A SYSTEM DYNAMICS MODEL OF AGRICULTURE AND RURAL DEVELOPMENT: THE TOPMARD CORE MODEL

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Abstract

The goal of the TOPMARD project is to develop a model of agriculture and rural development to better understand the agronomic, ecological, economic and social dimensions of rural regions. The resulting model, (Policy Model of Multifunctional Agriculture and Rural Development) was built collaboratively and hierarchically by the research teams from the 11 countries. The model features eight subsectors (Land, Agriculture, Tourism, Region, Human Resources, Non-commodities, Capital, and Quality of Life). Imbedded in the model are a complete dynamic input-output model, and an age-cohort education demographic model. The model has both supply-side and demand-side drivers. Land use is the key supply-side driver. Land use, coupled with production system choices, determine agricultural and non-commodity outputs. The Quality of Life sector incorporates the coefficients from a regression analysis of migration behaviour to develop a supply-side population response to local quality of life which is added to the demand-side response to job growth.

Key words: Multifunctionality, system dynamics, policy, model, rural development

1. Introduction

The goal of the TOPMARD project is to develop an interdisciplinary-based model of agriculture and rural development with which policy analysts can better understand the dynamics and interconnectedness of the agronomic, ecological, economic and social dimensions of rural regions (Bryden et al, 2006). To adequately capture these dimensions, and to accommodate the several disciplines that are involved, the research project built a system dynamics approach.

The resulting model, referred to as the Policy Model of Multifunctional Agriculture and Rural Development (POMMARD) was built collaboratively and hierarchically by a research team of policy analysts from 11 countries (Johnson et al, 2006). The full TOPMARD team designed the overall characteristics of the model while a small sub-group built the core model.

POMMARD is built with the Stella system dynamics software. The Stella software program was chosen because of its focus on group learning, interactivity and mixtures of quantitative and qualitative relationships. Figure 1 describes the overall structure of the model. The model contains 11 modules: Initial Conditions, Policy Controls, Indicators, Land, Non Commodities, Agriculture, Quality of Life, Human Resources, Region, Regional Capital, Tourism and Indicators.

Unlike many models of economic relationships, this model is partially supply oriented. Land use is the primary engine of this model. Land use determines agricultural production of commodities and non-commodities. It also determines the amount of labour employed in agriculture.
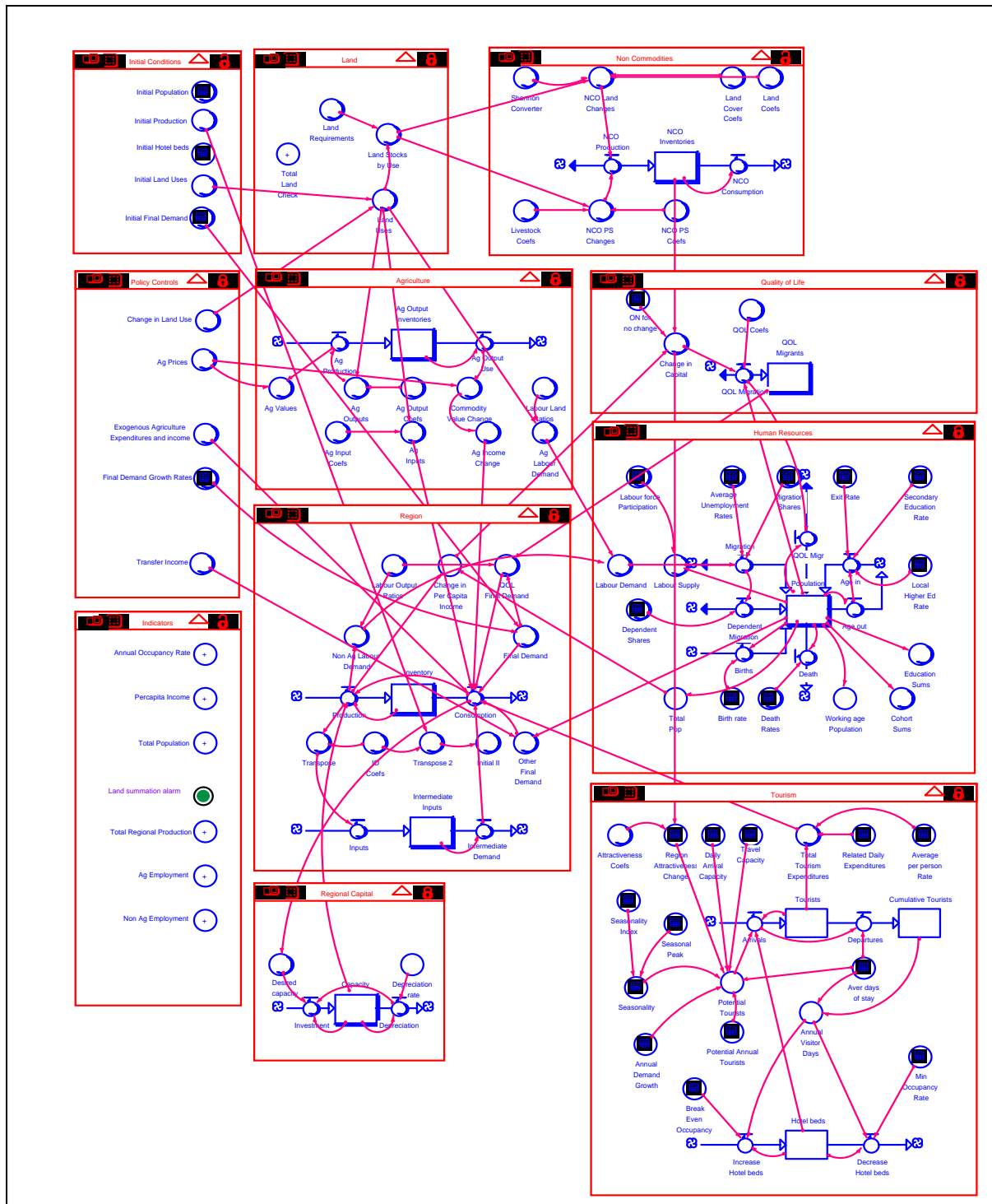
Figure 1. Overall Structure of the Model

The regional economy is, in turn, driven by the supply-oriented agriculture module (and other special modules), and demand drivers from the larger economy. Agriculture capital and regional capital determine the investment and capacity of agriculture and other modules, respectively. The initial conditions and policy controls provide inputs to the model for scenario analysis. Finally, indicators allow the user to monitor changes in key variables.

2. The Logic of POMMARD

2.1. Agriculture Module

Agriculture is the key sector in POMMARD. Agriculture is assumed to be supply-oriented. Agriculture is organized into alternative production systems. Allocation of land to production systems determines land use. Current land used in each production system is obtained as the sum of the Initial Land Use and the Change of Land Use. Agricultures purchases of inputs (including income to households) depends on land use and agricultural input coefficients for each production system. These input purchases augment demand for production elsewhere in the regional economy. Land use, together with the labour-land ratios, determines the agriculture demand for labour. Agricultural production, determined by the amount of land allocated to each production system and the agriculture output coefficients, add to the agriculture output inventories. The rate of outflow of these inventories is equal to the agriculture commodity use. The dynamic stock of agricultural commodities is then calculated by integrating the net of inflows and outflows over time.

One of the ways in which policy changes are introduced is through exogenous changes in the prices of agricultural commodities. These changes are introduced through a commodity price change vector. This vector introduces the change in price of agricultural commodities relative to the initial prices. The changes in values of commodities consumed are then calculated and the differences added to net farm income.

2.2. The Land Module

In POMMARD land is the primary resource or capital affecting supply of agricultural commodities. We assume a linear relationship between each production system and each land type required. Each value represents the proportion of total land required by each production system that comes from each land type.

Land stocks is a two dimensional array (land types and production system) which distributes the total land by type to the production systems over time.

2.3. The Non-Commodities Module

This module is an important link to Quality of Life module due to the migration it induces. There are eleven types of non-commodity outputs included in this study. Some of these are related to land use, and others to production systems. The 11 NCO categories (elements) are as follows:

1. Forest % (percentage point change): cumulative change in area devoted to forests
2. Arable Land % (percentage point change): cumulative change in area devoted to arable land
3. Grass Land % (percentage point change): cumulative change in area devoted to grass land
4. Permanent Crops % (percentage point change): cumulative change in area devoted to permanent crops

5. Shannon Index (index, 0 to infinity): entropy measure of land use diversity
6. Mineral Fertilizer (kg/ha/year): kg of mineral fertilizer applied per hectare per year
7. Excess Nitrogen (kg/ha/year): surplus of nitrogen applied over that used by plants applied per hectare per year
8. Biodiversity (proportion, 0 to 1): proportion of utilized agricultural land under low-input farming systems
9. Livestock Unit per Hectare (unit per ha): number of livestock unit per hectare
10. Land Cover Change (hectares): records the negative change in crop land
11. CO2 Balance: the net emissions of CO2 per hectare of each production system

The first four non-commodities are related to land changes. The NCO Land Changes array (non-commodity and land types) is the change in each of several types of land in percentage terms. Note that the percentages calculated are not percentage changes, but **percentage point changes**. Thus, an increase from 10% to 15% is a 50% increase, but only 5 percentage points. The fifth NCO type is the Shannon Index. This index is calculated from total land stocks of each type. Next is the NCO production system array (non-commodities and production systems) includes categories 6 through 9 and 11. This array is the total amount of each non-commodity, produced by one unit of each production system. NCO 10 is land cover change. Land cover change is equal to the negative of annual change in the stock of annual crop land. Since crop land is generally a less desirable land use than other farm uses, increases are recorded as negative changes.

Some of these NCOs are values that are calculated continuously (non-accumulating) while others are accumulating stocks. The Shannon Index, biodiversity and livestock units per hectares are of the non-accumulating type. For these, the outflow equals the inflow while for the accumulating NCOs, the outflows are equal to zero.

2.4. The Quality of Life Module

Changes in quality of life (QOL) create a supply-driven migration which is in addition to the demand driven migration (i.e. migration to fill vacant jobs). We assume that each autonomous in-migrant creates demand for his or her job.

The QOL elasticities are based on regression analyses of data collected in the study areas. The calculated elasticities are the proportion of net migration (in migration – out migration) of each cohort due to changes in each type of capital. The model allows for 5 capitals (natural, material, cultural, historical and social) but only natural and material capitals are being used at this time.

The first step in this process is to calculate the rate of change in each capital. Different calculations are used for each of the five capitals. In the natural capital calculation, the rate of change in NCO forest % is divided by 1.1 based on empirical estimates of this variable's contribution to natural capital. Similarly, in the case of material capital, the change in per capita income is divided by its regression coefficient, 1.767.

Next the level of migration induced by the changes in capitals is estimated. Changes in quality of life induce three different types of migration depending on the age of the migrant. The first category is youth (age 0-19). Here we are measuring the tendency for young people to leave the region after completion of secondary education. The second category includes those who are active in the labour market (age 20 to 64) but who migrate (in or out) without direct relationship to job opportunities. This group is accompanied by their dependents. The third group includes retirees (ages 65 plus) who migrate.

People in the second group are assumed to join the labour force and to add to the regional production proportionately to their numbers. Since their production is in addition to the demand driven production typical of an input-output based model, we assume that their addition to the labour force is accompanied by an in final demand sufficient to absorb their contribution to regional production. Migration of retirees does not affect the labour market directly but does change the population, demographics, and income in the region. All groups also add consumption in the region because of the change in household income.

2.5. The Human Resources Module

The demographics of the region are determined by a combination of births, deaths and aging, and migration. The model includes a typical cohort-survival procedure augmented by educational achievement and migration. There are four age cohorts (0-19 years, 20-39 years, 40-64 years, and 65 and over) and six levels of educational achievement (pre-school or in-primary, in-secondary, in-tertiary, primary educated, secondary educated and tertiary educated).

Births are determined by the annual rate of birth among families age 20-39. Death rates are specific to the four age cohorts. Aging is accomplished by a series of age-out and age-in flows. Out flows calculate the total number of people who because of age or school completion leave each age/education cohort to join the next older age cohort. In-flows add these people to the new age/education cohort. From the pre-school and in-primary cohort individuals flow into either the 0-19 primary educated cohort (1-Secondary Education Rate) or the 0-19 in-secondary cohort (Secondary Education Rate). From the 0- 19 in-secondary cohort, individuals flow into either the 0- 19 secondary educated cohort (1-Local Higher Education Rate-Exit Rate), or the 0-19 in-tertiary cohort (Local Higher Education Rate) or they exit the region (Exit Rate). The 0-19 in-tertiary education cohort ages into the 20-39 in-tertiary education cohorts who then age into the 20-39 tertiary educated cohort. Each primary educated cohort ages into the older primary cohort and on to retirement. Secondary and tertiary educated cohorts similarly flow into older cohorts until retirement.

Land use determines the agricultural labour needs. Demand and other internal and external changes determine the non-agricultural labour needs. The human resources module calculates the total labour demand, in and out migration, and typical demographic processes (births, deaths, ageing, etc.) This module also deals with the educational changes in the population. In addition, it uses information from the Region and Quality of Life Modules, and generates values that are subsequently used in the Region Module.

Labour demand is the sum of labour requirements in the agriculture and non-agriculture sectors. Labour supply is determined by the population and the labour force participation rate.

The two dimensional migration shares array (age cohorts and education level) controls the total migration (in and out) of working age people in response to changes in regional labour demand and quality of life. Migrants are assumed to migrate as families including both youth and elderly members. The migration of dependents is based on the migration rates of workers and the dependent:worker ratios. The model generates flows of dependents for the 0-19 in-primary and in-secondary school groups and over 65 age groups for the primary, secondary and tertiary education categories. It is assumed that the patterns of dependents are similar for both the 20 – 39 and 40 – 64 groups.

An important determinant of the changing demographics of a region is the migration behaviour of youth once they complete their secondary education. In POMMARD this is determined by a series of variables. The Exit Rate is the proportion of secondary school graduates that leave the region after completing secondary school. The Local Higher Education Rate is the proportion of secondary school graduates that continue onto higher education (tertiary education) at a local institution. The remaining graduates (1-local higher education rate-exit rate) are assumed to join the local labour force. The population in each age-education category is obtained by integrating inflows and outflows.

2.6. The Region Module

The regional economy module is based on the dynamic macroeconomic model developed by Leontief (1953) and adapted by Johnson (1986). These models are similar to ecological or mass-balance system. In such systems, mass changes from one state to another as a function of the difference between its current level and its equilibrium level. In an economic system, production and consumption move toward equilibrium at a rate which depends on the difference between demand and supply, that is, as a function of the unplanned change in inventory. When production and consumption are equal, inventories are in equilibrium. When inventories are larger than ideal, then production will decline. When inventories are too small, production will increase.

Regional sectoral output is the sum of intermediate outputs (production of goods and services to be used as inputs by other sectors) plus final demand. Final demand is disaggregated into external final demand, investment demand and planned inventory change.

In general, the economy is not in equilibrium. Because of unexpected changes in demand, there are unplanned changes in inventories of sector commodities. The actual change in inventories is the difference between production and consumption. Like an ecological system, the change in production is a function of planned and unplanned inventory change. The economy responds to the inventory change (the imbalance) by increasing or decreasing production in the opposite direction:

Because production is itself a rate, this is a second order differential equation—inventories are stocks which are determined by the flow, inventory change, but the level of inventory change determines the change in the rate of output change. Thus, the rate of production is determined by changes in the rate of production, which requires a second order differential system in order to solve the model. We do

this by treating the production flow as a stock (annual production) which is related to a flow, the change in production.

In POMMARD, the primary driver of the regional economy, and the main linkage between agriculture, tourism and the regional economy is final demand (consumption) of regionally produced goods and services. Consumption is also one of the more convenient places to introduce policy related shocks to the model. Thus, total consumption is the sum of several categories of demand including 1) intermediate demand by non-agriculture sectors; 2) intermediate demand by the agriculture sector; 3) exogenous final demand (including exogenous income to households, but excluding the agriculture and tourism sectors)[1]; 4) tourism final demand; 5) exogenous final demands generated by quality of life induced migration; 6) other final demand derived from transfer of income to the regions residents; 7) agriculture income change due to commodity price changes; and 8) changes in agriculture expenditure and income due to policy changes.

As explained above, rates of consumption and production are dynamically linked through changes in inventories of goods and services. An increase in consumption draws down inventories but induces a production response equal to the new consumption plus the decline in inventories.[2] To allow for sectoral capacity constraints, sectoral production is the minimum of consumption requirements (including replenishment of inventories) and the capacity of each sector.

Exports are the region's external final demands. Capital demand is determined by applying the capital coefficients (demands per unit of sectoral capacity) to the desired investment levels (described below). Intermediate demand is the input-output (or economic base) coefficients multiplied by the level of sectoral output. Inventory change is proportionate to the difference between desired and actual inventories. Finally, agriculture demands for commodities are equal to the agriculture output time the sector's input coefficients.

As indicated above, the quality of life in the region induces changes in migration to the region. This endogenous migration is complementary to the demand driven migration (people following jobs) and thus leads to endogenous growth (jobs following people). In order to accommodate this migration in the demand driven regional sector the increase in exports required to employ the endogenous migration is calculated and added to final demand (QOLFD). It is assumed that the structure of this new final demand and the accompanying employment mirrors the current structure.

The region module links to the labour market module through the non-agriculture labour demand. Non-agriculture labour demand is equal to the labour:output ratio times sectoral production. The region module also calculates percapita income to report to the quality of life module.

2.7. The Regional Capital Module

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[1] The final demand for the outputs of the household sector should be interpreted as the income from outside employment, investments, and government payments. This flow is distinguishable from the transfer payments, and agricultural income because it is not related to the levels of migration.
[2] In the POMMARD model we assume that desired inventories are equal to 1.0 time consumption which means that an increase in consumption induces a 2.0 time consumption production response until inventories recover and then attain the new desired level. Thus the dynamic response is 2.0 time consumption minus inventories.

The regional capital module determines the endogenous investment levels and sectoral capacity. Sectors will have some ideal excess capacity which they will compare to actual capacity. The ideal capacity is proportional to the expected level of consumption which in turn is related to current demand. Capacity is measured in units of Euro output possible rather than in value of investment. It increases with more investment but decreases with depreciation. Users are not required to enter initial values because the model automatically calculates near-equilibrium values from the Initial Capacity in each sector. Capacity is increased through investment and decreased through depreciation. The rate of output is limited by the capacity of the sector. Together these relationships create a series of lags between changes in demand, changes in capacity and limits on sectoral growth.

2.8. The Tourism Module

The Tourism Module determines total tourism expenditures which, in turn influences the size of the regional economy. Tourism is demand-driven in POMMARD. The attractiveness index links tourism to the levels of natural capital in the region. The sector is constrained by hotel beds, in-region tourist limits and daily arrival capacity. If all hotel beds are filled tourists are turned away. Those that stay, remain in the region for the specified time period. Moreover, the model makes the tourism sector subject to seasonality, which leads to periodic stress on hotel capacity during peak season and leaves relatively lower occupancy rates for the rest of the year. Hotels beds are added when the expected annual occupancy rises to a level that will justify investment in additional beds. Beds are allowed to decline when average occupancy rate falls below that level needed to cover variable costs. Additions and closures are based on the previous year's occupancy so that there is a lag in changes. Those within the limit arrive according to the seasonal schedule.

The tourism module is linked to the Land and Agriculture modules through the attractiveness index which is determined in part by land use and production systems. Tourism is linked to the Region Module through its income, purchases and employment. The attractiveness index is based on attractiveness coefficients that relate changes in the community capitals to the region's tourism demand. These coefficients were estimated from data on regional natural and other capital levels and tourism levels

The total potential annual tourists is the minimum among the following three levels: 1) the total potential arrivals wishing to visit, which is influenced by the region's attractiveness, the potential number of tourists, the seasonality information and the annual growth in tourism; 2) the current arrival constraint, which is based on the daily arrival capacity; and, 3) the infrastructure capacity constraint, which represents the maximum number of guests that infrastructure (other than hotel beds) can accommodate at anytime.

Changes in hotel beds are triggered by the break-even occupancy rate and minimum occupancy rate. The break-even occupancy is that level where each new bed can pay variable costs and a return on investment. The minimum occupancy rate is the level of use where variable costs can be covered. Increases and decreases in hotel beds are asymmetric because of two reasons: 1) the sunk-cost nature of hotel investments and 2) increases are based on actual losses of sales rather than on high occupancy

rates. This is critical because of the seasonal nature of the business. This assumes a perfectly competitive market in which a high average occupancy rate attracts investment, even though total profits in the sector may be driven down and marginal returns are less than average returns.

2.9. Other Modules

POMMARD include three other modules which facilitate the implementation of scenarios and the interpretation of the results. These are the Initial Conditions module, the Policy Controls module, and the Indicators Module.

3. Using POMMARD

POMMARD was designed to be applied to a variety of regions. Productions systems, land types and uses, sectoral definitions, commodities produced and other variables will differ from region to region. It was necessary, therefore, to make many model components adjustable. This requires a more sophisticated model structure in which relationships are generic rather than specific. It also means that data for particular regions must be easy to enter into the model. In order to simplify the process of data entry spreadsheet templates were created. These templates also facilitate the introduction of scenarios.

POMMARD was designed for policy analysis. The first step in analyzing policy is to generate a baseline projection for the regional economy. Baselines typically assume quite constant rates of change in exogenous factors. While it is possible to predict dynamic processes like business cycles and even policy changes in such models it is usually more useful to start with more simple baselines. POMMARD accommodates the construction of such baselines with a number of variables that permit the introduction of constant growth rates. Sector-specific annual growth rates in final demand for non-agriculture sectors and tourism can be introduced for example.

Scenarios are then developed by introduce by changing initial conditions, or more commonly, discrete changes in the exogenous drivers of the model. A wide variety of exogenous variables, especially policy intervention variables have been built into model, including such things as final demand, land use, mix of production systems, agricultural prices, household income and agricultural expenditures.

Two model runs are described below. The first is a baseline for a hypothetical region assuming slow growth in the economy, and thus in population. The second scenario is a simple one involving the shift of 3000 hectares from the beef cattle production system to mixed livestock production system. In Figures 2 and 3 below, case one is the baseline and case to is the land use change scenario.

Even this simple scenario demonstrates that all variables are potentially affected when a small change is made in the system. In this case the 3000 hectare shift changes the level of production in the agricultural sector which leads to different purchases from the rest of the regional economy. The change also increases the employment levels which stimulates an increase in net in-migration.

Another important source of dynamics in the economy is the effect of quality of life related migration. In this scenario, the change in land use increases per capita income by a small amount (no more than 120 Euros at any time). This increase in income induces a small increase in migration of retirees. Since the income of retirees is lower than average, this leads to a decline in per capita income and a reversal of the induced migration. Taken together, the effect is to generate more volatility in the economy until stability is re-established.
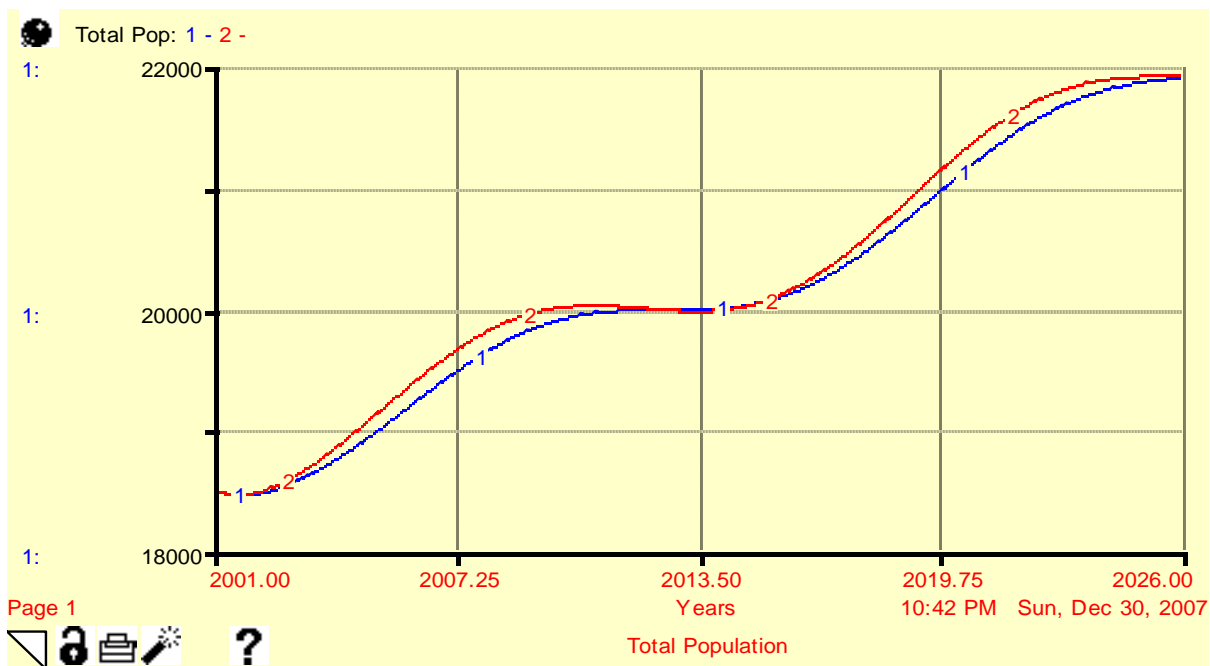

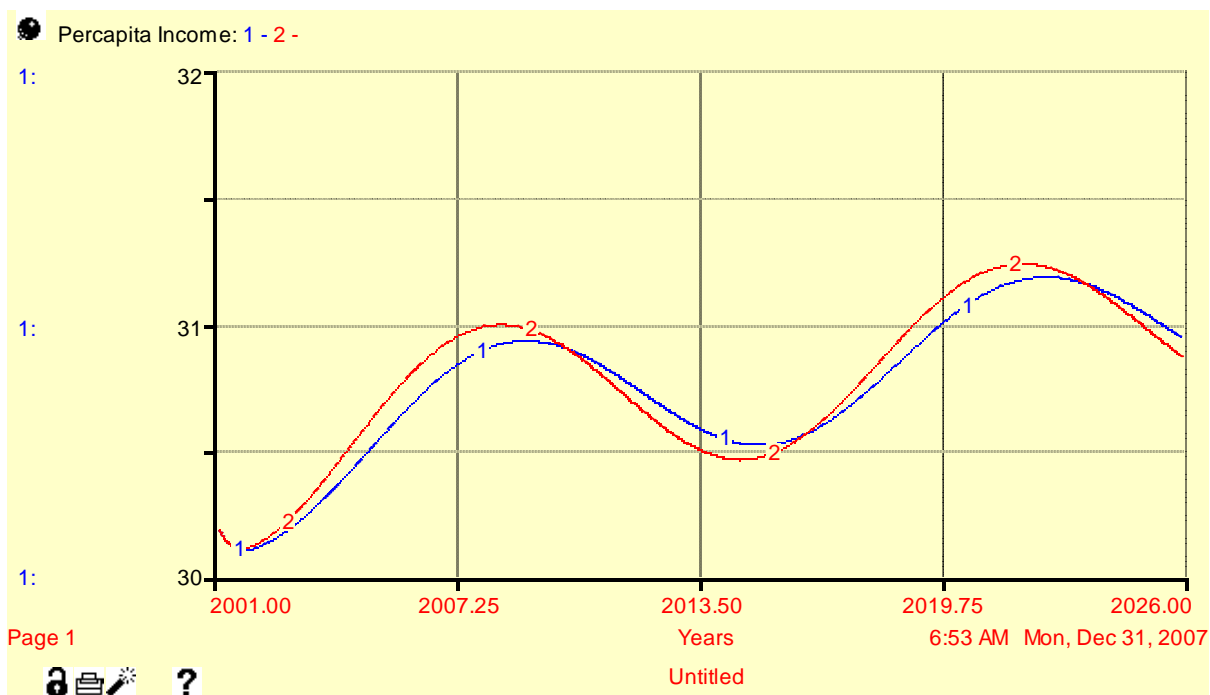Figure 2: Total Population in land use change scenario

Figure 3: Per capita income in land use change scenario

Finally, the change in land use leads to small changes in the production of non-commodities. As Figure 4 shows forest land and grass land change in relative magnitude, and the Shannon Index, a measure of diversity, declines slightly.
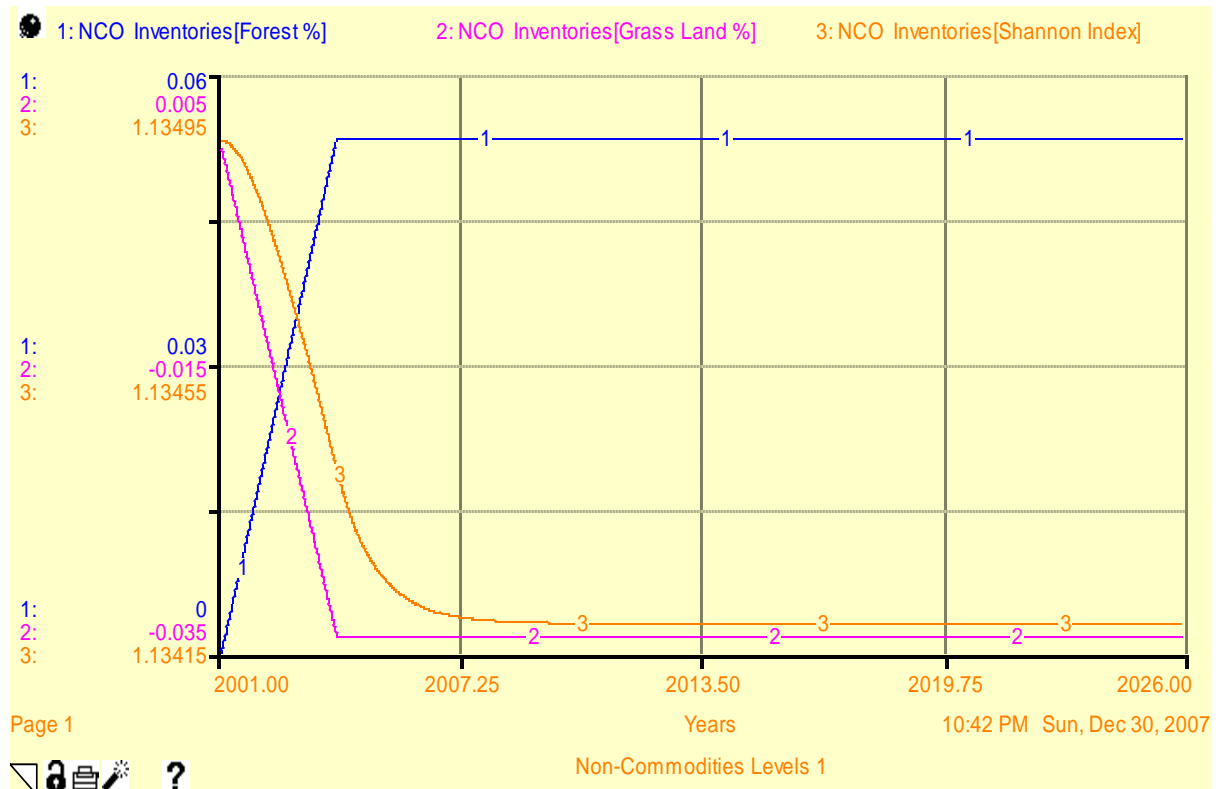

Figure 4: NCO Indicators in land use change scenario

4. Conclusions

The POMMARD model incorporates a variety of dynamic feed back mechanisms similar to ecological systems. Experimentation with the model indicates that there are short run, medium run and long run lags that make complicated dynamic patterns. In the short run, seasonal changes in tourism lead to dynamic patterns with periodicity of one year. Feed back between income and migration generate dynamic patterns with periodicity of a decade or more. Demographic feedback effects generate periods of several generations in length.

Experimentation also reveals how the interactions between economics, ecology, and quality of life sometimes involve negative feed back effects, such as the relationship between income and migration, and in other cases involve positive feedback effects, such as the multiplier process among regional sectors. Fortunately (and realistically) all these feedback effects are stable and lead to steady states.

Much work remains. As the model is populated with data from the 11 regions, we will discover the consequences of differences among places. The model is also being tested as a tool for policy analysis. Significant work remains to develop meaningful policy scenarios.

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