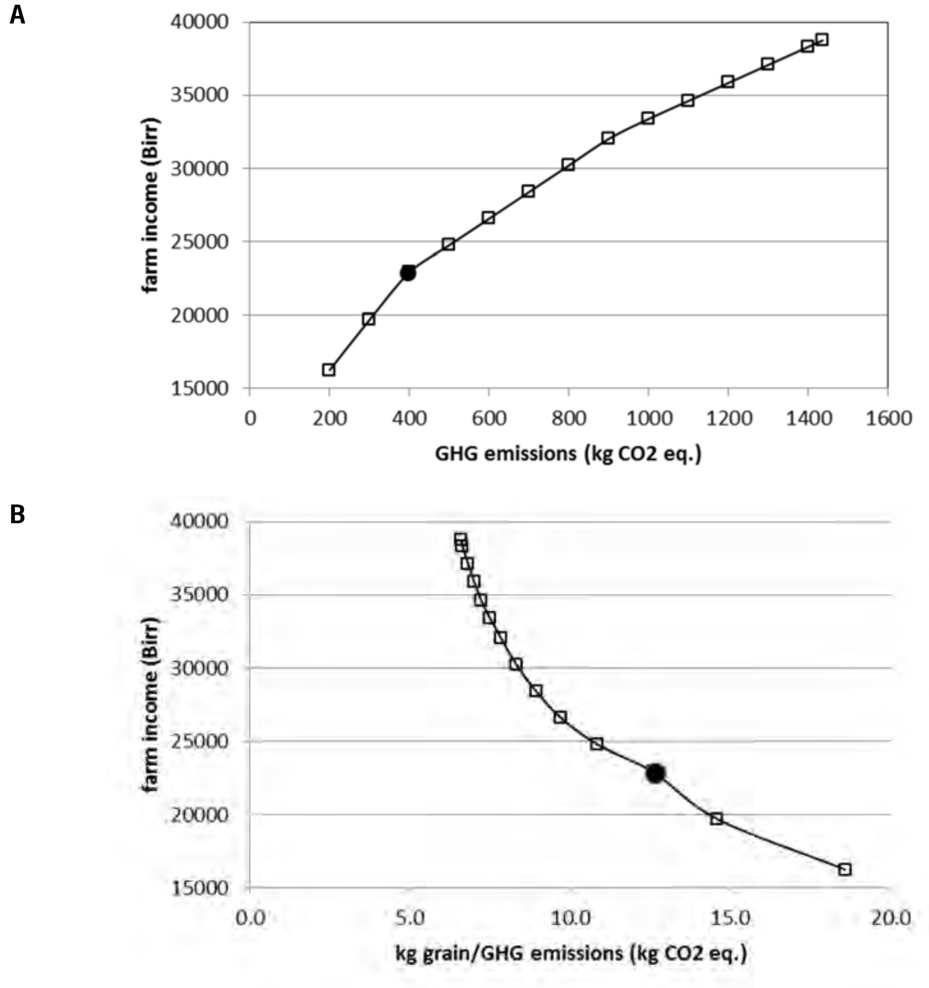

Figure 1. Relationship between farm level GHG emissions and farm income (a) and between kg grain production per kg emitted GHG and farm income (b) based on model runs with five crops and three production techniques. The solid marker indicates the maximum farm income and associated GHG emissions using current production techniques only.

Constraining the GHG emissions goes at the expense of maize-TBF systems which are replaced by maize-TACsystems. These have lower GHG emissions as N inputs are lower, but also lower yields and net returns. Below 1,000 kg CO_2 eq. maize is completely replaced by wheat-TAC systems with lower GHG emissions. Constraining the GHG emissions further means an increase of TAC cropping systems up to the point that the entire farm is under TAC. Using current cropping systems only, maximum farm income is nearly 23,000 Birr with an associated GHG emission of almost 400 kg CO_2 eq. (Solid marker in Fig. 1a). Further constraining the GHG emissions means a shift from wheat to sorghum which does not receive any fertilizers in current systems. Farm income decreases more rapidly after this point as sorghum is less profitable than wheat. The GHG emissions are related to the use of urea and DAP as manure and fuel are not used in any of these model runs.

Using the same data, Figure 1b presents the relationship between the amount of grain produced per kg emitted CO_2 eq. and farm income. At maximum farm income about 6.5 kg of grain is produced per kg CO_2 eq., while using TAC cropping systems only about 12.5 kg of grain is produced per kg CO_2 (solid marker in Fig. 1b). At lower farm incomes the grain productivity (kg grain per kg emitted CO_2 eq.) further increases to a maximum of about 18.5 kg grain as non-fertilized sorghum enters the crop rotation.

3.2 Scenario 2: Enlarging the land holding size

A farm holding of one hectare using only current (TAC) cropping systems while other household characteristics are as shown in Table 1 is able to generate a farm income of about 11,000 Birr, which is about 12,000 Birr less than the standard farm of 2 ha. Increasing the farm holding to 4.8 ha allows raising farm income to 40,000 Birr (Fig. 2). This farm size (4.8 ha) is the maximum area that can be cropped with the available family labour and hired labour. Figure 2 indicates that farm income increases less rapidly when the land holding exceeds 2.5 ha. At this farm size hired labour exceeds the maximum of 23 man days per month, which limits the further expansion of labour demanding maize systems at the expense of more labour extensive sorghum systems.

Offering cropping systems with all three production techniques to the household model also indicates at the importance of labour availability. At a farm size of 1 ha only TBF-wheat is selected. When the farm size increases with 0.5 ha maize is introduced as the maximum of 23 hired man days per month is reached. Especially during harvest labour requirements for wheat are higher than for maize. When a farm size of 3.5 ha is reached the less labour demanding TBF-sorghum starts to replace maize. At a farm size of 5 ha, mechanized TCF-wheat appears to be a profitable strategy as it is replacing (manually harvested) TBF-wheat. Mechanized wheat production increases till a land holding size of 6.2 ha when labour availability constrains further expansion of the cropped area; any additional land is left fallow.

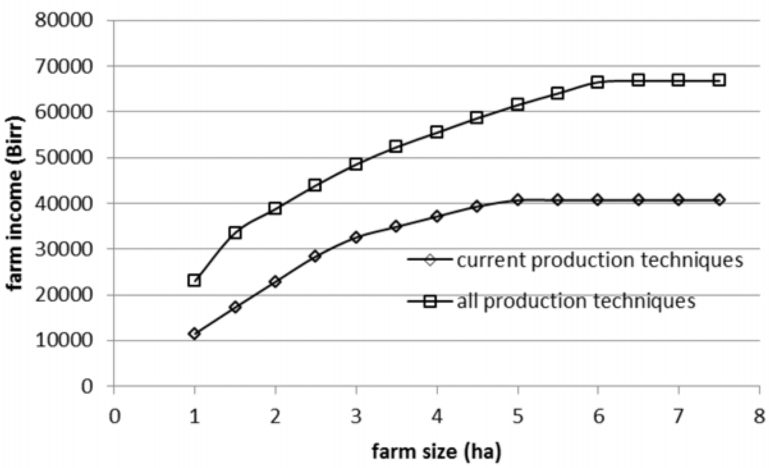

Figure 2. Relationship between farm size and farm income using current production techniques only and all three available production techniques.

Figure 3 shows the relationship between farm size and GHG emissions at farm level. When all production techniques are available GHG emissions increase steadily up to almost 4000 kg CO_2 eq. till the maximum farm size of 6.2 ha is reached. In case only current (TAC) production techniques are available total GHG emissions reach a maximum of 700 kg CO_2 eq. but this level declines after the farm size exceeds 3.5 ha and (zero nitrogen fertilizer) sorghum enters the crop rotation.

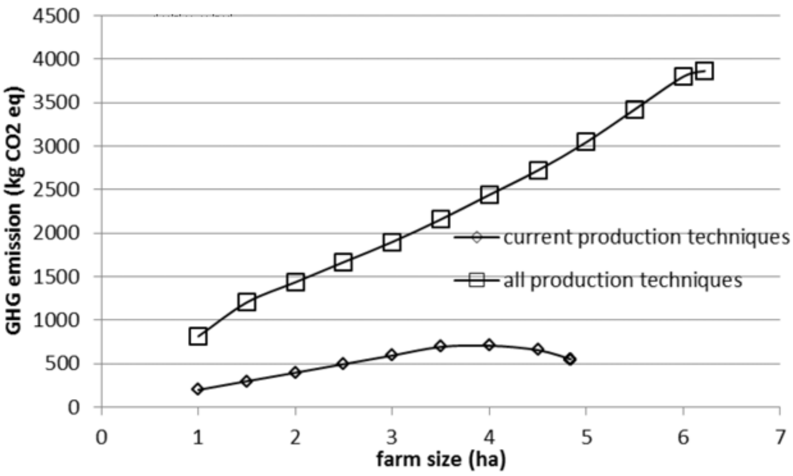

Figure 3. *Relationship between farm size and GHG emissions at farm level using current production techniques only and all three available production techniques.*

Figure 4 shows the labour productivities associated with the results from Figure 2. Labour productivity refers to the total farm income divided by the family (household) labour input, hence, excluding hired labour inputs as these are considered a cost component in the calculations (section 2.2). When all production techniques are available, farm labour productivity is highest at a farm size of 1.5 ha. This can be explained by the relatively high use of hired labour (so, low use of family labour) and a relatively high farm income. After this point farm income increases less sharply, see Figure 2. Between a farm size of 1.5 and 2.5 ha, the share of family labour in total labour input increases resulting in lower labour productivities. When farm size exceeds 2.5 ha, family labour is limited and more external labour needs to be hired, resulting again in higher (family) labour productivities till the maximum cropped area is reached, i.e. 6.2 ha, after which labour productivity stabilizes as additional land beyond this point can not be cropped given the available resources (see before).

In the case that only current production techniques are available similar interactions among farm income, family labour input and hired labour occur, but effects are less pronounced. Remarkably, at a farm size of about 2.5 ha family labour productivity is similar irrespective of the available production techniques.

Labour productivities appear high with a lowest value of more than 200 Birr/day (± 15 USD/day). However, in none of the scenarios the total available family labour (432 man days per year; Table 1) is completely used. In contrast, a maximum of 190 man days of family labour is used indicating at a large underemployment of family labour. The low use of family labour is associated with the typical peak labour requirements in rain fed farming systems especially during planting and harvesting while there are large periods of the year with little on-farm employment opportunities (Anderson, 1992).

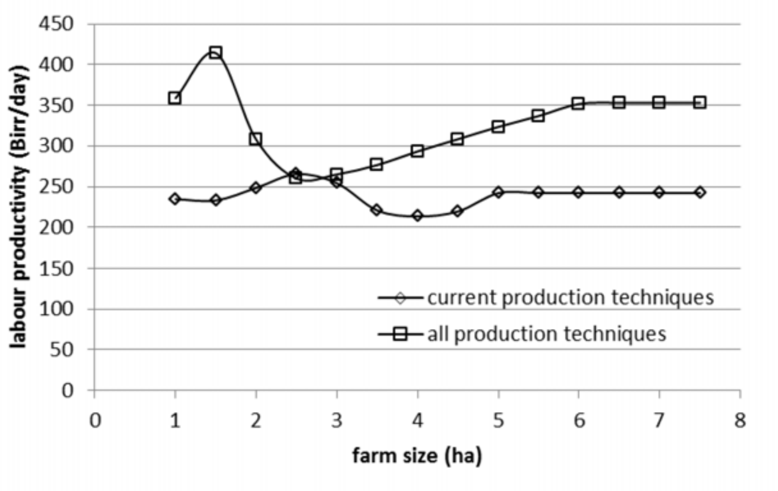

Figure 4. Relationship between labour productivity and farm size for the situation with only current production techniques available and with all production techniques available.

Figure 5 shows the GHG emissions per kg product as function of the farm size for the situation with only current production techniques available and with all three production techniques available. When only current production techniques are available the grain yield per emitted GHG is higher over the entire range of farm sizes. Towards larger farm sizes and using current production techniques, GHG emissions per kg product decrease because of extensification, i.e. a choice for more zero nitrogen fertilizer sorghum. In contrast, when all production techniques are available there is an intensification trend associated with the use of more mechanised production techniques resulting in more emissions per kg grain produced at larger farm sizes.

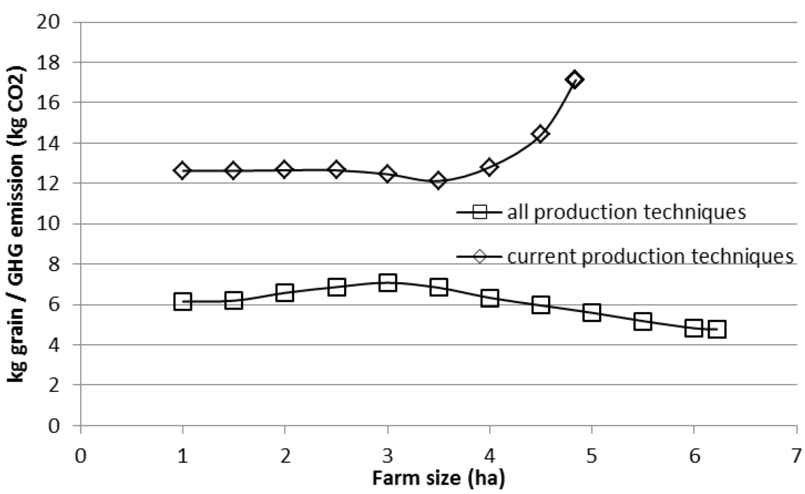

Figure 5. Relationship between farm size and the GHG emissions per kg product for the situation with only current production techniques available and with all three production techniques available.

Because of the importance of labour availability on model outcomes, we also have looked at the effects of increasing labour availability at farm household level. We have increased the availability of hired labour from 23 days per month to 46 days per month and the availability of family labour from 18 to 26 per month (Table 2). To assess the effect on farm income and the maximum farm size that can be cropped we use the model runs with all three production techniques in Figure 2 as benchmark. Figure 6 shows what might be expected when relaxing labour constraints: First, household income is higher than the benchmark already at small farm sizes. Second, household income is highest when more family labour is available as less (costly) labour needs to be hired. Maybe more remarkable is that relaxing the labour constraint does not result in a much larger maximum cropped area compared to the benchmark. In both cases the maximum farm size that can be cropped is about 7.6 ha, compared to 6.2 ha for the benchmark (Figure 6).

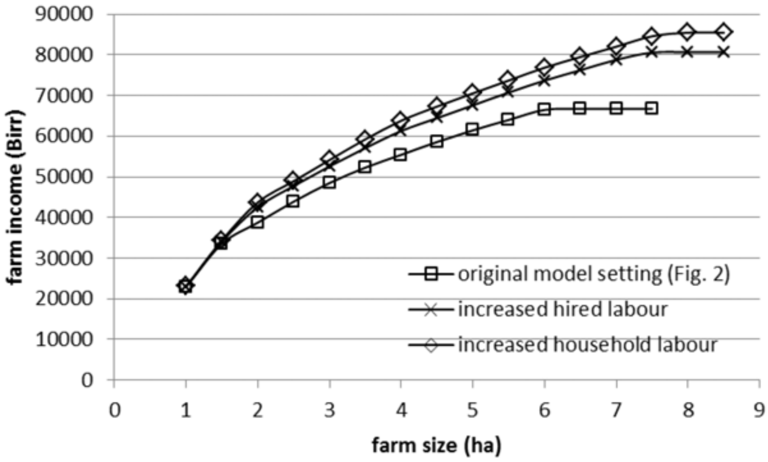

Figure 6. *Relationship between farm size and farm income using all three available production techniques: (i) default labour availability as used in Figure 2, (ii) increased availability of hired labour, and (iii) increased household labour availability.*

4. Discussion and conclusions

As indicated before, results should be used with care as both socio-economic and biophysical data need to be further verified and updated. In addition, important components of rain fed farming systems in the Central Rift Valley such as livestock affecting GHG emissions are not yet included. The strength of both analytical tools used, i.e. the farm household model and TechnoGIN is that data and assumptions can be easily modified according to the latest knowledge and new insights to analyse their consequences. In addition, the use of scenarios allows the rapid exploration of impacts of technologies and different anticipated developments on agricultural production, the livelihood of farm households and the environment.

In this assessment of cropping systems and production techniques at household level GHG emissions are associated with nitrogen and fuel use only. Current low-input cropping systems have correspondingly low GHG emissions at farm level and per kg grain produced. Any attempt to increase productivity and farm income using more external inputs will increase the direct GHG emissions. However, nutrient input of current systems is generally insufficient to maintain soil nitrogen and phosphorus stocks resulting in lower yields and reduced financial returns in the long run. These effects are difficult to account for in a static farm household model as presented in this study.

The household model shows the importance of labour requirements in improving the income performance of farming systems. Beyond a farm size of 2.5 ha the available family labour constrains income growth and the farming system increasingly depends on hired labour. When the farm size exceeds about 5 ha mechanized field operations become profitable given the machinery costs used in this study. However, mechanization of harvesting and planting operations is only relaxing labour constraints to a limited extent as labour availability during other parts of the growing season limits the expansion of the cropped area beyond a farm holding size of 6.2 ha.

The limited availability of labour is also reflected in the choice of fertilizers (urea and DAP) instead of manure to satisfy nitrogen and phosphorus requirements of cropping systems in the household model. In none of the model runs manure is selected as its processing and application is much more labour-demanding than fertilizers. We did not consider in the model the crop needs for potassium and micro nutrients which are also applied with the manure.

Even with the current household resource base considerable improvement in farm income appears to be possible given the alternative production techniques assessed in this illustrative study. However, important capital constraints such as credit availability for buying inputs at the start of the growing season have not been taken into account as information was lacking on capital access, though the household model allows accounting for such constraints.

With respect to the triple win hypotheses, the model outcomes suggest that increasing income of farm households in the Central Rift Valley is associated with an increase in GHG emissions, expressed both per land area and per kg product (Fig. 1a,b). This 'win-lose' situation is largely related to the current low to zero input rain fed cropping systems prevailing in the Central Rift Valley. Any intensification to increase crop productivity and farm income will go at the expense of more GHG emissions associated with the use of fertilizer or diesel. Therefore, results suggest that improving food security and mitigating GHG emission are difficult to achieve simultaneously in sub-Saharan Africa in situations where food insecurityprevails and external inputs are needed to increase crop productivity.

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Appendix I.
Farm household model programming code

```
$TITLE Basic farm household model for the Central Rift Valley, V1.0, April, 2011

*_______________________________________________________________
* This FHH model for the CRV is based on the model developed for Pujiang, China :
* Van den Berg et al. (2007)

* *There is no livestock production and there are only a limited number of crops.
* _______________________________________________________________

$Offlisting

* _______________________________________________________________
* set declarations and definitions: assignment of members
* _______________________________________________________________

SETS
crop       crops                  /HAR        Haricot bean
                                  MAI         Maize
                                  TEF         Tef
                                  SOR         Sorghum
                                  PEP         Pepper
                                  BAR         Barley
                                  WHT         Wheat/

cs         crop scenarios         /cs1/

dekad      dekads                 /1*36/

fert       fertilizers            /Urea
                                  DAP
                                  KNO3
                                  Manure/

h      household type             /H1/

lu     land units                 / RFMD/

lut   land use types              /LHAR       Haricot bean
                                  LMAI        Maize
                                  LTEF        Tef
                                  LSOR        Sorghum
                                  LPEP        Pepper
                                  LBAR        Barley
                                  LWHT        Wheat/

lutr(lut) subset of LUTS          /LHAR       Haricot bean
                                  LMAI        Maize
```

```
                                LTEF          Tef
                                LSOR          Sorghum
                                LPEP          Pepper
                                LBAR          Barley
                                LWHT          Wheat/

month                           /JAN,FEB,MAR,APR,MAY,JUN,JUL,AUG,SEP,OCT,NOV,DEC/

n_loss     type of n loss       /nleach       leaching
                                ngas          gaseous losses/

nutrient   nutrients            /N  Nitrogen
                                P  Phosphorus
                                K  Potassium/

r(crop)    for grain crop only                /MAI, TEF, SOR, BAR, WHT/
v(crop)    for non-grain crops only           / HAR, PEP/

season     seasons TechnoGIN    /s1           first crop
                                s2            second crop
                                s3            third crop/

tech       technologies         /TAC          average farmer practice
                                TBF           improved, double yield
                                TCF           improved, doubl yield, mech
                                TDF           not used/

t(tech)    available tech       /TAC
                                TBF
                                TCF/

veg(lutr)  vegetable land       /LHAR,LPEP/

cap1(dekad)                     /2*36/
;

* ____________________________________________________________
* parameter declarations (in alfabetic order)
* the value of parameters is given (see data input)
* ____________________________________________________________

PARAMETERS
 BIOCOST(lu,lut,tech,season)              biocide costs per season (Birr p. ha)
 BIOINDEX(lu,lut,tech)                    biocide index value per year(a.i. per ha)
 CAPITAL                                  working capital per household type (Birr)
 COST(lu,lut,tech,season)                 other costs per growing season(Birr per ha)
 CROPSHARE                                max share of crop income used for inputs
 DAYS_MAX                                 available labour days per person per month
 DAYSTOT_MAX                              available labour days per person per year
 FERTUSE(lu,lut,tech,season,nutrient)     nutrient use per lu lut t season (kg per ha)
 Fsize                                    family size (adult equivalents)
 FUEL(lu,lut,tech)                        fuel use per lu lut and tech (l per ha)
 HARVEST(lut,month)                       harvest in month yes (1) or no (0)
```

```
  HIR_MAX(month)                      maximum labor hired per month (days)
  HIR_MAXTOT                          maximum labor hired per year (days)
  INTEREST                            interest rate for a growing season (%)
  LAB_MAX                             household labourers available (number)
  LABUSE(lu,lut,tech,month)           labour use per lu lut t month (days per ha)
  LAND_FACTOR                         factor to change farm size
  LU_MAX(lu)                          land availability per land unit (ha)
  MAXSALES(crop)                      maximum amount sold per crop (kg)
  NLOSS(lu,lut,tech,season,n_loss)    N loss per lu lut tech season(kg per ha)
  NON_MAX(month)                      max non-farm employment per month (days)
  NUTCONTENT(fert,nutrient)           nutrient content of commercial fertilizers
  OFF_MAX(month)                      max off-farm employment per month (days)
  OPPORTUNITY                         opportunity costs of family labor(Birr p.day)
  P_FERT(fert)                        commercial fertilizer price (Birr per kg)
  PLANTING(lut,season,month)          planting of crop in decad yes(1) or no(0)
  PRICE_FACTOR(crop)                  multiplier to in or exclude crops rapidly or to change relative price of
crops
  P_SELL(crop)                        sales product price  in (Birr per kg)
  REMIT                               remittances (Birr)
  GRAIN_MIN                           minimum grain produced per hh member (kg)
  SCRED_MAX                           max. credit available (Birr)
  YIELD(lu,lut,tech,crop)             yield per crop of each lu lut t (kg per ha)
  WAGE_HIR(month)                     wage for hired labour (Birr per day)
  WAGE_OFF(month)                     wage for off-farm work (Birr per day)
  WAGE_NON(month)                     wage for non-farm work (Birr p day)
  MANLAB                              labour (mnd) for distribution of 1 m3
;

* ________________________________________________________________
* variable declarations (in alfabetic order)
* the value of variables is determined in the model
* ________________________________________________________________
  vBIOINDEX                           biocides per year (index value)
  vCAPITAL(month)                     working capital (Birr)
  vDEBT(lut,month)                    outstanding debt (Birr)
  vFERTUSE(lut,t,season,fert)         fertilizer use per season
  vGHGFERTN(fert)                     N-NO2 emissions per year from N fertilisers (kg N-NO2)
  vGHGFUEL(lutr)                      CO2 emissions from fuel use (kg CO2 eq)
  vGHG                                total CO2 emissions from fuel use and fertilizer N use (kg CO2 eq)
  vINCOME                             total farm income  per year (Birr)
  vINPUTS(lut,month)                  nonlabour input costs per growing season (Birr)
  vLABHIR(lut,month)                  hired labor per month (days)
  vLABNON(month)                      non-farm work in each month (days)
  vLABOFF(month)                      off-farm work in each month (days)
  vLABOWN(lut,month)                  family labour use by lu lut t per month (days)
  vLAND(lu,lut,t)                     area with certain lut ent t per lu(ha)
  vMWAGES(month)                      wage income per month (Birr)
  vNLOSS(lu)                          nitrogen loss per land unit per year (kg)
  vNGAS(lu)                           nitrogen gasseous losses per lu per year (kg)
  vNLEACH(lu)                         nitrogen leaching losses per lu per year (kg)
  vOWN(lut,month)                     own funds used for crop expenditures (Birr)
  vOWNDEBT(lut,month)                 monthly debts (Birr)
  vPRODUCT(crop)                      production per crop (kg)
```

```
  vREPAY(lut,month)                  repayment of loans per lu lut t (Birr)
  vREPAYOWN(lut,month)
  vSCREDIT(lut,month)                short-term credit taken (Birr)
  vVINCOME                           income from non-grain production (Birr)
  vWAGES                             wage income per year (Birr)
  vMLABUSE(lut,month)                labour use for manure application per lut and month (days)
;

* ________________________________________________________________
* variable definitions (in alfabetic order): assignment of type
* ________________________________________________________________
POSITIVE VARIABLE  vBIOINDEX,vCAPITAL,vDEBT,vFERTUSE,vINPUTS,vLABHIR
               vLABNON,vLABOFF,vLABOWN,vLAND,vMWAGES,vNLEACH,vNLOSS,vNGAS
               vOWN,vOWNDEBT,vPRODUCT,vREPAY,vREPAYOWN,vSCREDIT,vWAGES
               vVINCOME, vGHGFERTN, vMLABUSE, vGHGFUEL, vGHG
               ;

* variables that you optimize should be free variables.
FREE VARIABLE      vINCOME;

* ________________________________________________________________
* equation declarations (b_ for balances; c_ for constraints)
*   This part gives only the description of the equations. The actual equations are in the next section.
* ________________________________________________________________
EQUATIONS

* objective
*  This model maximizes income subject to a constriant on minimum
* cereal production to guarantee food self sufficiency.
  b_INCOME                 farm income plus wage income plus remittances
  b_vincome                income from non-grain
  b_WAGE                   total wage income per year is the sum of all month incomes
  b_monthWAGE              off-farm wage income plus non-farm wage income per month
  c_MINGRAIN               minimum production constraint for grain

* crop production
*  The production balance computes total production for each crop
  b_PROD                   total production is the sum of production on all land units

* land use
*  Total use of land cannot exceed the amount of land available. This holds per land unit.
  c_LAND                   use of land units by LUS and technology

* nonlabour costs
*  Nonlabour costs are calcalated per lu,lut,t,season
  b_COST                   total costs is the sum of biocide-fertilizer and other costs
  b_FERTUSE                fertilizers used to fullfill nutrient requirements

* working capital
*  The household needs working capital to purchase nonlabour inputs and to hire labourers. The household
*  will use crop working capital and funds available from off and non-farm employment and, if these are not
*  sufficient, take an additional short-term credit. This credit is bound to a maximum and cannot be used for
*  hiring labor. Initial working capital is given. We assume that the household needs to purchase all inputs for a
```

```
*  specific crop at planting. Crop loans are repayed after the harvest of the specific crop. After each harvest, the
* household uses (a share of) crop revenues to replenish working capital. Maximum working capital is set at the
*  initial level. Production funds available from off and non-farm employment..
  b_LIQUIDITY               total expenditures cannot exceed use of own funds and credit
  b_DEBT1                   outstanding debt= previous debt-previous repayment+new credit
  b_DEBT2
  b_REPAY                   after harvest the household repays the loan for this crop
  c_DEBT                    total debt may never exceed the total credit reserve
  b_OWN1                    working capital=previous capital+previous replenishment-use
  b_OWN2
  b_OWNDEBT1
  b_OWNDEBT2
  b_REPAYOWN
  c_OWN

* labour allocation
*  The household uses family and hired labour in crop production. Besides,
*  family members can work on the farm, for other farmers, and for non-agricultural employers.
*  There is a maximum to the hours worked by the family. In some months, labor hiring is difficult
*  (e.g. harvesting season). Also, employment outside the own farm is limited. This results in a balance for
*  labour on the family farm (this balance computes the amount of labourers to be hired and three constraints:
*  total family labour, maximum off-farm employment, and maximum on-farm employment.
  b_LABFARM               total labor used is the sum of family and hired labor
  c_LABHIR                hired labor on a field is not more than 10 times family labor
  c_OWNLAB                household labour availability per month
  c_OWNLABTOT             household labor availability per year
  c_LABOFF                restriction on possibility to work off-farm per month
  c_LABNON                restriction on possibility to work non-farm per month
  c_LABHIRING             limits on hiring labor
  c_LABHIRING2            hired labor availability per year
  b_LABMUSE               labour required for manure application

* sustainability
* We include sustainability indicators on nutrient balances, GHG emissions and biocide use.
  b_NLOSS                   nitrogen losses per land unit
  b_NGAS                    nitrogen gasseous losses per land unit
  b_NLEACH                  nitrogen leaching losses per land unit
  b_BIOINDEX                balance of biocide use
  b_GHGFERTN                GHG emissions per land unit and fert (N-N2O equivalents)
  b_GHGFUEL                 GHG emissions from fuel use (CO2 eq)
  b_GHG                     Total GHG emissions from fertiliser N and fuel (CO2 eq)
  c_GHG                     GHG emission constraint

* output market constraints
* The market for some crops, e.g. vegetables, is limited. Farmers can only sell small amounts of these crops.
  c_MARKETLIM               market limits for crop production
;
* ____________________________________________________________
*      equation definitions
*      These are the actual model equations.
*      For explanations see above
* ____________________________________________________________
b_INCOME..
  vINCOME =E= SUM(crop, P_SELL(crop)*vPRODUCT(crop)*PRICE_FACTOR(crop))
```

```
      - SUM((lutr,month), vREPAY(lutr,month)+vREPAYOWN(lutr,month))
      + vWAGES + REMIT;

b_WAGE..
  vWAGES =E= SUM(month,vMWAGES(month));

b_monthWAGE(month)..
  vMWAGES(month) =E= WAGE_OFF(month)*vLABOFF(month)
                 + WAGE_NON(month)*vLABNON(month);

b_VINCOME..
  vVINCOME =E= SUM(v, P_SELL(v)*vPRODUCT(v)*PRICE_FACTOR(v))
      - SUM((veg,month), vREPAY(veg,month)+vREPAYOWN(veg,month));

* minimum grain
c_MINGRAIN..
  SUM(r,vPRODUCT(r)) =G= GRAIN_MIN*FSIZE;

* crop production
b_PROD(crop) ..
  vPRODUCT(crop) =E= SUM((lu,lutr,t), YIELD(lu,lutr,t,crop) * vLAND(lu,lutr,t));

* land use
c_LAND(lu) ..
  SUM((lutr,t), vLAND(lu,lutr,t)) =L= LU_MAX(lu);

* nonlabour inputs
b_COST(lutr,month) ..
  vINPUTS(lutr,month) =E= SUM((lu,t,season),PLANTING(lutr,season,month)*
  (COST(lu,lutr,t,season)+ BIOCOST(lu,lutr,t,season))* vLAND(lu,lutr,t))
           + SUM((season),PLANTING(lutr,season,month)*
            SUM((t,fert), P_FERT(fert) * vFERTUSE(lutr,t,season,fert)));

b_FERTUSE(lutr,season,t,nutrient)..
  SUM(fert,vFERTUSE(lutr,t,season,fert) * NUTCONTENT(fert,nutrient)) =G=
  SUM((lu),FERTUSE(lu,lutr,t,season,nutrient)*vLAND(lu,lutr,t));

*CAPITAL RELATED EQUATIONS
* working capital balance
b_LIQUIDITY(lutr,month) ..
  vINPUTS(lutr,month) + WAGE_HIR(month) * vLABHIR(lutr,month) =E=
     vSCREDIT(lutr,month) + vOWN(lutr,month);

*CREDIT MARKET
b_DEBT1(lutr,month)..
  vDEBT(lutr,"JAN") =E= 0;

b_DEBT2(lutr,month+1)..
  vDEBT(lutr,month+1) =E= vDEBT(lutr,month)*(1+interest)-vREPAY(lutr,month)
                  + vSCREDIT(lutr,month);
* debt is previous period debt minus previous period repayment plus credit
b_REPAY(lutr,month)..
  vREPAY(lutr,month)=E= HARVEST(lutr,month)*(vDEBT(lutr,month)+vSCREDIT(lutr,month))
```

```
                    *(1+interest);
* Repayment takes place at the end of the harvesting month.

*credit constraint
c_DEBT(month)..
  SUM((lutr),vDEBT(lutr,month)) =L= SCRED_MAX ;
*Total outstanding debt (including interest due) cannot be higher than a maximum

*OWN CAPITAL
* 3 equations to compute available working capital
b_OWN1(month)..
  vCAPITAL("JAN")=E= CAPITAL;
*initial capital is given
b_OWN2(month+1)..
  vCAPITAL(month+1) =E= vCAPITAL(month)
                  + SUM((lutr), vREPAYOWN(lutr,month))
                  - SUM((lutr),vOWN(lutr,month));
*available working capital equals previous working capital plus "repayment" minus use
* "debt to own capital is computed to be able to compute "repayment"
b_OWNDEBT1(lutr,month)..
  vOWNDEBT(lutr,"JAN") =E= 0;
*initial use of working capital is 0.
b_OWNDEBT2(lutr,month+1)..
  vOWNDEBT(lutr,month+1) =E= vOWNDEBT(lutr,month)
                          + vOWN(lutr,month)
                          - vREPAYOWN(lutr,month);
*working capital used is working capital used in the previous decad plus new
*working capital used minus "repayment"

*repayment of working capital
b_REPAYOWN(lutr,month)..
  vREPAYOWN(lutr,month) =E= HARVEST(lutr,month)
                            *(vOWNDEBT(lutr,month)+ vOWN(lutr,month)) ;
* at harvesting, the household repays "debt to own working capital"
* i.e. working capital used in this crop becomes available again

* constraint on the use of own working capital
c_OWN(month)..
  SUM((lutr),vOWN(lutr,month)) =L= vCAPITAL(month);
*the household cannot use more own capital than it has

* labour allocation
b_LABFARM(lutr,month) ..
  SUM((lu,t), LABUSE(lu,lutr,t,month) * vLAND(lu,lutr,t))  + vMLABUSE(lutr,month) =E=
       vLABOWN(lutr,month) +  vLABHIR(lutr,month) ;

* labour requirement for manure application. This labour adds to OWNLAB.
b_LABMUSE(lutr,month)..
  vMLABUSE(lutr, month)=E=  MANLAB * SUM((season),PLANTING(lutr,season,month) *
                   SUM((t),vFERTUSE(lutr,t,season,"manure")) /1000);

c_LABHIR(lutr,month)..
  vLABHIR(lutr,month)=L= 1 * (vLABOWN(lutr,month)+vMLABUSE(lutr,month));
```

```
*c_OWNLAB(month) ..
*   SUM((lutr),vLABOWN(lutr,month)) + vLABOFF(month)+vLABNON(month)=L=
*                                                  LAB_MAX * DAYS_MAX;

c_OWNLAB(month) ..
   SUM((lutr),vLABOWN(lutr,month)) + SUM((lutr),vMLABUSE(lutr,month)) + vLABOFF(month)+vLABNON(month)=L=
                                                  LAB_MAX * DAYS_MAX;

c_OWNLABTOT ..
   SUM((lutr,month),vLABOWN(lutr,month))+ SUM((lutr,month), vMLABUSE(lutr,month))
   + SUM(month,vLABOFF(month)+vLABNON(month))=L= LAB_MAX * DAYSTOT_MAX;

c_LABHIRING(month) ..
  SUM((lutr), vLABHIR(lutr,month)) =L= HIR_MAX(month);

c_LABHIRING2 ..
  SUM((lutr,month), vLABHIR(lutr,month)) =L= HIR_MAXTOT;

c_LABOFF(month) ..
   vLABOFF(month) =L= OFF_MAX(month);

c_LABNON(month) ..
  vLABNON(month) =L= NON_MAX(month);

* sustainability
b_NLOSS(lu)..
  vNLOSS(lu) =e= SUM((lutr,t,season,n_loss),nloss(lu,lutr,t,season,n_loss)*
                                            vLAND(lu,lutr,t));
b_NGAS(lu)..
  vNGAS(lu) =e= SUM((lutr,t,season),nloss(lu,lutr,t,season,"ngas")*
                                            vLAND(lu,lutr,t));
b_NLEACH(lu)..
  vNLEACH(lu) =e= SUM((lutr,t,season),nloss(lu,lutr,t,season,"nleach")*
                                            vLAND(lu,lutr,t));
b_BIOINDEX ..
  vBIOINDEX =E= SUM((lu,lutr,t), BIOINDEX(lu,lutr,t) * vLAND(lu,lutr,t)) ;

b_GHGFERTN(fert)..
  vGHGFERTN(fert)=E= SUM((lutr,t,season), (0.0125 * NUTCONTENT(fert,"N")* vFERTUSE(lutr,t,season,fert)));

b_GHGFUEL(lutr)..
  vGHGFUEL(lutr)=E=SUM((lu,t), (2.98 * FUEL(lu,lutr, t))*vLAND(lu,lutr,t));

b_GHG..
  vGHG=E=SUM((lutr), vGHGFUEL(lutr)) + SUM((fert), vGHGFERTN(fert)* 44/28 * 296) ;

c_GHG..
  vGHG=L=  30000;

* output market constraints, defined in crvhhdata.prn; this constraint is not used;
* Sales are set at +INF in the file crvhhdata.prn
c_MARKETLIM(crop) ..
  vPRODUCT(crop) =L= MAXSALES(crop);
```

```
* ______________________________________________________________
* import data
* ______________________________________________________________
* These *.prn refer to technoGIN output files used as input files for this model
$include Biocost.prn
$include Bioindex.prn
$include Cost.prn
$include Fertuse.prn
$include Labuse.prn
$include Nloss.prn
$include Yield.prn
$include Fuel.prn

*Other files with HH information, prices, etc.
$include CRVhhdata.prn
$include CRVprices.prn
$include CRVtiming.prn
$include CRVrest.prn
$include CRVsetrunsbasic.txt

* ___________________________________________________________
* model statements
* ___________________________________________________________

MODEL CRV /ALL/;

$include CRVothermodels.txt

* ________________________________________________________________
* solve statements
* ________________________________________________________________
*initiate the output files.
file outcap /outcap.csv/; outcap.pc=5; outcap.nd=0; outcap.ap=1;
file outsum /outsum.csv/; outsum.pc=5; outsum.nd=0; outsum.ap=1;
file outlab /outlab.csv/; outlab.pc=5; outlab.nd=0; outlab.ap=1;
file outcrop /outcrop.csv/; outcrop.pc=5; outcrop.nd=2; outcrop.ap=1;
file outsus /outsus.csv/; outsus.pc=5; outsus.nd=2; outsus.ap=1;
file outGHG /outGHG.csv/; outGHG.pc=5; outGHG.nd=2; outGHG.ap=1;

* parameters to store output data
PARAMETERS
v_BIOINDEX(cs)
v_CAPITAL(cs,month)
v_DEBT(cs,month)
v_FERTUSE(cs,lutr,t, fert)
v_INCOME(cs)
v_INPUTS(cs,month)
v_INPUTS2(cs,lutr,month)
v_LABHIR(cs,month)
v_LABNON(cs,month)
v_LABOFF(cs,month)
v_LABOWN(cs,month)
```

```
v_LAND(cs,lu,lutr,t)
v_TOTLAND(cs)
v_MWAGES(cs,month)
v_NLOSS(cs,lu,lutr,t)
v_NLOSSTOT(cs)
v_NGAS(cs,lu,lutr,t)
v_NGASTOT(cs)
v_NLEACH(cs,lu,lutr,t)
v_NLEACHTOT(cs)
v_OWN(cs,month)
v_OWNDEBT(cs,month)
v_PRODUCT(cs,crop)
v_REPAY(cs,month)
v_REPAYOWN(cs,month)
v_GHG(cs)
v_SCREDIT(cs,month)
v_SUNIT(cs,lu,lutr,t)
v_WAGES(cs)
v_COST(cs)
v_SCOST(cs)
m_LAND(cs,lu)
m_DEBT(cs,month)
m_LABNON(cs,month)
m_LABOFF(cs,month)
m_OWNLAB(cs,month)
m_LABHIRING(cs,month)
m_marketlim(cs,crop)
constrained(cs,month)
v_CAPITALM(cs)
v_HIRMAX(cs)
v_VINCOME(cs)
v_NUTUSE1(cs,lutr,t)
v_NUTUSE2(cs,lutr, t)
v_NUTUSE3(cs,lutr, t)
v_NUTUSE4(cs,lutr,t)
v_GHGFERTN(cs,lutr,t, fert)
v_YIELD(cs,lu,lutr, t)
;

* the loop assures that the model is run for each farm type. Not used in CRV.
loop(h,
* household-specific data is read and assigned to the relevant variables
  CAPITAL = dCAPITAL(h);
  FSIZE = dFSIZE(h);
  INTEREST = dINTEREST(h);
  LAB_MAX = dLAB_MAX(h);
  LU_MAX(lu) = dLU_MAX(h,lu);
  OFF_MAX(month) = dOFF_MAX(h,month);
  MAXSALES(crop) = dMAXSALES(h,crop);
  NON_MAX(month) = dNON_MAX(h,month);
  REMIT = dREMIT(h);
  SCRED_MAX = dSCRED_MAX(h);
```

```
*the loop assures that the model runs for different crop scenarios
loop(cs,
  PRICE_FACTOR(crop) = DPRICE_FACTOR(crop,cs);

* the model is solved.
SOLVE CRV USING LP MAXIMIZING vINCOME;

* write relevant data to the output parameters
v_BIOINDEX(cs)              = vBIOINDEX.l;
v_CAPITAL(cs,month)         = vCAPITAL.l(month);
v_DEBT(cs,month)            = SUM((lutr),vDEBT.l(lutr,month));
v_OWN(cs, month)            = SUM((lutr),vOWN.l(lutr,month));
v_OWNDEBT(cs, month)        = SUM((lutr),vOWNDEBT.l(lutr,month));
v_REPAY(cs,month)           = SUM((lutr),vREPAY.l(lutr,month));
v_REPAYOWN(cs,month)        = SUM((lutr),vREPAYOWN.l(lutr,month));
v_SCREDIT(cs,month)         = SUM((lutr),vSCREDIT.l(lutr,month));
m_DEBT(cs,month)            = c_DEBT.m(month);
v_FERTUSE(cs,lutr,t, fert)  = SUM((season), vFERTUSE.l(lutr,t,season,fert));
v_GHGFERTN(cs,lutr,t,fert)  = sum((season), (vFERTUSE.l(lutr,t,season, fert)*NUTCONTENT(fert,"N")*0.0125 )) ;
v_GHG(cs)                   = vGHG.l;
v_COST(cs)                  = SUM((lutr,month), vINPUTS.l(lutr,month) + WAGE_HIR(month) *vLABHIR.l(lutr,month));
v_INCOME(cs)                = vINCOME.l;
v_VINCOME(cs)               = vVINCOME.l;
v_INPUTS(cs,month)          = SUM((lutr),vINPUTS.l(lutr,month));
v_INPUTS2(cs,lutr,month)    = vINPUTS.l(lutr,month);
v_LABHIR(cs,month)          = SUM((lutr),vLABHIR.l(lutr,month));
v_LABNON(cs,month           = vLABNON.l(month);
v_LABOFF(cs,month           = vLABOFF.l(month);
v_LABOWN(cs,month)          = SUM((lutr),vLABOWN.l(lutr,month))+ SUM((lutr),vMLABUSE.l(lutr,month));
v_LAND(cs,lu,lutr,t)        = vLAND.l(lu,lutr,t);
v_TOTLAND(cs)               = SUM((lu,lutr,t),vLAND.l(lu,lutr,t));
v_MWAGES(cs,month)          = vMWAGES.l(month);
v_NLOSS(cs,lu,lutr,t)       = SUM((season),nloss(lu,lutr,t,season,"ngas")) + SUM((season),nloss(lu,lutr,t,season,"nleach"));
v_NLOSSTOT(cs)              = SUM(lu,vNLOSS.l(lu));
v_NGAS(cs,lu,lutr,t)        = SUM((season),nloss(lu,lutr,t,season,"ngas"));
v_NGASTOT(cs)               = SUM(lu,vNGAS.l(lu));
v_NLEACH(cs,lu,lutr,t)      = SUM((season),nloss(lu,lutr,t,season,"nleach"));
v_NLEACHTOT(cs)             = SUM(lu,vNLEACH.l(lu));
v_PRODUCT(cs,crop)          = vPRODUCT.l(crop);
v_SUNIT(cs,lu,lutr,t)       = vLAND.l(lu,lutr,t);
v_WAGES(cs)                 = vWAGES.l;
m_LAND(cs,lu)               = c_LAND.m(lu);
m_LABNON(cs,month)          = c_LABNON.m(month);
m_LABOFF(cs,month)          = c_LABOFF.m(month);
m_OWNLAB(cs,month)          = c_OWNLAB.m(month);
m_LABHIRING(cs,month)       = c_LABHIRING.m(month);
m_MARKETLIM(cs,crop)        = c_marketlim.m(crop);
v_CAPITALM(cs)              = MAX((SUM(lutr,vDEBT.l(lutr,"JAN")+vOWNDEBT.l(lutr,"JAN"))),
          (SUM(lutr,vDEBT.l(lutr,"FEB")+vOWNDEBT.l(lutr,"FEB"))),
          (SUM(lutr,vDEBT.l(lutr,"MAR")+vOWNDEBT.l(lutr,"MAR"))),
          (SUM(lutr,vDEBT.l(lutr,"APR")+vOWNDEBT.l(lutr,"APR"))),
          (SUM(lutr,vDEBT.l(lutr,"MAY")+vOWNDEBT.l(lutr,"MAY"))),
          (SUM(lutr,vDEBT.l(lutr,"JUN")+vOWNDEBT.l(lutr,"JUN"))),
```

```
            (SUM(lutr,vDEBT.l(lutr,"JUL")+vOWNDEBT.l(lutr,"JUL"))),
            (SUM(lutr,vDEBT.l(lutr,"AUG")+vOWNDEBT.l(lutr,"AUG"))),
            (SUM(lutr,vDEBT.l(lutr,"SEP")+vOWNDEBT.l(lutr,"SEP"))),
            (SUM(lutr,vDEBT.l(lutr,"OCT")+vOWNDEBT.l(lutr,"OCT"))),
            (SUM(lutr,vDEBT.l(lutr,"NOV")+vOWNDEBT.l(lutr,"NOV"))),
            (SUM(lutr,vDEBT.l(lutr,"DEC")+vOWNDEBT.l(lutr,"DEC"))));
v_HIRMAX(cs)                    = MAX(SUM(lutr,vLABHIR.l(lutr,"JAN")),
     SUM(lutr,vLABHIR.l(lutr,"FEB")),SUM(lutr,vLABHIR.l(lutr,"MAR")),
     SUM(lutr,vLABHIR.l(lutr,"APR")),SUM(lutr,vLABHIR.l(lutr,"MAY")),
     SUM(lutr,vLABHIR.l(lutr,"JUN")),SUM(lutr,vLABHIR.l(lutr,"JUL")),
     SUM(lutr,vLABHIR.l(lutr,"AUG")),SUM(lutr,vLABHIR.l(lutr,"SEP")),
     SUM(lutr,vLABHIR.l(lutr,"OCT")),SUM(lutr,vLABHIR.l(lutr,"NOV")),
     SUM(lutr,vLABHIR.l(lutr,"DEC")));
v_NUTUSE1(cs,lutr, t)       = SUM((season), vFERTUSE.l(lutr,t, season, "urea"));
v_NUTUSE2(cs,lutr, t)       = SUM((season), vFERTUSE.l(lutr,t, season, "DAP"));
v_NUTUSE3(cs,lutr, t)       = SUM((season), vFERTUSE.l(lutr,t, season, "KNO3"));
v_NUTUSE4(cs,lutr, t)       = SUM((season), vFERTUSE.l(lutr,t, season, "manure"));
v_YIELD(cs,lu,lutr,t)       = SUM(crop, YIELD(lu,lutr,t,crop));
 );

*______________________________________________________________
* write output
*______________________________________________________
*write output to ASCII files
$include putfiles.txt
);
```

Appendix II.
Input output files for farm household model

This Appendix contains the files with input and output coefficients of cropping systems generated with TechnoGIN and used as input files in the farm household model.

File: Fertuse.prn
TABLE FERTUSE(lu,lut,tech,season,nutrient)
* nutrient use per season per ha)
* Calculated with long-term nutrient supply from soil stock
* K use set to zero as availability of K fertiliser sources limits choices in LP model

	N	P	K
RFMD.LHAR.TAC.S1	18	18	0
RFMD.LHAR.TAC.S2	0	0	0
RFMD.LHAR.TAC.S3	0	0	0
RFMD.LHAR.TBF.S1	31	1.8	0
RFMD.LHAR.TBF.S2	0	0	0
RFMD.LHAR.TBF.S3	0	0	0
RFMD.LHAR.TCF.S1	35.5	2.1	0
RFMD.LHAR.TCF.S2	0	0	0
RFMD.LHAR.TCF.S3	0	0	0
RFMD.LMAI.TAC.S1	34	10	0
RFMD.LMAI.TAC.S2	0	0	0
RFMD.LMAI.TAC.S3	0	0	0
RFMD.LMAI.TBF.S1	79.8	18.3	0
RFMD.LMAI.TBF.S2	0	0	0
RFMD.LMAI.TBF.S3	0	0	0
RFMD.LMAI.TCF.S1	89.2	20.4	0
RFMD.LMAI.TCF.S2	0	0	0
RFMD.LMAI.TCF.S3	0	0	0
RFMD.LTEF.TAC.S1	34	10	0
RFMD.LTEF.TAC.S2	0	0	0
RFMD.LTEF.TAC.S3	0	0	0
RFMD.LTEF.TBF.S1	32.7	0	0
RFMD.LTEF.TBF.S2	0	0	0
RFMD.LTEF.TBF.S3	0	0	0
RFMD.LTEF.TCF.S1	148.4	0	0
RFMD.LTEF.TCF.S2	0	0	0
RFMD.LTEF.TCF.S3	0	0	0
RFMD.LPEP.TAC.S1	34	10	0
RFMD.LPEP.TAC.S2	0	0	0
RFMD.LPEP.TAC.S3	0	0	0
RFMD.LPEP.TBF.S1	205.3	26.1	0
RFMD.LPEP.TBF.S2	0	0	0
RFMD.LPEP.TBF.S3	0	0	0
RFMD.LPEP.TCF.S1	247	31.2	0
RFMD.LPEP.TCF.S2	0	0	0
RFMD.LPEP.TCF.S3	0	0	0
RFMD.LWHT.TAC.S1	34	10	0
RFMD.LWHT.TAC.S2	0	0	0

RFMD.LWHT.TAC.S3	0	0	0
RFMD.LWHT.TBF.S1	139.8	24.3	0
RFMD.LWHT.TBF.S2	0	0	0
RFMD.LWHT.TBF.S3	0	0	0
RFMD.LWHT.TCF.S1	156	27.2	0
RFMD.LWHT.TCF.S2	0	0	0
RFMD.LWHT.TCF.S3	0	0	0
RFMD.LBAR.TAC.S1	34	10	0
RFMD.LBAR.TAC.S2	0	0	0
RFMD.LBAR.TAC.S3	0	0	0
RFMD.LBAR.TBF.S1	147.2	18.8	0
RFMD.LBAR.TBF.S2	0	0	0
RFMD.LBAR.TBF.S3	0	0	0
RFMD.LBAR.TCF.S1	164.4	21.1	0
RFMD.LBAR.TCF.S2	0	0	0
RFMD.LBAR.TCF.S3	0	0	0
RFMD.LSOR.TAC.S1	0	0	0
RFMD.LSOR.TAC.S2	0	0	0
RFMD.LSOR.TAC.S3	0	0	0
RFMD.LSOR.TBF.S1	90.6	12.9	0
RFMD.LSOR.TBF.S2	0	0	0
RFMD.LSOR.TBF.S3	0	0	0
RFMD.LSOR.TCF.S1	101.5	14.6	0
RFMD.LSOR.TCF.S2	0	0	0
RFMD.LSOR.TCF.S3	0	0	0

;

File: Nloss.prn
TABLE NLOSS(lu,lut,tech,season,n_loss)
* Nitrogen losses (kg per ha)
* Calculated with long term nutrient supply from soil stock

	NLEACH	NGAS
RFMD.LHAR.TAC.S1	14.3	6.3
RFMD.LHAR.TAC.S2	1.9	0.8
RFMD.LHAR.TAC.S3	0	0
RFMD.LHAR.TBF.S1	11.1	4.9
RFMD.LHAR.TBF.S2	1.9	0.8
RFMD.LHAR.TBF.S3	0	0
RFMD.LHAR.TCF.S1	14.2	6.3
RFMD.LHAR.TCF.S2	1.9	0.8
RFMD.LHAR.TCF.S3	0	0
RFMD.LMAI.TAC.S1	17.9	8.4
RFMD.LMAI.TAC.S2	1.8	0.8
RFMD.LMAI.TAC.S3	0	0
RFMD.LMAI.TBF.S1	23.4	10.9
RFMD.LMAI.TBF.S2	1.8	0.8
RFMD.LMAI.TBF.S3	0	0
RFMD.LMAI.TCF.S1	29.8	13.9
RFMD.LMAI.TCF.S2	1.8	0.8
RFMD.LMAI.TCF.S3	0	0
RFMD.LTEF.TAC.S1	7.6	3.4
RFMD.LTEF.TAC.S2	1.9	0.8
RFMD.LTEF.TAC.S3	0	0

RFMD.LTEF.TBF.S1	39.5	17.5
RFMD.LTEF.TBF.S2	1.9	0.8
RFMD.LTEF.TBF.S3	0	0
RFMD.LTEF.TCF.S1	50.4	22.3
RFMD.LTEF.TCF.S2	1.9	0.8
RFMD.LTEF.TCF.S3	0	0
RFMD.LPEP.TAC.S1	26.3	12
RFMD.LPEP.TAC.S2	1.7	0.7
RFMD.LPEP.TAC.S3	0	0
RFMD.LPEP.TBF.S1	109.3	49.9
RFMD.LPEP.TBF.S2	1.7	0.7
RFMD.LPEP.TBF.S3	0	0
RFMD.LPEP.TCF.S1	137.9	63
RFMD.LPEP.TCF.S2	1.7	0.7
RFMD.LPEP.TCF.S3	0	0
RFMD.LWHT.TAC.S1	6.3	2.9
RFMD.LWHT.TAC.S2	1.7	0.7
RFMD.LWHT.TAC.S3	0	0
RFMD.LWHT.TBF.S1	41.3	19.2
RFMD.LWHT.TBF.S2	1.7	0.7
RFMD.LWHT.TBF.S3	0	0
RFMD.LWHT.TCF.S1	52.3	24.3
RFMD.LWHT.TCF.S2	1.7	0.7
RFMD.LWHT.TCF.S3	0	0
RFMD.LBAR.TAC.S1	6.3	2.9
RFMD.LBAR.TAC.S2	1.8	0.8
RFMD.LBAR.TAC.S3	0	0
RFMD.LBAR.TBF.S1	44	20.1
RFMD.LBAR.TBF.S2	1.8	0.8
RFMD.LBAR.TBF.S3	0	0
RFMD.LBAR.TCF.S1	55.7	25.4
RFMD.LBAR.TCF.S2	1.8	0.8
RFMD.LBAR.TCF.S3	0	0
RFMD.LSOR.TAC.S1	0	0
RFMD.LSOR.TAC.S2	1.8	0.8
RFMD.LSOR.TAC.S3	0	0
RFMD.LSOR.TBF.S1	27.3	12.7
RFMD.LSOR.TBF.S2	1.8	0.8
RFMD.LSOR.TBF.S3	0	0
RFMD.LSOR.TCF.S1	34.8	16.2
RFMD.LSOR.TCF.S2	1.8	0.8
RFMD.LSOR.TCF.S3	0	0

;

File: Labuse.prn
TABLE LABUSE(lu,lut,tech,month)
* Labour use of each LUST in each month (labour-days per ha)

	Jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
RFMD.LHAR.TAC	0	0	0	0	0	5.3	18.7	16	1.4	0	0	0
RFMD.LHAR.TBF	0	0	0	0	0	5.3	18.7	16	2.8	0	0	0
RFMD.LHAR.TCF	0	0	0	0	0	0.5	1.9	16	2.8	0	0	0
RFMD.LMAI.TAC	0	0	0	5.3	26.7	14.8	14.8	14.4	0	0	0	0
RFMD.LMAI.TBF	0	0	0	5.3	26.7	14.8	14.8	28.8	0	0	0	0

RFMD.LMAI.TCF	0	0	0	0.5	2.7	14.8	14.8	28.8	0	0	0	0
RFMD.LTEF.TAC	0	0	0	0	0	8	15	12	12.5	0	0	0
RFMD.LTEF.TBF	0	0	0	0	0	8	15	12	25	0	0	0
RFMD.LTEF.TCF	0	0	0	0	0	0.8	5.1	12	25	0	0	0
RFMD.LPEP.TAC	0	0	0	0	4	53	6	6	30	0	0	0
RFMD.LPEP.TBF	0	0	0	0	4	53	6	6	60	0	0	0
RFMD.LPEP.TCF	0	0	0	0	0.4	5.3	6	6	60	0	0	0
RFMD.LWHT.TAC	0	0	0	0	4	13	5.6	5.6	21.2	0	0	0
RFMD.LWHT.TBF	0	0	0	0	4	13	5.6	5.6	40.6	0	0	0
RFMD.LWHT.TCF	0	0	0	0	0.4	1.3	5.6	5.6	40.6	0	0	0
RFMD.LBAR.TAC	0	0	0	0	4	13	6.5	6.5	15.5	0	0	0
RFMD.LBAR.TBF	0	0	0	0	4	13	6.5	6.5	31	0	0	0
RFMD.LBAR.TCF	0	0	0	0	0.4	1.3	6.5	6.5	31	0	0	0
RFMD.LSOR.TAC	0	0	0	2	9	11.1	11.1	5.2	0	0	0	0
RFMD.LSOR.TBF	0	0	0	2	9	11.1	11.1	10.4	0	0	0	0
RFMD.LSOR.TCF	0	0	0	0.2	0.9	11.1	11.1	10.4	0	0	0	0

;

File: Fuel.prn

PARAMETER FUEL(lu,lut,tech)

* fuel use of each LUST per year (l per ha)

/

RFMD.LHAR.TAC	0
RFMD.LHAR.TBF	0
RFMD.LHAR.TCF	45
RFMD.LMAI.TAC	0
RFMD.LMAI.TBF	0
RFMD.LMAI.TCF	45
RFMD.LTEF.TAC	0
RFMD.LTEF.TBF	0
RFMD.LTEF.TCF	60
RFMD.LPEP.TAC	0
RFMD.LPEP.TBF	0
RFMD.LPEP.TCF	30
RFMD.LWHT.TAC	0
RFMD.LWHT.TBF	0
RFMD.LWHT.TCF	52.5
RFMD.LBAR.TAC	0
RFMD.LBAR.TBF	0
RFMD.LBAR.TCF	52.5
RFMD.LSOR.TAC	0
RFMD.LSOR.TBF	0
RFMD.LSOR.TCF	52.5

/ ;

File: cost.prn

TABLE COST(lu,lut,tech,season)

* nonlabour (seed + machine + animal + irrigation + fuel) costs of each LUST per growing season (Birr per ha)

	S1	S2	S3
RFMD.LHAR.TAC	700.00	0.00	0.00
RFMD.LHAR.TBF	700.00	0.00	0.00
RFMD.LHAR.TCF	2110.00	0.00	0.00
RFMD.LMAI.TAC	652.00	0.00	0.00

RFMD.LMAI.TBF	652.00	0.00	0.00
RFMD.LMAI.TCF	1962.00	0.00	0.00
RFMD.LTEF.TAC	706.00	0.00	0.00
RFMD.LTEF.TBF	706.00	0.00	0.00
RFMD.LTEF.TCF	2516.00	0.00	0.00
RFMD.LPEP.TAC	1452.00	0.00	0.00
RFMD.LPEP.TBF	1452.00	0.00	0.00
RFMD.LPEP.TCF	2162.00	0.00	0.00
RFMD.LWHT.TAC	1225.00	0.00	0.00
RFMD.LWHT.TBF	1225.00	0.00	0.00
RFMD.LWHT.TCF	2785.00	0.00	0.00
RFMD.LBAR.TAC	1060.00	0.00	0.00
RFMD.LBAR.TBF	1060.00	0.00	0.00
RFMD.LBAR.TCF	2620.00	0.00	0.00
RFMD.LSOR.TAC	354.40	0.00	0.00
RFMD.LSOR.TBF	354.40	0.00	0.00
RFMD.LSOR.TCF	2014.40	0.00	0.00

;

File: yield.prn
TABLE YIELD (lu,lut,tech,crop)
* yield per product (kg per ha)

	HAR	MAI	TEF	PEP	WHT	BAR	SOR
RFMD.LHAR.TAC	700	0	0	0	0	0	0
RFMD.LHAR.TBF	1400	0	0	0	0	0	0
RFMD.LHAR.TCF	1400	0	0	0	0	0	0
RFMD.LMAI.TAC	0	2000	0	0	0	0	0
RFMD.LMAI.TBF	0	4000	0	0	0	0	0
RFMD.LMAI.TCF	0	4000	0	0	0	0	0
RFMD.LTEF.TAC	0	0	1000	0	0	0	0
RFMD.LTEF.TBF	0	0	2000	0	0	0	0
RFMD.LTEF.TCF	0	0	2000	0	0	0	0
RFMD.LPEP.TAC	0	0	0	6000	0	0	0
RFMD.LPEP.TBF	0	0	0	12000	0	0	0
RFMD.LPEP.TCF	0	0	0	12000	0	0	0
RFMD.LWHT.TAC	0	0	0	0	2500	0	0
RFMD.LWHT.TBF	0	0	0	0	5000	0	0
RFMD.LWHT.TCF	0	0	0	0	5000	0	0
RFMD.LBAR.TAC	0	0	0	0	0	2000	0
RFMD.LBAR.TBF	0	0	0	0	0	4000	0
RFMD.LBAR.TCF	0	0	0	0	0	4000	0
RFMD.LSOR.TAC	0	0	0	0	0	0	1200
RFMD.LSOR.TBF	0	0	0	0	0	0	2400
RFMD.LSOR.TCF	0	0	0	0	0	0	2400

;

File: Bioindex.prn
TABLE BIOINDEX(lu,lut,tech)
* Biocide index value per technology

	TAC	TBF	TCF
RFMD.LHAR	0	1.8	1.8
RFMD.LMAI	0	0.6	0.6
RFMD.LTEF	0	0	0

RFMD.LPEP	0	0	0
RFMD.LWHT	0	0	0
RFMD.LBAR	0	0	0
RFMD.LSOR	0	0.5	0.5

;

File: Biocost.prn

TABLE BIOCOST(lu,lut,tech,season)

* biocide costs of each LUST per growing season (Birr per ha)

	S1	S2	S3
RFMD.LHAR.TAC	0.00	0.00	0.00
RFMD.LHAR.TBF	164.50	0.00	0.00
RFMD.LHAR.TCF	164.50	0.00	0.00
RFMD.LMAI.TAC	0.00	0.00	0.00
RFMD.LMAI.TBF	52.64	0.00	0.00
RFMD.LMAI.TCF	52.64	0.00	0.00
RFMD.LTEF.TAC	0.00	0.00	0.00
RFMD.LTEF.TBF	0.00	0.00	0.00
RFMD.LTEF.TCF	0.00	0.00	0.00
RFMD.LPEP.TAC	0.00	0.00	0.00
RFMD.LPEP.TBF	0.00	0.00	0.00
RFMD.LPEP.TCF	0.00	0.00	0.00
RFMD.LWHT.TAC	0.00	0.00	0.00
RFMD.LWHT.TBF	0.00	0.00	0.00
RFMD.LWHT.TCF	0.00	0.00	0.00
RFMD.LBAR.TAC	0.00	0.00	0.00
RFMD.LBAR.TBF	0.00	0.00	0.00
RFMD.LBAR.TCF	0.00	0.00	0.00
RFMD.LSOR.TAC	0.00	0.00	0.00
RFMD.LSOR.TBF	45.12	0.00	0.00
RFMD.LSOR.TCF	45.12	0.00	0.00