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Modelling the impact of El Niño-related drought on smallholder farmers in Central Sulawesi, Indonesia: An interdisciplinary approach combining climatic and hydrologic modelling with regression analysis and linear programming

Keil[a], Alwin, Nils Teufel[b], Dodo Gunawan[c] and Constanze Leemhuis[d]

a Institute of Agricultural Economics and Social Sciences in the Tropics and Subtropics, University of Hohenheim, Stuttgart, Germany
b International Livestock Research Institute (ILRI), Delhi, India
c Research and Development Center, Meteorological and Geophysical Agency (BMG), Jakarta, Indonesia
d Center for Development Research (ZEF), Bonn, Germany

Abstract

Crop production in the tropics is subject to considerable climate variability caused by the El Niño-Southern Oscillation (ENSO) phenomenon. In Southeast Asia, El Niño causes comparatively dry conditions leading to substantial declines of crop yields with severe consequences for the welfare of local farm households. Using a modelling approach that combines regression analysis with linear programming and integrates climatic and hydrologic modelling results, the objective of this paper is to assess the impact of El Niño on agricultural incomes of smallholder farmers in Central Sulawesi, Indonesia, and to identify suitable crop management strategies to mitigate the income depressions. The results contribute to the formulation of enhanced development policies and provide guidance for future research activities. Based on resource endowment and location within the mountainous research area, we identify five classes of smallholder farms by cluster analysis. Our linear programming model maximizes their cash balance at the end of the six-month period most severely affected by El Niño. Main activities are the cultivation of rice, maize, and cocoa, for which external Cobb-Douglas production functions are estimated that include water supply as an input factor; they generate output according to level of production intensity as well as predicted weather patterns. The results illustrate that, even within a relatively small geographic area, advisable crop management strategies diverge between different types of farm households during El Niño events, depending on the micro-climatic and hydrologic characteristics of their location, the farming system, and resource endowment. Hence, related recommendations and policy measures need to be carefully tailored according to these factors if they are to be effective and economically efficient.

Keywords: El Niño, adaptation strategies, interdisciplinary modelling, linear programming, Indonesia

1. Introduction

Crop production in the tropics is subject to considerable climate variability that is mostly attributable to the El Niño - Southern Oscillation (ENSO) phenomenon (Salafsky 1994; Amien *et al.* 1996; Datt and Hoogeveen 2003). In Southeast Asia, El Niño is associated with comparatively dry conditions. In four El Niño years between 1973 and 1992, the average annual rainfall amounted to only around 67% of the 20-year average in two major rice growing areas in Java, Indonesia, causing a yield decline of approximately 50% (Amien *et al.* 1996). There is strong evidence that, in concert with global warming, the frequency and severity of extreme climatic events will increase during the 21st century, and the impacts of these changes will notably hit the poor (Easterling *et al.* 2007: 283-284).

Several macro-scale studies model the impact of climate variability and climate change on crop production in the Asia-Pacific region (see Zhao *et al.*, 2005, for a review). However, in order to evaluate specific climate variability impacts and corresponding optimal agricultural adaptation strategies, it is necessary to study the associated systems at the community and household levels. Against this background, the objective of this paper is (1) to quantify the impact of ENSO-related drought on crop yields and, hence, agricultural incomes in a rainforest margin area in Indonesia, and (2) to identify suitable crop management strategies for different climate scenarios using linear programming (LP).

2. Description of the research area

The research area encompasses the Palu River watershed in Central Sulawesi province, Indonesia. Its mountainous topography results in a distinct rainfall gradient, with the coastal zone receiving only around 500 mm of rain per annum, while precipitation exceeds 3,000 mm at higher elevations (WWF 1981). In our modelling approach, we therefore differentiate between the three sub-districts of Sigi Biromaru (50 – 90 m a.s.l.), Palolo (550 – 650 m a.s.l.), and Kulawi (560 – 980 m a.s.l.), which feature diverging climatic and hydrologic characteristics. Overall, irrigated rice and cocoa are the two dominant crops grown; while there are no clearly defined planting periods in the equatorial climate, the planting of rice peaks in January/February for a first and in June to August for a second rice crop. In general, the El Niño-related depression in rainfall largely coincides with the second cropping season.

3. Methodology

ENSO scenarios used in the simulation model

Based on existing time series data of rainfall in Central Sulawesi we calculate the monthly precipitation anomaly of ENSO years in percent relative to the long-term mean and generate two graded ENSO scenarios reflecting the mean anomaly of all observed ENSO events (1987, 1991, 1994, and 1997) on the one hand, and the extreme ENSO event of 1997 on the other. Applying interpolation techniques, rainfall deviations in the two scenarios are calculated for the research villages, whereby the non-ENSO year 2003[1] serves as a reference year for 'normal' meteorological conditions (Gunawan 2006).

In the case of irrigated rice water is not only supplied through rainfall, but, most importantly, through irrigation water. As a proxy of the amount of irrigation water available in a given village, the total discharge ($m^3 d^{-1}$) in the corresponding sub-catchment during the vegetation period is calculated based on ENSO scenario simulation results of the hydrological model WASIM-ETH; the total discharge is then divided by the total area of irrigated rice[2], resulting in the specific discharge (mm) available for irrigation in each research village (Leemhuis 2006). Table 1 summarizes rainfall and available irrigation water for the three sub-districts and the three considered scenarios.

Table 1. Rainfall and available irrigation water in Central Sulawesi during the period June 01 to Nov 30 for three climate scenarios, differentiated by sub-district

Climate scenario and sub-district	Rainfall [mm] (% of 'normal' in brackets)	Irrigation water [mm] (% of 'normal' in brackets)
‚Normal' year[a]:		
Sigi Biromaru	539 (100)	7,872 (100)
Palolo	1,379 (100)	2,904 (100)
Kulawi	1,134 (100)	6,110 (100)
Average El Niño scenario[b]:		
Sigi Biromaru	341 (63)	4,286 (54)
Palolo	675 (49)	847 (29)
Kulawi	790 (70)	4,568 (75)
Severe El Niño scenario[c]:		
Sigi Biromaru	248 (46)	3,751 (48)
Palolo	627 (45)	808 (28)
Kulawi	565 (50)	3,407 (56)

[a] ‚Normal' refers to the non-ENSO year 2003.
[b] Based on the mean of the El Niño years 1987, 1991, 1994, 1997.
[c] Based on the El Niño year 1997.

Modelling the impact of ENSO on crop yields

To quantify the impact of different climatic and crop management scenarios on the yields of the major crops in the area, irrigated rice, maize, and cocoa, Cobb-Douglas production functions of the following general form are estimated:

$$\ln Y_{it} = \beta_0 + \sum_{m=1}^{n} \beta_{0m} D_{mit} + \sum_{k=1}^{l} \beta_k \ln(X_{kit}) + \varepsilon_{it} \quad (1)$$

[1] Based on the Southern Oscillation Index. Source: BOM (2007) Australian Government Bureau of Meteorology. http://www.bom.gov.au/climate/current/soi2.shtml, accessed on 23.03.2007.
[2] The calculation of the irrigated rice area is based on the Landsat/ETM+ classification of the year 2002.

where

$\ln Y$ = Natural logarithm (ln) of the output

i = Household index (i = 1,…,N; N = 113, 97, and 34 for rice, cocoa, and maize, respectively)

t = Time index (t = 1,…,T_{max}; T_{max} = 4 [cropping seasons] for rice and maize, T_{max} = 2 [years] for cocoa)

β = Vector of parameters to be estimated

D_m = Vector of dummy variables

$\ln X_k$ = ln of the input vector, including climate-related variables

ε = N (0, σ_ε) distributed random error term

The dependent variables are the natural logarithms of the reported yields of husked rice, dried maize seeds, and dried cocoa seeds. Apart from variables measuring the input of land, labour, and capital, the production functions contain climatic and hydrologic variables as additional input factors, again as natural logarithms; squared terms allow the partial production elasticity of rainfall to be non-constant and output to decline at very high precipitation levels. Several dummy variables account for differences in important qualitative factors. The definition of all variables and regression results are provided in Table 3 (section 5).

Simulating cropping strategy decisions using linear programming

To include the effects of changing resource allocation into the analysis of the effects of climate variation at the household level, we construct an LP-model. Its aim is to simulate farmers' crop management decisions under reduced yield expectations due to predicted adverse weather patterns. An LP-model determines the levels of activity variables (such as cultivating different crops, buying inputs, or selling outputs) under a set of constraints (such as resource availability) in order to optimise the level of an objective variable (Hazell and Norton 1986). We assume that the objective driving farming decisions is the maximisation of farm income, but we account for competing household objectives, such as leisure and rice production for home consumption, through the formulation of respective constraints. Through the introduction of time-steps, seasonal effects are also considered. Rather than seeking to identify improved farm management strategies under the current conditions, the objective of the model is to reveal the consequences of changes in the production environment. The effects of climate variation are simulated based on the ENSO scenarios presented in Table 1. In these scenarios, yield expectations of the major crops are reduced according to the predicted rainfall patterns and the estimated production functions, thus altering the relative attractiveness of the major crops.

4. The household model applied, and data used

Model structure

The LP-model covers 12 half-monthly time-steps from June to November, the period during which ENSO-induced droughts are felt most acutely. In each of these balances are calculated for labour, cash and outputs. The model objective is to maximise the level of cash in the last period.

The determination of cropping patterns takes three types of crop land into account: Irrigated and non-irrigated land for annual crops as well as cocoa plantations. All three major crops can be grown at three levels of production intensity (average observed level of input use, 75% of observed level, 125% of observed level). There is no statistically significant evidence that the reduced supply of either rice or cocoa lead to an increase in farm gate prices mitigating the impact of reduced yields on agricultural income (Keil 2004: 77); hence, constant prices are assumed. Two crops more adapted to dry conditions, soybeans and groundnuts, are also included in the model to test their attractiveness under the defined ENSO scenarios. With water requirements of around 500 mm during the 4-6 month vegetation period (Rehm and Espig 1991: 95; 99), they are assumed to produce full yields also under El Niño conditions.

In the case of rice we correct for a limitation in the estimation of the production function (see section 5) by introducing a minimum water availability threshold as an additional production constraint to adequately account for its water requirements. According to the International Rice Research Institute, 10 mm of water per day are required to irrigate a rice crop, amounting to 1,000 mm for a crop that matures in 100 days; longer maturing varieties require proportionately more water (IRRI 2005). Thus, in our model, rice can only be grown if total water supply from rainfall and irrigation exceeds 1,000 mm during the cropping season.

Data used

Based on farmer recall, production data were collected in early 2005 in a stratified random sample of 228 farm households for the three most important crops, rice, maize, and cocoa, covering the years 2003 and 2004. The total number of observations is 408, 190, and 79 for rice, cocoa, and maize production, respectively. For the same time period measured rainfall data are derived from weather stations set up in each research village, and discharge data from hydrologic instruments installed in key locations of the watershed. Output levels and input requirements of the two alternative crops considered, soybeans and groundnuts, are based on secondary data from the local agricultural extension service.

Household classification

To capture differences in resource endowment and farming systems, the household-level data are classified into typical farm household classes through cluster analysis, which is performed separately on the 96 survey households from the low-lying sub-district of Sigi Biromaru and on the 132 survey households from the higher elevation areas of Palolo and Kulawi (cf. section 0). Clustering variables are related to resource endowment, cropping characteristics, and drought risk exposure. The classification results are presented in Table 2.

To focus on the differences in household reactions to climate variation, only the four most disparate household classes are considered in the subsequent analysis, which are classes d2 and d4 in the low-lying area and classes u1 and u5 in the upland area. To account for differences in climatic and hydrologic conditions between Palolo and Kulawi (cf. Table 1), class u1 is duplicated with one version (denoted u1) being linked to the production functions and climate scenarios defined for Palolo and the other (denoted u6) being linked to Kulawi.

Table 2. Results of the cluster analysis, indicating mean values of the clustering variables for nine household classes d1 to u5

	Lowland (d = down)				Upland (u = up)				
Cluster notation (N)	**d1** (16)	**d2** (37)	**d3** (23)	**d4** (15)	**u1** (19)	**u2** (27)	**u3** (25)	**u4** (20)	**u5** (34)
Drought impact index[1]	3.7	3.5	3.7	4.1	2.4	3.6	3.2	2.6	1.8
Cropped area [ares]	119.1	89.9	84.1	319.7	176.6	121.7	150.0	492.8	181.9
HH labour capacity (>=10 years of age) [AE]	3.5	2.7	2.9	3.9	5.0	2.3	3.3	4.2	3.3
Irrigated rice area per cropped area [%]	27	90	12	42	27	15	67	23	3
Cocoa area per cropped area [%]	52	2	2	26	38	37	17	22	80
Poverty Index[2]	-0.38	-0.17	-0.25	1.21	0.53	-0.93	-0.46	-0.03	0.66
Total off-farm income [‘000 IDR]	991.6	970.9	963.3	1751.1	5405.4	971.9	773.5	553.2	1124.7

[1]Based on the perceived impact of the most severe drought experienced by the household, on a scale from 0 (no impact) to 5 (very serious impact on the welfare of the household) (Keil 2004: 73).

[2]Based on asset- and consumption-related indicators. The Poverty Index is the first factor extracted by Principal Component Analysis. It has a mean of 0 and a standard deviation of 1 (Keil 2004: 154-155).

5. Results

Modelling the impact of ENSO on crop yields

Table 3 presents the regression results; variable definitions are given underneath. The signs of all regression coefficients, notably those of the rainfall-related explanatory variables *Rain*, *Rain squared*, and *Water*, are as expected, and the coefficients are statistically highly significant. The likely underestimation of the magnitude of the *Water* coefficient led to the introduction of an absolute water availability threshold into the LP-model, as elaborated in section 4.

Optimal resource allocation under different climate scenarios

As an example of the model output produced, Figure 1 depicts the optimal solution for a non-ENSO and a severe El Niño season for the upland household classes u1 (Palolo valley) and u6 (Kulawi valley), which feature identical socio-economic characteristics but differ in terms of location; the more favourable hydrologic conditions in Kulawi (cf. Table 1) have important implications: in the non-ENSO scenario both household classes dedicate 25% of their cropping area to rice and 22% to maize while 53% are occupied by cocoa[3]. During the severe ENSO scenario u6 can continue to grow rice while replacing maize by the more drought-tolerant soybeans. In contrast, it is not possible for u1-households to continue growing rice since the specified minimum water requirement of 1,000 mm during the 120-day growing period is not met (cf. section 4). It is important to note that the total water supply in the Palolo valley during the first 100 days after transplanting, during which rice is particularly sensitive to water stress (IRRI

[3] The discrepancy in planting dates for the maize crop is caused by small differences in the relative yields of the three crops due to the different climatic and hydrologic conditions, leading to slight deviations in labour allocation.

2005), is estimated to be a mere 410 mm for the average-ENSO and 390 mm for the severe-ENSO scenario. Therefore, even under the assumption of considerably lower minimum water requirements rice cultivation is not a viable option.

Table 3. Ordinary Least Squares (OLS) estimates of the parameters in the Cobb-Douglas production functions for rice, maize, and cocoa production in Central Sulawesi

	Rice		Maize		Cocoa	
Variable	**Coefficient**	**t-value**	**Coefficient**	**t-value**	**Coefficient**	**t-value**
Constant	- 0.161	- 0.359	-18.672	- 2.150*	- 60.808	- 3.688***
Land	0.465	8.249***	0.448	3.529**	0.757	9.618***
Labour	-		0.213	2.107*	0.265	4.927***
Seeds	0.301	4.782***	-		-	
Fertilizer	0.148	4.958***	0.357	2.937**	-	
Herbicides	0.110	3.796***	-		-	
Materials	-		-		0.106	2.035*
Rain	-		6.008	2.129*	13.430	3.330**
Rain squared	-		- 0.480	- 2.066*	- 0.867	- 3.191**
Water	0.119	3.606***	-		-	
Temperature	-		-		2.646	2.085*
Age	-		-		0.399	2.989**
Pests/diseases	- 0.377	- 8.008***	- 0.954	- 4.895***	- 0.640	- 6.383***
HYV	0.201	2.682**	-		-	
Several plots	-		-		0.297	2.520*
No fertilizer	1.255	3.829***	3.285	2.388*	-	
No herbicides	0.955	3.294**	-		-	
No materials	-		-		0.946	1.502
	N = 408		N = 79		N = 190	
	F = 165.966***		F = 39.747***		F = 72.949***	
	R^2 = 0.790		R^2 = 0.797		R^2 = 0.803	
	Adjusted R^2 = 0.785		Adjusted R^2 = 0.777		Adjusted R^2 = 0.792	

*(**)[***] Statistically significant at the 5% (1%) [0.1%] level of error probability.

The definition of variables is as follows:

Output = Logged total crop output (kg of husked rice; kg of dried maize seeds; kg of dried cocoa seeds).

Land = Logged total input of land (ares).

Labour = Logged total input of labour (manhours).

Seeds = Logged total input of rice seed (litres).

Fertilizer/Herbicides/Materials = Logged total input of fertilizer/herbicides/all materials (IDR); IDR = Indonesian Rupiah; 1 US$ = 8,900 IDR (February 2003).

Rain = Logged total amount of rainfall (mm) during the cropping season (maize)/during the year (cocoa).

Water = Logged total amount of rainfall and available irrigation water during the cropping season (mm).

Temperature = Logged mean annual temperature (°C).

Age = Logged weighted mean age of the cocoa plantation (years).

Pests/diseases = Dummy, = 1 if yield was drastically reduced by pests/diseases, 0 otherwise.

HYV = Dummy, = 1 if high-yielding variety was used, 0 otherwise.

Several plots = Dummy, = 1 if household cultivates several plots [which often differ significantly in terms of location and, hence, micro-climatic and soil characteristics], 0 otherwise.

No fertilizer/No herbicides/No materials = Zero-observation dummies, = 1 if Fertilizer/Herbicides/Materials is zero, 0 otherwise.

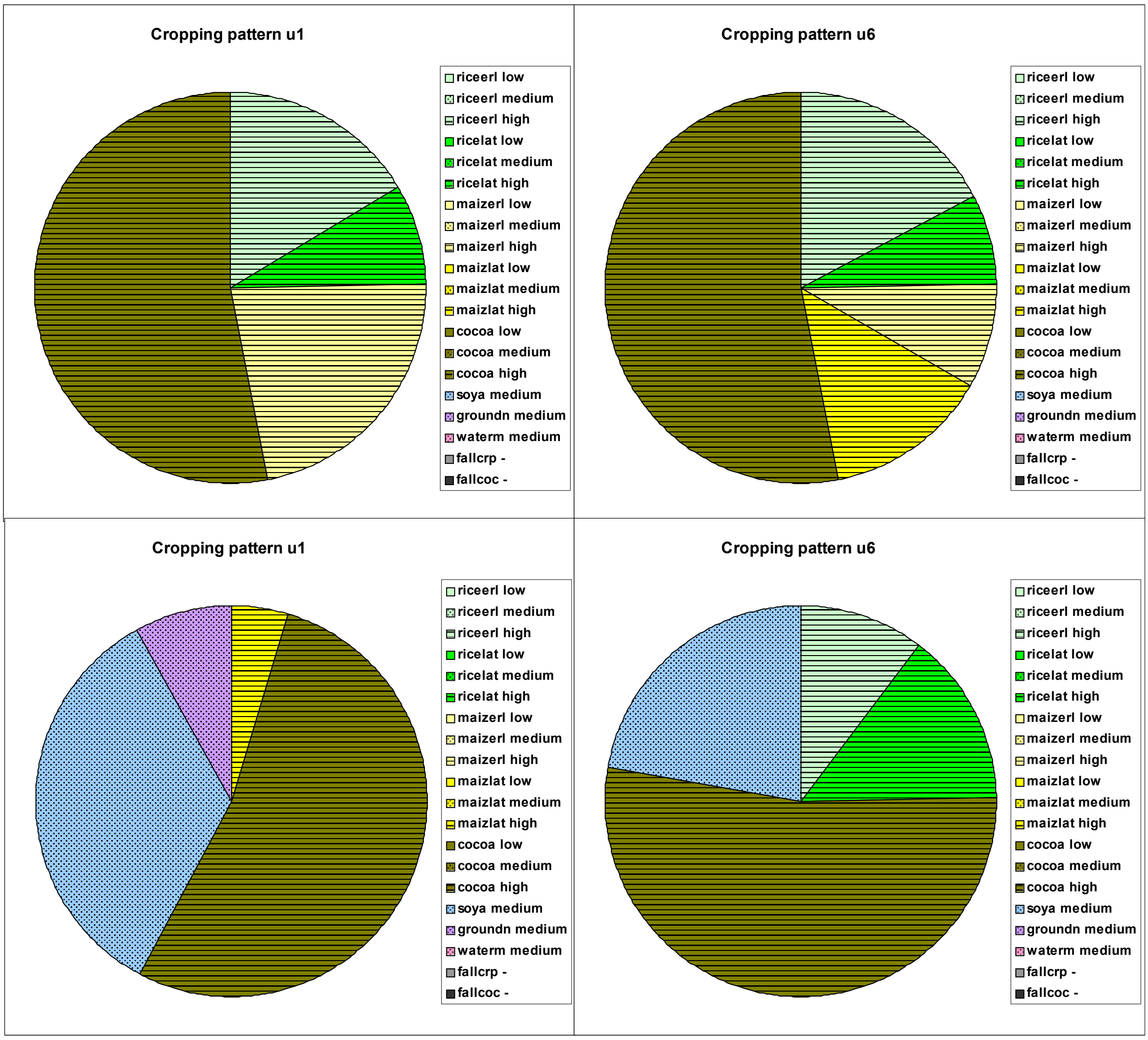

Figure 1. Optimal cropping strategies in Central Sulawesi during a non-ENSO year (top) and a severe El Niño year (bottom) for farm household classes u1 (left) and u6 (right).

For all five household classes considered in the analysis, Figure 2 visualizes the susceptibility towards drought-induced income reductions. To make income levels comparable and more easily interpretable, the total agricultural income generated in the six-month simulation period is converted into USD per Adult Equivalent (AE) per day; an AE is based on caloric requirements, differentiated by gender and age (WHO/FAO 1973). While the daily agricultural income of d2 is the lowest at 0.41 USD/AE during the non-ENSO scenario, it is also the most stable with a reduction to 83 and 78% of the 'normal' level in the average and the severe El Niño scenarios, respectively. At 1.64 USD/AE the daily agricultural income of the cocoa-based household class u5 is the highest, followed by the large, diversified farms in class d4 (1.40 USD/AE); however, both classes experience considerable income reductions in the two ENSO scenarios, at 60 and 44% of the 'normal' level for d4, and 54 and 47% for u5, respectively. While daily incomes of household classes u1 (Palolo) and u6 (Kulawi) are similar under non-ENSO conditions at 0.64 and 0.69 USD/AE, respectively, Palolo-households suffer greater income losses during El Niño, mainly because the disadvantageous hydrologic conditions impede a successful cultivation of rice: their income is drastically reduced to 46 and 39% in the two ENSO scenarios, as opposed to a much more moderate reduction to 80 and 56% in the case of their Kulawi counterparts.

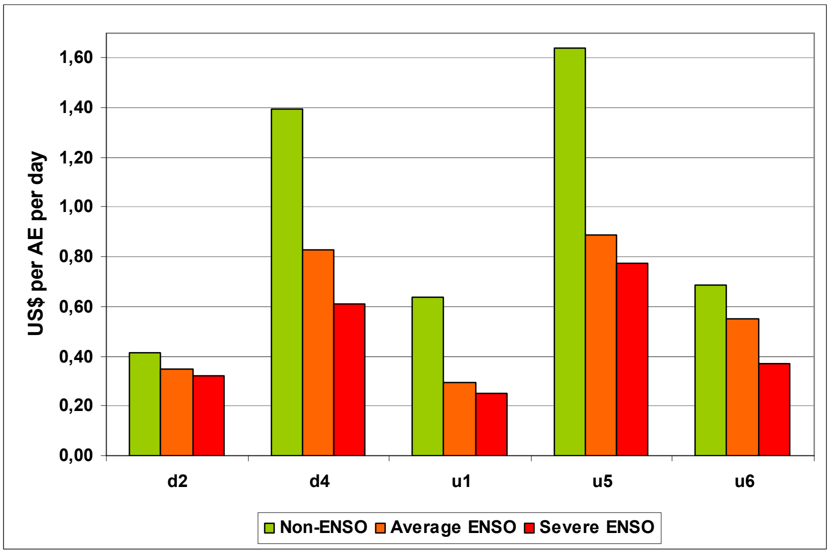

Figure 2. Comparison of agricultural income levels in USD per Adult Equivalent* per day of all farm household classes modelled during the period June 01 to Nov. 30 for a non-ENSO, an average El Niño, and a severe El Niño year.

* Adult Equivalents are based on caloric requirements, differentiated by gender and age (WHO/FAO, 1973)

6. Conclusions

There are marked differences in the severity of drought impact between different types of farm households, depending on their location, farming system, and resource endowment. In general, adaptation strategies to mitigate the adverse impact on agricultural incomes should encompass a reduction of production intensities and, in the case of serious drought conditions, a replacement of the predominant annual crops rice and maize by more drought tolerant ones, e.g., soybeans or groundnuts. However, a crucial prerequisite to the recommendation of a particular alternative crop is a thorough assessment of the agronomic and marketing potential under the specific frame conditions of a given area. By highlighting the diversity among farm households and its implications on El Niño impacts, the modelling results demonstrate that a one-fits-all type of policy strategy is not appropriate with regard to climate impact mitigation in an area characterised by a high degree of agro-ecological and socio-economic diversity: policy measures need to be carefully tailored to the farming systems and environmental frame conditions found in a given area if they are to be both effective and economically efficient.

References

Amien I, Rejekiningrum P, Pramudia A, Susanti E (1996) Effects of interannual climate variability and climate change on rice yields in Java, Indonesia. *Water, Air, and Soil Pollution* **92**, 29-39.

Datt G, Hoogeveen H (2003) El Nino or El Peso? Crisis, poverty and income distribution in the Philippines. *World Development* **31**, 1103-1124.

Easterling WE, Aggarwal PK*, et al.* (2007) Food, fibre and forest products. In 'Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change'. (Eds ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson) pp. 273-313. (Cambridge University Press, Cambridge, UK.

Gunawan D (2006) Atmospheric Variability in Sulawesi, Indonesia - Regional Atmospheric Model Results and Observations. PhD thesis. Faculty of Forestry and Forest Ecology, Georg-August-University Göttingen, Germany.

Hazell PBR, Norton RD (1986) Mathematical programming for economic analysis in agriculture. Macmillan, New York.

IRRI (2005) Rice knowledge bank. International Rice Research Institute, Los Banos, Philippines. http://www.irri.org, accessed on 15.02.07.

Keil A (2004) The socio-economic impact of ENSO-related drought on farm households in Central Sulawesi, Indonesia. Shaker Verlag, Aachen, Germany.

Leemhuis C (2006) The impact of El Niño Southern Oscillation events on water resource availability in Central Sulawesi, Indonesia: A hydrological modelling approach. Shaker Verlag, Aachen, Germany.

Rehm S, Espig G (1991) The cultivated plants of the tropics and subtropics. Verlag Josef Margraf, Göttingen, Germany.

Salafsky N (1994) Drought in the rainforest: Effects of the 1991 El Nino-Southern Oscillation event on a rural economy in West Kalimantan, Indonesia. *Climatic Change* **27**, 373-396.

WHO/FAO (1973) Energy and protein requirements. World Health Organisation Technical Report Series No. 522. World Health Organisation (WHO), Geneva, Switzerland.

WWF (1981) Lore Lindu National Park Management Plan 1981-1986. A World Wildlife Fund report for the Directorate of Nature Conservation. Bogor, Indonesia.