

FALLOW model: assessment tool for landscape level impact of farmer land use choices

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Abstract FALLOW is a landscape-dynamics model, comprising of the following main annual dynamic processes: (1) plot-level soil fertility dynamics in crop and fallow phases affecting agricultural crop production; (2) food storage, use and sale at the village level, with options along the spectrum from ‘full dependence on local food production’ to ‘fully market-integrated’ economy; (3) farmer decisions on increase or decrease of the area cropped, depending on labour availability and expected profitability of various land use options, as they have learnt from past experiences within the simulation; (4) spatial implementation of choices for land clearing land; and (5) impact assessment of how the resultant mosaic of land cover will affect watershed functions (annual water yield, base flow, net sediment loss), biodiversity indicators and carbon stocks. Initially developed as a Stella model, FALLOW has now been re-implemented in the spatially explicit modelling environment of PCRaster, making it possible to apply the model to larger landscapes with real spatial data sets. FALLOW can be used for impact assessment and scenario studies, assisting the negotiation process between stakeholders in a changing landscape by visualizing possible/likely consequences of factors such as changes in prices, population density and human migration, availability of new technology, spatial zoning of land use, pest and disease pressure or climate. We describe an application for the meso-scale catchment of a coffee producing area in Sumberjaya, Lampung, Sumatra, predicting impacts on watershed functions of 1) various ways of spatially allocating ‘forest reserves’ and 2) land use/cover changes as farmers’ response to coffee price shocks. For a 25% forest cover, maintenance of riparian forest is predicted to have the lowest sediment load of rivers, compared to allocating forest to steepest slopes or ridge tops. The likely farmer response to price shocks in coffee depends on farmer learning style and has significant impacts on predicted net sediment loss.

Keywords: *landscape-dynamics model; annual time step; spatially explicit; PCRaster; Sumatra.*

1. INTRODUCTION

The FALLOW¹ model has been developed as impact assessment tool at landscape level to help integrate our understanding of landscape-mosaic-resource interactions (van Noordwijk, 2002). It considers roles of actors/stake-holders in transforming the landscape, biophysical responses from plot- to landscape-levels through explicit scaling rules, and actors’/stake-holders’ feedbacks on the changing landscape.

The loop of dynamic modules of FALLOW (Figure 1) can be understood by starting from the dynamics of soil fertility at plot-level based on the simple Trenbath model (van Noordwijk, 2002), where soil fertility is depleted during cropping periods and recovers during fallow period. Current fertility at plot-scale determines agricultural crop yield (depending on crop type, with stochastic effects of weather, pest and diseases). Total crop production from the whole landscape together with the yield gained from

other economical production systems (e.g. agroforestry, forest resource utilisation activities, monoculture plantations) contributes to food sufficiency and/or household economical resources. People, starting from initial knowledge and learning from experience during the simulation, will make strategic decisions regarding agricultural land demand and/or labour allocation for various economical production activities. Once agricultural land demand is determined, people will select suitable plots for clearing and planting based on their estimates of attractiveness of the plots, which integrates relative soil fertility and land accessibility with regards to transportation costs, land tenure status and spatially explicit rules on forest reserves. The choice of crop to be cultivated may be based on people’s knowledge about crop response to soil fertility. Activities related to agricultural land expansion will disturb natural succession as well as soil fertility recovery processes of the cleared plots.

FALLOW initially focussed on the transition from a shifting cultivation system to more intensive crop-fallow rotations, but has been augmented to include ‘agroforests’ and other land

¹ FALLOW stands for (F)orests, (A)groforests, (L)ow-value-(L)andscape, (O)r, (W)astelands?

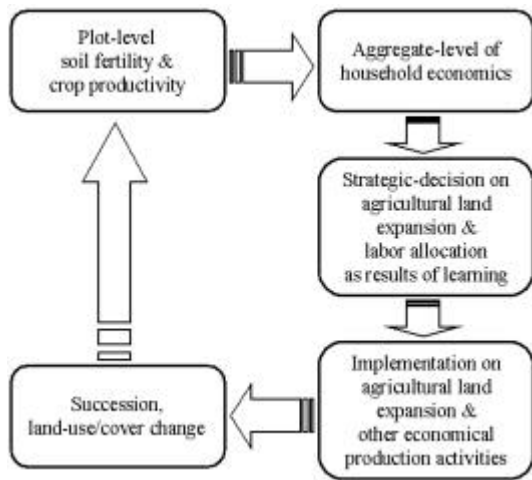


Figure 1. The dynamic core modules in the FALLOW model

use options and successional series (van Noordwijk, 2002). Currently FALLOW has incorporated further sequences of land use and/or natural resource utilisation systems, ranging from agroforestry system to monoculture plantation systems. Moreover, FALLOW provides toolboxes to assess the consequences of landscape dynamics in terms of human carrying capacity (food sufficiency), watershed functions, biodiversity and carbon stocks. The model is available in spatially explicit modelling environment of PCRaster, making it possible to apply the model to larger landscapes with real spatial data sets.

Forest protection in parts of watershed areas remains one of the main tools for 'integrated watershed management', but is often contested by farmers seeking livelihood options in these areas. According to Indonesia's *Tata Guna Hutan Kesepakatan* (agreement on forests function allocation) around 30% of a catchment should be allocated as forest reserve (*hutan lindung*) in order to maintain hydrological functions. Existing criteria are criticised and the best spatial allocation of such 'protection forest' remains open to discussion, with options as riparian forest, steep slopes and the tops of ridges as candidates.

This paper overviews the FALLOW model's conceptual framework and presents a model application for a mesoscale coffee growing catchment area of Sumberjaya, West Lampung, Sumatera with pixel resolution of 1 ha. Two questions will be addressed. First, we explore the impacts of different rules for spatial allocation of forest reserve on watershed functions, expanding the analysis of Verbist et al. (2002) from hillslope

and subcatchment scale to a landscape with interactive farmer decisions on land clearing.

Secondly, we explore farmers' response to coffee market shocks that affect the dynamics of the area from time to time (Leimona, 2001) and assess its consequences on watershed functions.

2. MODEL OVERVIEW

2.1. Landscape Dynamics

Plot-level soil fertility and crop productivity

Following equations proposed by Trenbath (1989), soil fertility (operationally defined as 'the ability of a soil to support crop growth') is assumed to proportionally decline during cropping periods and improve during fallow periods, with a characteristic half time of recovery. Fertilizer application may affect soil fertility through reductions on the depletion rate. Current soil fertility of cultivated plots is translated into crop productivity through a conversion efficiency of the crop. Crop sensitivity to stochastic weather and pressure of pest and diseases is also taken into account, with user-defined ranges for these impacts. Part of the landscape can be initialized as 'wetland', allowing for paddy rice cultivation with different yield trajectories and soil fertility dynamics than occur in the 'upland' plots.

Aggregate-level household economics

Compared to the previous version (van Noordwijk, 2002), FALLOW has now explicitly incorporated an open economy by fully integrating household and market, where people can exchange food (with a certain cost associated to any transaction), and by introducing financial capital as second household reserve in addition to the food store. Hence, expected crop yield and expected food demand in the next year is no longer the sole basis to adjust cropping intensity. The monetary reserve derived from marketing other products can be a supplementary or dominant source of food security. Expenditure for non-food purposes can drive decisions to the stage that all available labour is fully utilized. A conservative preference for local food production as security mechanism can be considered in the labour allocation decisions.

Strategic-decision making

Strategic decisions reflects what the people in the simulation model have learnt about actual performance of production systems in the area, with a learning style that may range from conservative (dominated by long term trends) to

creative (dominated by recent experience) types of learning. The dynamic 'expected return to labour' will affect not only strategic-decision regarding cropping intensity, but also tactical (annual) decisions on labour allocation to various economical production activities. Where $M_{a,t}$ is farmers' memory on returns to labour of certain activity a at time t and $E_{a,t}$ is currently experienced returns to labour of certain activity a at time t , the change in expectations is $\alpha(E_{a,t} - M_{a,t})$. The parameter α indicates the learning style and varies between 1 when farmers ignore any experience of the past (they are here indicated as 'creative') and 0 when they are extremely 'conservative' and ignore any new information.

Cropping implementation

Actual choice of fields for land clearing is based on a comparison and ranking of 'field attractiveness', which is determined by its current soil fertility, tenure status (with a preference for establishing private tenure through land clearing and planting on land that is not yet claimed) and accessibility, and by rules restricting clearing on parts of the landscape. The implementation module in FALLOW also considers farmer's choice of the type of crop, based on expected yield for a number of crop options determined by soil fertility of the fields actually cropped.

Succession, land use/cover change

FALLOW explicitly considers succession process of fallow-type vegetations into forest, as well as the various phases of tree crop production systems. The successional status of each patch determines its role relative to C stocks, biodiversity and watershed functions.

2.2. Consequences for Watershed Functions

FALLOW includes a simple annual water balance at patch level, with an allocation of incoming rain over evapotranspiration, overland flow and infiltration, that depends on a soil physical quality that changes in a positive or negative direction depending on current land cover type and its assumed supply of food for soil biota. In interaction with soil physical quality, water infiltration is also determined by slope at plot level (Figure 2). Surplus from this first filtering step determines the overland flow. Under saturated soil conditions, infiltrated water will flow out as subsurface quick flow and together with the overland flow produce storm flow. Water that reaches the groundwater storage is released as base flow. Overland flow multiplied with a user-defined average sediment concentration per land cover class determines gross erosion. FALLOW also assigns a potential

filter function to each plot — depending on contact cover by litter — and derives a net erosion loss that leads to the sediment load of rivers. The most critical phase of land use/cover change is found within the pioneer phase, due to relatively low filter efficiency. Filter effects only can be exerted along the pathway of overland flow, giving a specific relevance to 'riparian filter zones'.

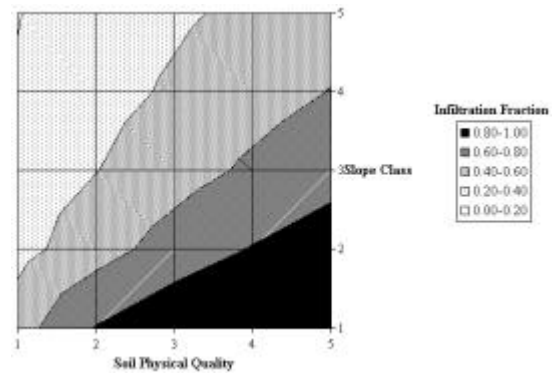


Figure 2. Infiltration fraction of a plot depending on slope and soil physical quality; slope is classified according to USLE (**1**: slope < 1%, **2**: 1% ≤ slope < 3%, **3**: 3% ≤ slope < 5%, **4**: 5% ≤ slope < 20%, **5**: slope > 20%); where soil physical quality represents its aggregate stability.

3. EFFECTIVENESS OF FOREST RESERVE ALLOCATION

3.1. Parametrization

General attributes of the Sumber Jaya area were discussed by Verbist et al. (2002) and van Noordwijk et al. (2002).

Five forested zones with the same allocation fraction of 0.25 were generated on the basis of a digital elevation model (DEM) of the area. The zones (Figure 3) are delineated according to distance to river with a threshold of 100 m nearby the river (riparian forests), steepness with threshold of 20% (sloping forests), elevation with threshold of 1000 m a.s.l. (ridge top forests), a uniformly random choice (random forests) and 'remote forests' at a distance to settlements of more than 1 km.

3.2. Results

Based on simulation results over 100 years, riparian forests gave the lowest net sediment loss of the five patterns compared (Figure 3F). Variations with time depend on the stochastic nature of rainfall as well as decisions on land clearing depending on yields and the completion of production cycles.

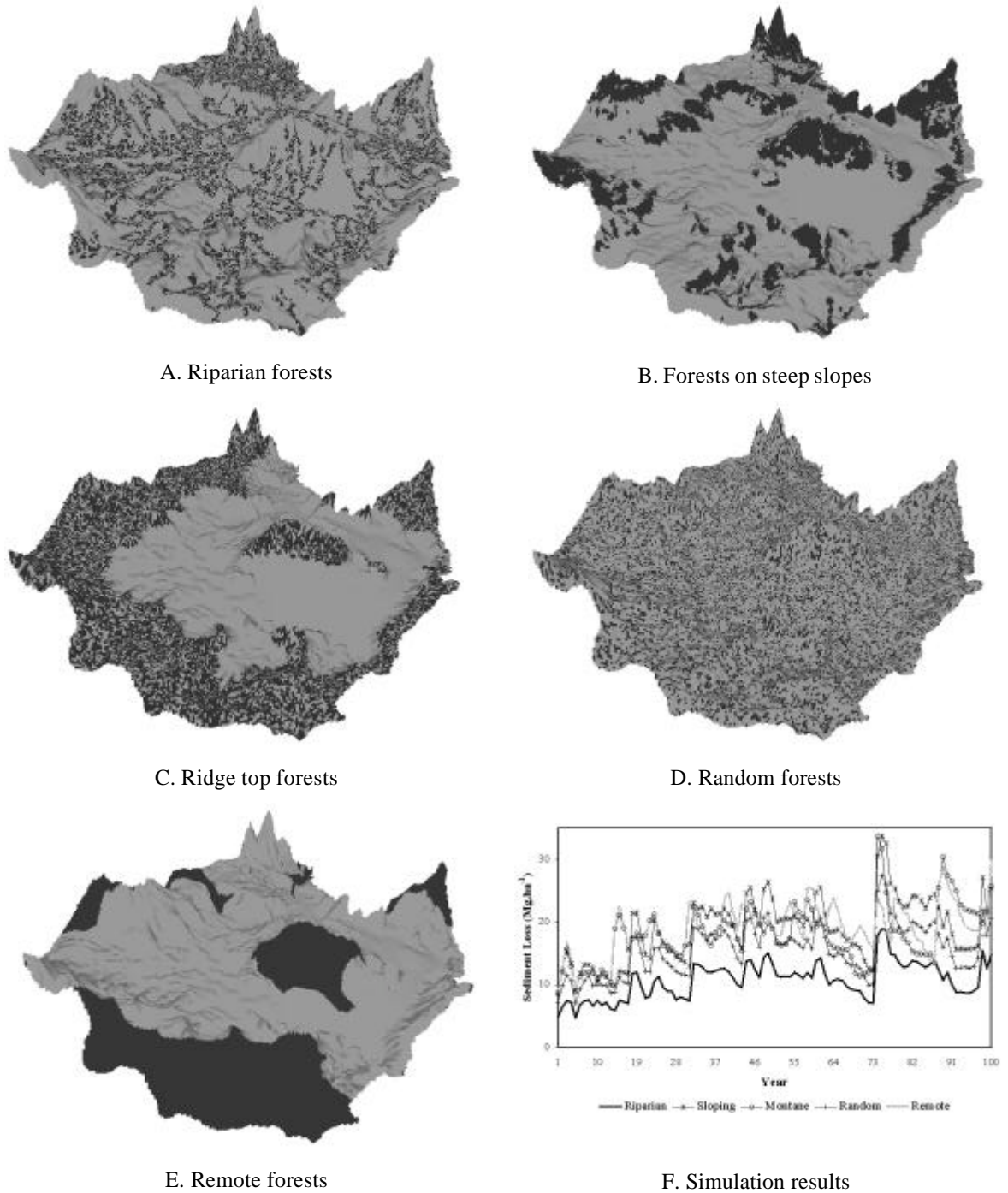


Figure 3. Rules on forest reserve allocation preference for: (A) riparian zone, (B) zone with steep slopes, (C) ridge top zone, (D) random and (E) remote zone. All rules apply the same fraction of 0.25. (F) Simulated net sediment loss for a 100-year period ($\text{Mg}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$).

4. FARMER'S RESPONSE TO COFFEE MARKET SHOCKS AND CONSEQUENCES FOR WATERSHED FUNCTIONS

4.1. Rationale

Price shocks of major agricultural commodities either at the world market or local markets can be caused by natural disasters (e.g. drought, frost or pest/disease outbreak) or by dramatic economical/political events (e.g. embargo, war or

political reform). These can lead farmers to adjust their current agricultural activities, which will in turn affect the landscape dynamics. Sumberjaya is an example of a sensitive area to land use/cover change, where its dynamics are related to coffee market shocks (Leimona, 2001; Verbist et al., 2002). Over the past three decades, farmers in Sumberjaya have coped with such shocks by adopting more diverse coffee farming system where fruits, timber and crop products can increase farmers' resilience to uncertain coffee prices. We explored the interactions between the

type of shock, farmer learning style and landscape impacts as measure of the adaptive capacity of complex systems (Holling, 2001).

As a reference, we use simulation results at artificial stable coffee price (IDR 3000 kg⁻¹). A monoculture clove plantation option was parameterised with an assumed stable price of IDR 2500 kg⁻¹, in addition to agroforestry options based on coffee and crop-fallow rotations. Three input strings of coffee price were generated representing high frequency (0.615) or large magnitude of the immediate shocks and a long recovery time (14 years) of shocks (Figure 4) for 100-year sensitivity simulations that were initialised using land use/cover pattern of Sumberjaya on 1985. The drops in high frequency and long recovery of price shocks are IDR 1500 kg⁻¹, while in large magnitude of the immediate shocks is IDR 2500 kg⁻¹ from the stable price.

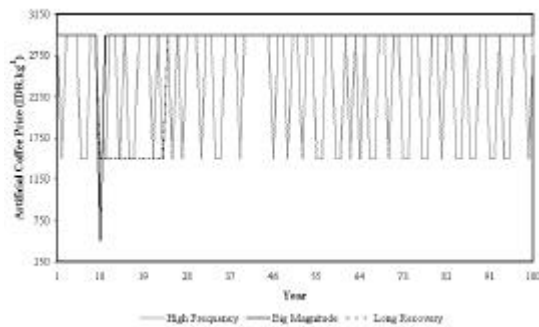


Figure 4. Coffee price fluctuations used as input for sensitivity analysis of price shocks.

4.2. Results

Land use/cover change

With stable coffee prices (Figure 5A), the first 20 years of the simulation show a decline in forest cover while farmers 'experiment' with both coffee monoculture and coffee agroforestry before settling on coffee agroforestry as the more rewarding enterprise (higher actual returns per unit labour allocated over a production cycle). At relatively high frequency of shocks (Figure 5B), low coffee prices during the 'experimental phase' induce farmers to also try the clove monocultures, which in the long run, however, is less rewarding than coffee agroforestry with the parameters chosen. It takes 55 years, however, before the landscape reaches a stable land use configuration with these frequent price shocks. A relatively big magnitude of an immediate shock (Figure 5C) induces farmers to diversify to clove, for about 40 years of experimentation.

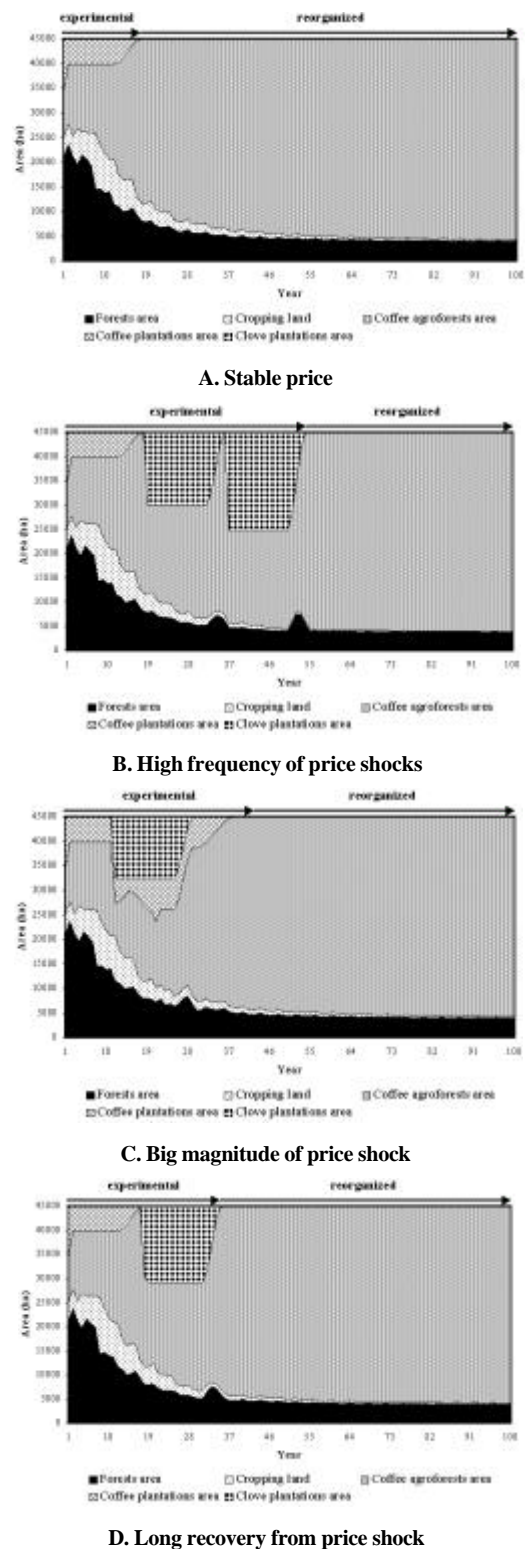


Figure 5. Landscape dynamics as resulted by farmers' response to coffee price scenario. (A) stable price, (B) high frequency shocks, (C) big magnitude shock, (D) long recovery shock.

With a relatively slow recovery from an immediate shock (Figure 5D), farmers respond it similarly as if they have frequent shocks, but in this case, at shorter period of experimentation.

Consequences for Watershed Functions

As a consequence of the human adaptive capacity to experiment and reorganize land use patterns in response to shocks in coffee prices which in turns will affect filtering functions of the land, the sediment load of rivers is expected to increase by 60 to 400% of the value obtained for stable prices (Figure 6). These outcomes suggest that measures to stabilize coffee prices may provide an effective way to reduce negative environmental impacts of land use in upper watersheds.

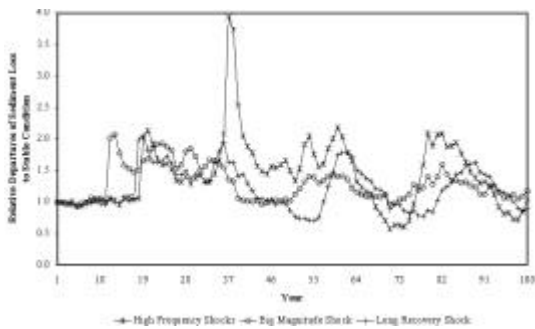


Figure 6. Landscape scale sediment loss due to reorganization of land use in response to shocks in coffee prices. All shocks on coffee price give significant departures of sediment loss, relative to that on stable condition, ranging from about 0.6 to 4 times.

5. DISCUSSION

The simulations presented here are initial attempts to test model sensitivity to changes in various parameters, as part of a qualitative 'sensitivity' test ('does it make sense?'). We do not expect our outcomes to quantitatively correspond with the real historical or potential future evolution of land use in the area, as major human demographic drivers were not yet considered for these runs.

Across all scenarios tested the possible sediment loss from Sumberjaya ranges from 5 to 35 Mg.ha⁻¹.y⁻¹. These results agree with average sediment loss in Sumatra of about 24 Mg ha⁻¹ y⁻¹, as estimated by Milliman et al. (1999) using a sediment-scale relation.

Including the dynamics of experimentation with land use options as part of the model offers interesting opportunities to explore impacts of price variations, learning styles and information flow.

6. MODEL AVAILABILITY

FALLOW can be downloaded from <http://www.worldagroforestrycentre.org/sea/AgroModels/FALLOW/Fallow.htm> as a STELLA

linked to EXCEL workbook, or as a PC Raster model embedded within EXCEL.

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