The European Forest and Agricultural Sector Optimization Model - EUFASOM

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Abstract

Land use is a key factor to social wellbeing and has become a major component in political negotiations. This paper describes the mathematical structure of the European Forest and Agricultural Sector Optimization Model. The model represents simultaneously observed resource and technological heterogeneity, global commodity markets, and multiple environmental qualities. Land scarcity and land competition between traditional agriculture, forests, nature reserves, pastures, and bioenergy plantations is explicitly captured. Environmental change, technological progress, and policies can be investigated in parallel. The model is well-suited to estimate competitive economic potentials of land based mitigation, leakage, and synergies and trade-offs between multiple environmental objectives.

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The European Forest and Agricultural Sector Optimization Model

Introduction and Literature

Land use is a key factor to social wellbeing and has become a major component in political negotiations. Land use affects food supply, employment, energy security, water, climate, and ecosystems. Over the last few decades, technical progress and intensifications have ensured a large increase in food supply (Briunsma, 2003) enough to potentially eradicate malnutrition. However, projected population developments and their impacts on demand for food, land, energy, and water as well as feedbacks of environmental change may put additional pressure on food production technologies in the next decades.

The food and fiber production achievements of past decades in the agricultural and forest sectors have taken a toll on the environment. Particularly, these sectors are blamed for contributions to greenhouse gas emissions, ecosystem destruction and associated biodiversity losses, water shortage and contamination, and land degradation. On the other hand, land use changes in agriculture and forestry are considered as potential remedies to environmental problems (Smith et al. 2008).

The European Union has formulated ambitious objectives regarding bioenergy production, reduction of greenhouse gas emissions, and biodiversity protection (European Economic Community 1992, European Union 2003; Commission of the European Communities 2008). By 2020, the EU has committed to a reduction by at least 20% of its total greenhouse gas emissions relative to 1990 levels, a 20% share of renewable energies in its energy production, and a 10% share of biofuels in its petrol and diesel consumption. Meeting these targets will involve significant impacts on land use and land use management. These developments have raised questions regarding their effects on agricultural and forestry products markets and competition for land between forestry, food and non-food agriculture. Concern has also been growing regarding the net environmental impacts of these changes and the potential sources of leakage (for example through intensification of agricultural production leading to increased agricultural emissions or international displacements of emissions through deforestation, e.g. Rajagopal, D. & Zilberman, D. 2007). Therefore, integrated modeling approaches are needed to tackle these issues.

While the production of food, fiber, fuel, and timber is internalized through international markets, most environmental and welfare distributional impacts are not. Because markets for most environmental goods and services do not exist, private land use decisions are socially inefficient. To include external environmental costs in land use planning, political interference is required. However, land use policies without scientific guidance are dangerous. The scarcity of land and other resources and the complexity of interactions between land use and environment may turn today's solution into tomorrow's problem (Cowie et al. 2007). EUFASOM has been developed as an integrated scientific tool for the comprehensive economic and environmental analysis of land use and land use change.

To place EUFASOM in perspective, let us briefly review previously developed and applied tools. Existing economic land use assessment models can be distinguished a) regarding the flow of information in top-down and bottom-up systems, b) regarding the dominating analysis technique in engineering, econometric, and optimization approaches, c) regarding the system dynamics in static, recursive dynamic, and fully dynamic designs,

d) regarding the spatial scope in farm level, regional, national, multi-national, and global representations, and e) regarding the sectoral scope in agricultural, forestry, multi-sector, full economy, and coupled economic and environmental models. Additional differences involve various modeling assumptions about functional relationships (demand, supply, factor and commodity substitution) and the applied resolution over space, time, technologies, commodities, resources, and environmental impacts with the associated data. For a more detailed survey over specific land use models we refer to Lambin et al. (2000), Heistermann et al. (2006) and van der Werf and Peterson (2007).

The variation in methods indicates that land use is a complex system, whose interdependencies cannot be appropriately captured by a single approach. Instead, different methods are applied to address different questions. Using the above described classifications, EUFASOM could be characterized as a bottom-up, optimization, fully dynamic, multi-national, agricultural and forest sector model. In addition, the model portrays detailed environmental relationships and global agricultural and forestry commodity trade.

Why build another land use model? Three major arguments can be made. First, EUFASOM and its US counterpart (Alig et al. 1998) are currently the only bottom-up models, which portray the competition between agriculture, forestry, bioenergy, and nature reserves for scarce land at large scales. These models integrate observed variation in land qualities and technologies with environmental impacts and global market feedbacks. This approach enables the quantification of economic potentials for environmental problem mitigation but also the estimation of leakage effects. Leakage of environmental impacts is perhaps the biggest threat to land use policies, yet it is typically ignored in bottom-up models. Second, EUFASOM goes beyond the majority of existing economic models in portraying the environmental effects of land use. Multiple greenhouse gas and soil state impacts are estimated with detailed environmental process models. The complex dynamic relationship between land management trajectories and soil quality is represented through Markov chains (Schneider 2007). A parallel to EUFASOM developed European wetland optimization model (Jantke and Schneider 2007) estimates the impacts of land use impacts on conservation of 69 wetland species. Thus, EUFASOM is better equipped than previous models to assess impacts and interdependencies of climate, biodiversity, soil, and food policies.

Thirdly, although searches through the scientific literature may reveal numerous integrated land use assessments, the number of maintained state-of-the-art models is small. Essentially, many land use models are dissertation products where the requirement of independent work limits the quality of data and model. EUFASOM is part of an integrated assessment framework where a large team of collaborating researchers from different countries and different disciplines synthesize data, models, and expertise. The model is available for other researchers provided that improvements are shared.

Data

Bottom-up models are generally data intensive both with respect to inputs and outputs. Input data for EUFASOM describe important properties of resources, production technologies, and agricultural and forestry markets. Generally, while resource data are mainly derived from observations, economic data are computed based on producer surveys or engineering methods, environmental impacts based of land management from simulations with biophysical process models, and market data from national and international statistics. The following descriptions of EUFASOM input data can only give a brief overview. Detailed information on specific data item are available from the authors.

Most raw data are not directly used in EUFASOM but undergo transformations involving model processing, aggregation, and calibration. Detailed meteorological, nitrogen deposition, and soil data over more than 1,000 homogeneous response units (HRU) within the European Union (Balkovič 2007) are used as inputs to the EPIC model. For each HRU and all land use and land management alternatives, the EPIC model simulates in daily time steps biomass growth and multiple environmental impacts concerning greenhouse gas emissions, soil organic carbon, erosion, and nutrient leaching. However, only biomass yields and environmental impacts are passed to EUFASOM. As a result, climate and soil data are only implicitly contained in EUFASOM.

Resource data in EUFASOM include region and time period specific endowments for land quality classes, existing forests, labor, and water. National soil type distributions are estimated from a European Soil Database as described in Balkovič 2007. Existing and suitable areas for five wetland types are estimated through a GIS based spatial analysis (Schleupner 2007).

Economic data for basic agricultural management technologies are derived from the European Farm Accountancy Data Network surveys (European Commission 2008). Bioenergy data for production and processing of bioenergy are taken from results of the European Non-Food Agriculture consortium (ENFA 2008). Agricultural management costs, for which data do not exist, are estimated based on engineering equations (Hallam et al. 1999). Forest stand data are estimated with the OSKAR model based on sub-country level inventories of forest stocks, tree species and age classes covering most of Europe.

The OSKAR model employs globally applicable biophysical principles, species characteristics, and expected climate change effects predicted by the LPJ global ecosystem model (Sitch et al. 2003) to estimate forest biomass, carbon storage, forestry production and forest management costs. Forest industry inputs are based on Pöyry consulting expert estimates. Forest products life time data are based on Eggers (2002).

Current production, consumption, trade, and price data for agricultural and forest commodities are taken from EUROSTAT and FAOSTAT. Assumptions about population and gross domestic product developments and technical progress are taken from GTAP.

Model structure

This section documents the principal mathematical structure of EUFASOM, which is relatively unaffected by data updates or model expansion towards greater detail. EUFASOM is designed to emulate the full impacts of European land use on agricultural and forest markets and on environmental qualities related to land use. The model contains several key components: natural and human resource endowments, agricultural and forest production factor markets, primary and processed commodity markets, agricultural and forest technologies, and agricultural policies. Because of data requirements and computational restrictions, sector models cannot provide the same level of detail as do farm level or regional models. Rather than trying to depict millions of individual farms, EUFASOM represents typical crop, livestock, forest, and bioenergy enterprises for 23 EU member states. Possible producer adaptation is integrated through a large set of alternative land management technologies (Table 1). These technologies are described through Leontief production possibilities each of it specifying fixed quantities of multiple inputs and multiple outputs. International markets and trade relationships are currently portrayed through eleven international regions.

EUFASOM is a large mathematical program. The objective function maximizes total agricultural economic surplus subject to a set of constraining equations, which define a convex feasible region for all endogenous land use decision variables. Full model activations contains more than 6 Million individual variables and more than 1 Million individual equations. Equations and variables are condensed into indexed blocks (see Table 2). Solving EUFASOM involves the task of finding the optimal levels for all endogenous variables, i.e. those levels which maximize the economic surplus subject to compliance with all constraining equations. Economic surplus is computed as the sum across time, space, commodities, and resources of total consumers' surplus, producers' or resource owners' surplus, and governmental net payments to the agricultural sector minus the total cost of production, transportation, and processing. Basic economic theory demonstrates that maximization of the sum of consumers' plus producers' surplus yields the competitive market equilibrium. Thus, the optimal variable levels can be interpreted as equilibrium levels for land use activities under given economic, political, and technological conditions. The shadow prices on resource and commodity balance equations give market clearing prices.

To facilitate understanding of the EUFASOM structure, we will first describe the set of constraining equations and subsequently explain the objective function. Variables are denoted by capital letters. Constraint coefficients and right hand side values are represented by small italic letters. Indices of equations, variables, variable coefficients, and right hand sides are denoted by subscripts. The constraining equations depict resource and technological restrictions, intertemporal relationships, and environmental interactions.

Resource and technological restrictions

Supply and demand balance equations link agricultural and forest activities to commodity markets (Equation 1) and to factor markets and resource endowments (Equation 2). Specifically, for each region, period, and product, the total amount allocated to domestic consumption (DEMD), processing (PROC), and exports (TRAD[1]) cannot exceed the total supply through crop production (CROP), bioenergy plantations (BIOM), timber harvesting (HARV), production from standing forests (TREE), nature reserves (ECOL), livestock raising (LIVE), or imports (TRAD). Note that the explicit supply variable SUPP depicts special animal feeds and agricultural commodities in non-EU regions, for which technological data are not available.

The technical coefficients $\alpha^{CROP}_{r,t,i,j,c,u,q,m,p,y}$, $\alpha^{PAST}_{r,t,i,j,s,u,q,m,p,y}$, $\alpha^{BIOM}_{r,t,i,j,b,u,q,m,p,y}$, $\alpha^{HARV}_{r,t,i,j,f,u,a,m,p,y}$, $\alpha^{TREE}_{r,t,i,j,f,u,a,m,p,y}$, $\alpha^{ECOL}_{r,t,i,j,s,u,x,m,p,y}$, $\alpha^{LIVE}_{r,t,l,u,m,p,y}$, $\alpha^{FEED}_{r,t,l,m,y}$, and $\alpha^{PROC}_{r,t,m,y}$ indicate input requirements (negative values) of output yields (positive values). The structure of Equation 1 allows for an efficient representation of multi-input and multi-output production and for multi level processing, where outputs of the first process become inputs to the next process. Supply and demand relationships for agricultural production factors are shown in Equation 2. Particularly, the total use of each production factor or resource over all agricultural and forest activities cannot exceed the total supply of these factors (RESR) in each region and period.

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[1] The first index of the TRAD variables denotes the exporting region or country, the second denotes the importing region or country.

$$
\begin{pmatrix}
+\sum_{m}\left(\alpha^{PROC}_{r,t,m,y}\cdot PROC_{r,t,m}\right) \\
+\sum_{m}\left(\alpha^{FEED}_{r,t,l,m,y}\cdot FEED_{r,t,l,m}\right) \\
+\sum_{\tilde{r}} TRAD_{r,\tilde{r},t,y} \\
+DEMD_{r,t,y}
\end{pmatrix}
\le
\begin{pmatrix}
+\sum_{j,v,c,u,q,m,p}\left(\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,y}\cdot CROP_{r,t,j,v,c,u,q,m,p}\right) \\
+\sum_{j,v,s,u,q,m,p}\left(\alpha^{PAST}_{r,t,j,v,s,u,q,m,p,y}\cdot PAST_{r,t,j,v,s,u,q,m,p}\right) \\
+\sum_{j,v,b,u,q,m,p}\left(\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,y}\cdot BIOM_{r,t,j,v,b,u,q,m,p}\right) \\
+\sum_{j,v,f,u,a,m,p}\left(\alpha^{HARV}_{r,t,j,v,f,u,a,m,p,y}\cdot HARV_{r,t,j,v,f,u,a,m,p}\right) \\
+\sum_{j,v,f,u,a,m,p}\left(\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,y}\cdot TREE_{r,t,j,v,f,u,a,m,p}\right) \\
+\sum_{j,v,s,u,x,m,p}\left(\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,y}\cdot ECOL_{r,t,j,v,s,u,x,m,p}\right) \\
+\sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,y}\cdot LIVE_{r,t,l,u,m,p}\right) \\
+\sum_{\tilde{r}} TRAD_{\tilde{r},r,t,y} \\
+SUPP_{r,t,y}
\end{pmatrix}
$$

Equation 1 Commodity balance (∀ t, r, and y)

Livestock farmers have a choice between different animal diets. These diets are depicted by the variable FEED and contain unprocessed crops, processed concentrates, and special feed additives. Depending on animal type and performance, diets have to meet certain nutritional targets. These nutritional restriction are integrated in EUFASOM as shown in Equation 3. Several things should be noted. First, restrictions are only active if the nutritional coefficients $\alpha^{LIVE}_{r,t,l,u,m,p,n}$ are non-zero. Second, the nutritional coefficients for feeds differ between animals types.

Livestock raising produces different types of animal manure. Manure can be returned as organic fertilizer to fields or digested to generate energy. EUFASOM restricts the total usage of manure from animal houses as fertilizer or energy source to be equal or less than the total amount of manure produced through all livestock operations. Note that the impact of manure from grazing animals is not part of this balance but is included in Equation 9.

$$\left(\begin{array}{l}+\sum_{j,v,c,u,q,m,p}\left(\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,i}\cdot CROP_{r,t,j,v,c,u,q,m,p}\right)\\+\sum_{j,v,s,u,q,m,p}\left(\alpha^{PAST}_{r,t,j,v,s,u,q,m,p,i}\cdot PAST_{r,t,j,v,s,u,q,m,p}\right)\\+\sum_{j,v,b,u,q,m,p}\left(\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,i}\cdot BIOM_{r,t,j,v,b,u,q,m,p}\right)\\+\sum_{j,v,f,u,a,m,p}\left(\alpha^{HARV}_{r,t,j,v,f,u,a,m,p,i}\cdot HARV_{r,t,j,v,f,u,a,m,p}\right)\\+\sum_{j,v,f,u,a,m,p}\left(\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,i}\cdot TREE_{r,t,j,v,f,u,a,m,p}\right)\\+\sum_{j,v,s,u,x,m,p}\left(\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,i}\cdot ECOL_{r,t,j,v,s,u,x,m,p}\right)\\+\sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,i}\cdot LIVE_{r,t,l,u,m,p}\right)\\+\sum_{m}\left(\alpha^{PROC}_{r,t,m,i}\cdot PROC_{r,t,m}\right)\\+\sum_{m}\left(\alpha^{FEED}_{r,t,l,m,i}\cdot FEED_{r,t,l,m}\right)\end{array}\right)\leq RESR_{r,t,i}$$

Equation 2 Resource balance (∀ r, t, and i)

$$\sum_{l,m}\left(\alpha^{FEED}_{r,t,l,m,n^{max}}\cdot FEED_{r,t,l,m}\right)\leq\sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,n^{max}}\cdot LIVE_{r,t,l,u,m,p}\right)$$
$$\sum_{l,m}\left(\alpha^{FEED}_{r,t,l,m,n^{min}}\cdot FEED_{r,t,l,m}\right)\geq\sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,n^{min}}\cdot LIVE_{r,t,l,u,m,p}\right)$$

Equation 3 Animal feeding restrictions (∀ r, t, and n^{min}/n^{max})

$$\begin{pmatrix} +\sum_{j,v,c,u,q,m,p}\left(\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,i}\cdot CROP_{r,t,j,v,c,u,q,m,p}\right) \\ +\sum_{m}\left(\alpha^{PROC}_{r,t,m,i}\cdot PROC_{r,t,m}\right) \end{pmatrix} \le \sum_{l,u,m,p}\left(\alpha^{LIVE}_{r,t,l,u,m,p,i}\cdot LIVE_{r,t,l,u,m,p}\right)$$

Equation 4 Manure balance (∀ r, t, and i)

Limits to agricultural production arise not only from technologies but also from the use of scarce and immobile resources. Particularly, the use of agricultural land, labor, irrigation water, and grazing units is either physically limited by regional endowments or economically limited by upward sloping supply curves for these private or public resources. In EUFASOM, all production, processing, and nature reserve variables (CROP, LIVE, BIOM, ECOL, TREE, HARV, FEED, and PROC) have associated with them resource use coefficients ($\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,i}$, $\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,i}$, $\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,i}$, $\alpha^{LIVE}_{r,t,l,u,m,p,i}$, $\alpha^{HARV}_{r,t,j,v,f,u,a,m,p,i}$, $\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,i}$, $\alpha^{FEED}_{r,t,l,m,i}$, $\alpha^{PROC}_{r,t,m,i}$), which resource requirements per unit of production. The mathematical representation of physical resource constraints in EUFASOM is straightforward and displayed in Equation 5. These equations simply force the total use of natural or human resources to be at or below given regional endowments $\beta_{r,t,i}$. Economic resource constraints are part of the objective function.

$$RESR_{r,t,i} \le \beta_{r,t,i}$$

Equation 5 Resource limitations (∀ r, t, and i)

Intertemporal restrictions

Intertemporal restrictions form an important part of EUFASOM and include initial conditions, forest and soil state transition equations, and land use change restrictions. Terminal values for forests are included in the objective function section. Initial conditions link activities in the first model period (INIT) to observed values (Equation 6). These conditions can be placed at a detailed or aggregated level. For example, while forest activities in EUFASOM include three alternative thinning regimes, observed forest inventories are only available by region, age cohort, and species. Thus, Equation 6 enforces these aggregated identities but let the model choose the optimal distribution of thinning regimes in the first period. Similarly, the distribution of existing and potential wetlands can be enforced for individual wetland types and size classes or for aggregates.

$$\mathrm{INIT}_{r,j,v,s,u,q,m,p} = \phi_{r,j,v,s,u,q,m,p}$$

Equation 6 Initial land allocation (∀ r, t, v, s, u, q, m, and p)

In each region and for each period, EUFASOM explicitly distinguishes standing forests by species composition, age cohort, ownership, management, and soil characteristics. Age cohorts and time periods are both resolved to 5-year intervals. The distribution of forest types in a certain period is constrained by planting and harvesting activities in previous time periods (Equation 7). Particularly, the area of standing and harvested forests above the first age cohort cannot exceed the area of the same forest type one period earlier and one age class lower. However, if a forest has reached the last age cohort, it will remain in this cohort in the next period as well.

$$\begin{pmatrix} +\text{TREE}_{r,t,j,v,f,u,a,m,p}\big|_{a>1} \\ +\text{HARV}_{r,t,j,v,f,u,a,m,p}\big|_{a>1} \end{pmatrix} \leq \begin{pmatrix} +\text{TREE}_{r,t-1,j,v,f,u,a-1,m,p}\big|_{t>1\wedge a>1} \\ +\text{TREE}_{r,t-1,j,v,f,u,a,m,p}\big|_{t>1\wedge a=A} \\ +\text{INIT}_{r,j,v,f,u,a,m,p}\big|_{t=1} \end{pmatrix}$$

Equation 7 Forest transition (∀ r, t, j, v, f, u, a, m, and p)

While new forest plantations are not affected by Equation 7, EUFASOM limits the possible species change via reforestation (Equation 8). Particularly, only if the parameter $\vartheta_{r,f,\tilde{f}}$ has a value of 1, then species $\tilde{f}$ can be fully planted on all previously harvested areas of species f. For values less than 1, allowed reforestation of $\tilde{f}$ on harvested areas of f is accordingly reduced. No restriction is currently placed on afforestation, i.e. if agricultural land is converted to forest, all possible species for this region can be planted.

$$\begin{pmatrix} +\sum_{v,\tilde{f},m,p} \vartheta_{r,f,\tilde{f}} \cdot \text{TREE}_{r,t,j,v,\tilde{f},u,a,m,p}\Big|_{a=1} \\ +\text{LUCH}_{r,t,j,f,u,-} \end{pmatrix} \leq \begin{pmatrix} +\sum_{\tilde{t},v,m,p} \text{HARV}_{r,\tilde{t},j,v,f,u,a,m,p}\Big|_{\tilde{t}\leq t} \\ +\text{LUCH}_{r,t,j,f,u,+} \end{pmatrix}$$

Equation 8 Reforestation (∀ r, t, j, and f)

The land management path over time influences crop yields and emissions. While reduced tillage may sequester soil organic carbon on previously deep-tilled soils, positive net emissions may occur if reduced tillage is employed after several decades of zero tillage. The complex relationship between management dynamics and soil fertility is approximated in EUFASOM by a Markov Process (Equation 9). Different soil states are represented by the index v. The soil state transition probability matrices $\rho_{r,j,\tilde{v},s,u,x,m,p,v}$ for crops, biomass plantations, forests, and ecological reserves contain the probabilities of moving from soil state $\tilde{v}$ to soil state v after one time period. These matrices are exogenously derived from EPIC model simulations (Schmid et al. 2007). Transition probabilities differ across regions, soil textures, planted species, and management alternatives. A more detailed technical explanation and application to the effects different tillage methods is contained in Schneider (2007).

$$\begin{pmatrix} +\sum\limits_{c,u,q,m,p} CROP_{r,t,j,v,c,u,q,m,p} \\ +\sum\limits_{s,u,q,m,p} PAST_{r,t,j,v,s,u,q,m,p} \\ +\sum\limits_{b,u,q,m,p} BIOM_{r,t,j,v,b,u,q,m,p} \\ +\sum\limits_{f,u,a,m,p} TREE_{r,t,j,v,f,u,a,m,p} \\ +\sum\limits_{s,u,x,m,p} ECOL_{r,t,j,v,s,u,x,m,p} \end{pmatrix} \leq \begin{pmatrix} +\sum\limits_{\tilde{v},c,u,q,m,p} \left(\rho^{CROP}_{r,j,\tilde{v},c,u,q,m,p,v} \cdot CROP_{r,t-1,j,\tilde{v},c,u,q,m,p}\right) \\ +\sum\limits_{\tilde{v},s,u,q,m,p} \left(\rho^{PAST}_{r,j,\tilde{v},s,u,q,m,p,v} \cdot PAST_{r,t-1,j,\tilde{v},s,u,q,m,p}\right) \\ +\sum\limits_{\tilde{v},b,u,q,m,p} \left(\rho^{BIOM}_{r,j,\tilde{v},b,u,q,m,p,v} \cdot BIOM_{r,t-1,j,\tilde{v},b,u,q,m,p}\right) \\ +\sum\limits_{\tilde{v},f,u,a,m,p} \left(\rho^{TREE}_{r,j,\tilde{v},f,u,a,m,p,v} \cdot TREE_{r,t-1,j,\tilde{v},f,u,a,m,p}\right) \\ +\sum\limits_{\tilde{v},s,u,x,m,p} \left(\rho^{ECOL}_{r,j,\tilde{v},s,u,x,m,p,v} \cdot ECOL_{r,t-1,j,\tilde{v},s,u,x,m,p}\right) \end{pmatrix}$$

Equation 9 Soil state transition (∀ r, t, j, and v)

Dynamic changes in the agricultural and forest sector include changes in land allocation between forests, crop production, bioenergy plantations, and nature reserves. For each period, EUFASOM traces these land use changes (LUCH) explicitly, both with respect to the preceding period (Equation 10) and with respect to the initial allocation (Equation 11). Changes to the preceding periods are penalized with adjustment costs in the objective function. Land use changes with respect to the initial situation are restricted to maximum transfer $\eta_{r,t,j,s,u,\{+,-\}}$. These upper bounds on land use changes are determined by geographical analyses regarding suitability. Suitability criteria for wetland restoration are described in Schleupner (2007). If $\eta_{r,t,j,s,u,\{+,-\}}$ equals zero, then Equation 11 is not enforced.

$$\text{LUCH}_{r,t,j,s,u,\{+,-\}} = \psi_{\{+,-\}} \cdot \begin{pmatrix} +\sum_{v,q,m,p}\left(\text{CROP}_{r,t,j,v,s,u,q,m,p} - \text{CROP}_{r,t-1,j,v,s,u,q,m,p}\Big|_{t>1}\right) \\ +\sum_{v,q,m,p}\left(\text{PAST}_{r,t,j,v,s,u,q,m,p} - \text{PAST}_{r,t-1,j,v,s,u,q,m,p}\Big|_{t>1}\right) \\ +\sum_{v,q,m,p}\left(\text{BIOM}_{r,t,j,v,s,u,q,m,p} - \text{BIOM}_{r,t-1,j,v,s,u,q,m,p}\Big|_{t>1}\right) \\ +\sum_{v,a,m,p}\left(\text{TREE}_{r,t,j,v,s,u,a,m,p} - \text{TREE}_{r,t-1,j,v,s,u,a,m,p}\Big|_{t>1}\right) \\ +\sum_{v,x,m,p}\left(\text{ECOL}_{r,t,j,v,s,u,x,m,p} - \text{ECOL}_{r,t-1,j,v,s,u,x,m,p}\Big|_{t>1}\right) \\ -\sum_{v,q,m,p}\phi_{r,j,v,s,u,q,m,p}\Big|_{t=1} \end{pmatrix}$$

Equation 10 Land use change (∀ r, t, j, s, u, and $\{+,-\}$)

$$\text{LUCH}_{r,t,j,s,u,\{+,-\}} \leq \eta_{r,t,j,s,u,\{+,-\}}\Big|_{\eta_{r,t,j,s,u,\{+,-\}} \geq 0}$$

Equation 11 Land use change limits (∀ r, t, j, s, and u)

Environmental Interactions

The quantification of interactions between regulated and unregulated environmental qualities and agricultural, forest, and nature conservation activities is a major component for integrated land use analyses. The basic EUFASOM contains accounting equations a) for environmental fluxes (Equation 12), i.e. greenhouse gas, nutrient, and soil emissions, and b) for environmentally important stocks (Equation 13) other than resources accounted in Equation 2. These stocks include dead wood pools in forests but also wood product pools both of which impact greenhouse gas balances. The mathematical formulation of Equation 12 is a simple summation of activity levels multiplied by impact coefficients over species, soil qualities, management, sites, and policies. The environmental impact coefficients, i.e. $\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,e}$, $\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,e}$, $\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,e}$, $\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,e}$, $\alpha^{PROC}_{r,t,m,e}$, and $\alpha^{FEED}_{r,t,l,m,e}$, form one part of the link from biochemophysical process models to EUFASOM.

$$
EMIT_{r,t,e} = \begin{pmatrix}
+\sum_{j,v,c,u,q,m,p} \left(\alpha^{CROP}_{r,t,j,v,c,u,q,m,p,e} \cdot CROP_{r,t,j,v,c,u,q,m,p}\right) \\
+\sum_{j,v,c,u,q,m,p} \left(\alpha^{PAST}_{r,t,j,v,c,u,q,m,p,e} \cdot PAST_{r,t,j,v,c,u,q,m,p}\right) \\
+\sum_{j,v,b,u,q,m,p} \left(\alpha^{BIOM}_{r,t,j,v,b,u,q,m,p,e} \cdot BIOM_{r,t,j,v,b,u,q,m,p}\right) \\
+\sum_{j,v,f,u,a,m,p} \left(\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,e} \cdot TREE_{r,t,j,v,f,u,a,m,p}\right) \\
+\sum_{j,v,s,u,x,m,p} \left(\alpha^{ECOL}_{r,t,j,v,s,u,x,m,p,e} \cdot ECOL_{r,t,j,v,s,u,x,m,p}\right) \\
+\sum_{s,u,m,p} \left(\alpha^{LIVE}_{r,t,s,u,m,p,e} \cdot LIVE_{r,t,s,u,m,p}\right) \\
+\sum_{s,u,\{+,-\}} \left(\alpha^{LUCH}_{r,t,s,u,\{+,-\},e} \cdot LUCH_{r,t,s,u,\{+,-\}}\right) \\
+\sum_{m} \left(\alpha^{PROC}_{r,t,m,e} \cdot PROC_{r,t,m}\right) \\
+\sum_{m,l} \left(\alpha^{FEED}_{r,t,l,m,e} \cdot FEED_{r,t,l,m}\right) \\
+STCK_{r,t,e} - STCK_{r,t-1,e}
\end{pmatrix}
$$

Equation 12 Emission accounting equation (∀ r, t, and e)

$$
STCK_{r,t,d} = \begin{pmatrix}
+\partial_{r,t-1,d} \cdot STCK_{r,t-1,d} \\
+\sum_{j,v,f,u,a,m,p} \left(\alpha^{TREE}_{r,t,j,v,f,u,a,m,p,d} \cdot TREE_{r,t,j,v,f,u,a,m,p}\right) \\
+\sum_{j,v,f,u,a,m,p} \left(\alpha^{HARV}_{r,t,j,v,f,u,a,m,p,d} \cdot HARV_{r,t,j,v,f,u,a,m,p}\right) \\
+\sum_{f,u} \left(\alpha^{LUCH}_{r,t,f,u,-,d} \cdot LUCH_{r,t,f,u,-}\right)
\end{pmatrix}
$$

Equation 13 Dead wood and commodity stock equation (∀ r, t, and d)

Equation 13 computes the current stock levels as sum of discounted previous stocks plus stock additions from current activities. Stock discounts are derived from dead wood decomposition and product lifetime functions (Eggers 2002).

All environmental qualities (EMIT, STCK, RESR) can be subjected to minimum or maximum restrictions[1]. In addition, objective function coefficients on emission or technology variables allow the representation of environmental taxes and subsidies. Note that the basic model setup establishes only a one-directional link from environmental impact models to EUFASOM. Environmental feedbacks can be included via iterative links. Similarly, inconsistencies between aggregated and geographically downscaled EUFASOM results could be decreased through iterative procedures.

Objective Function

EUFASOM simulates detailed land use adaptations, market and trade equilibrium changes, and environmental consequences for political, technical, and environmental scenarios related to agriculture, forestry, and nature. The objective function incorporates all major drivers for these changes, i.e. cost coefficients for land use and commodity processing alternatives, adjustment costs for major land use changes, market price changes for commodities and production factors, trade costs, political incentives and disincentives, and terminal values for standing forests. Mathematically, EUFASOM maximizes consumer surplus in final commodity markets plus producer or resource owner surplus in all price-endogenous factor markets minus technological, trade, adjustment, and policy related costs plus subsidies and terminal values. Future costs and benefits are discounted by an exogenously specified rate.

[1] The corresponding equations are trivial and therefore omitted.

$$
\text{Maximize WELF} = \sum_{t} \left(\partial_t \cdot \left(\begin{array}{l}
\sum_{r,y} \left[\int_{y} \varphi^{DEMD}_{r,t,y} \left(\mathrm{DEMD}_{r,t,y} \right) d(\cdot) \right] \\
- \sum_{r,y} \left[\int_{n} \varphi^{SUPP}_{r,t,y} \left(\mathrm{SUPP}_{r,t,y} \right) d(\cdot) \right] \\
- \sum_{r,i} \left[\int_{n} \varphi^{RESR}_{r,t,i} \left(\mathrm{RESR}_{r,t,i} \right) d(\cdot) \right] \\
- \sum_{r,j,v,c,u,q,m,p} \left(\tau^{\mathrm{CROP}}_{r,t,j,v,c,u,q,m,p} \cdot \mathrm{CROP}_{r,t,j,v,c,u,q,m,p} \right) \\
- \sum_{r,j,v,s,u,q,m,p} \left(\tau^{\mathrm{PAST}}_{r,t,j,v,s,u,q,m,p} \cdot \mathrm{PAST}_{r,t,j,v,s,u,q,m,p} \right) \\
- \sum_{r,j,v,b,u,q,m,p} \left(\tau^{\mathrm{BIOM}}_{r,t,j,v,b,u,q,m,p} \cdot \mathrm{BIOM}_{r,t,j,v,b,u,q,m,p} \right) \\
- \sum_{r,j,v,f,u,a,m,p} \left(\tau^{\mathrm{HARV}}_{r,t,j,v,f,u,a,m,p} \cdot \mathrm{HARV}_{r,t,j,v,f,u,a,m,p} \right) \\
- \sum_{r,j,v,f,u,a,m,p} \left(\tau^{\mathrm{TREE}}_{r,t,j,v,f,u,a,m,p} \cdot \mathrm{TREE}_{r,t,j,v,f,u,a,m,p} \right) \\
- \sum_{r,j,v,s,u,x,m,p} \left(\tau^{\mathrm{ECOL}}_{r,t,j,v,s,u,x,m,p} \cdot \mathrm{ECOL}_{r,t,j,v,s,u,x,m,p} \right) \\
- \sum_{r,l,u,m,p} \left(\tau^{\mathrm{LIVE}}_{r,t,l,u,m,p} \cdot \mathrm{LIVE}_{r,t,l,u,m,p} \right) \\
- \sum_{r,m} \left(\tau^{\mathrm{PROC}}_{r,t,m} \cdot \mathrm{PROC}_{r,t,m} \right) \\
- \sum_{r,l,m} \left(\tau^{\mathrm{FEED}}_{r,t,l,m} \cdot \mathrm{FEED}_{r,t,l,m} \right) \\
- \sum_{r,j,u,\{+,-\}} \left(\tau^{\mathrm{LUCH}}_{r,t,j,s,u,\{+,-\}} \cdot \mathrm{LUCH}_{r,t,j,s,u,\{+,-\}} \right) \\
- \sum_{r,\tilde{r},y} \left(\tau^{\mathrm{TRADE}}_{r,\tilde{r},t,y} \cdot \mathrm{TRAD}_{r,\tilde{r},t,y} \right) \\
- \sum_{r,e} \left(\tau^{\mathrm{EMIT}}_{r,t,e} \cdot \mathrm{EMIT}_{r,t,e} \right)
\end{array} \right) \right) + \sum_{r,j,v,f,u,a,m,p} \left(\nu^{\mathrm{TREE}}_{r,j,v,f,u,a,m,p} \cdot \mathrm{TREE}_{r,T,j,v,f,u,a,m,p} \right)
$$

Equation 14 Economic surplus maximizing objective function

The technical realization of EUFASOM's objective function is displayed in Equation 14[1]. Note that consumers' and producers' surplus is not directly calculated. Instead, EUFASOM computes the difference between the areas underneath all demand curves minus the areas underneath all supply curves. For competitive markets, this technique is equivalent to surplus maximization. Moreover, the theoretically nonlinear supply and demand area integrals in EUFASOM are linearly approximated. The approximation is given in the appendix. Supply and demand curves are specified as linear or constant elasticity functions. To avoid infinite integrals, constant elasticity demand functions are truncated. A truncated demand curve is horizontal between zero and a small demand quantity and downward sloping thereafter.

To place EUFASOM solutions in perspective, alternative objectives can be specified. In particular, Equation 15 allows the computation of commodity supply frontiers and technical limits on emission reductions. Alternative objectives can be activated for single or multiple regions, periods, commodities, and emission accounts by assigning a value of one to exogenous control parameters ($\theta^{DEMD}_{r,t,y}$, $\theta^{ECOL}_{r,t,j,v,s,u,x,m,p}$, $\theta^{EMIT}_{r,t,e}$). If the sum over all control parameters is non-zero, EUFASOM automatically deactivates the primary surplus maximizing objective and uses the alternative objective function. The use of Equation 15 provides not only model and data insight but also shows important differences between economic and technical constraints.

---

[1] In displaying the objective function, several modifications have been made to ease readability: a) the linearly approximated integration terms are not shown explicitly, b) artificial variables for detecting infeasibilities are omitted, and c) conditions are omitted.

$$
\text{Maximize OBJ2} = \begin{pmatrix} +\sum_{r,t,y}\left(\theta^{DEMD}_{r,t,y}\cdot DEMD_{r,t,y}\right) \\ +\sum_{r,t,j,v,s,u,x,m,p}\left(\theta^{ECOL}_{r,t,j,v,s,u,x,m,p}\cdot ECOL_{r,t,j,v,s,u,x,m,p}\right) \\ -\sum_{r,t,e}\left(\theta^{EMIT}_{r,t,e}\cdot EMIT_{r,t,e}\right) \end{pmatrix}
$$

Equation 15 Alternative objective function

European Bioenergy and Wetland Targets – An EUFASOM Illustration

The main purpose of this study is to document the mathematical structure of EUFASOM. However, in this section we will briefly illustrate the use of the model through a small scenario experiment. Bioenergy production and wetland preservation constitute two major political objectives of the European government. While the first goal includes managed dedicated energy crop plantations, the second one usually requires the establishment of rather undisturbed nature reserves. Moreover, both options are mutually exclusive with food production. This raises an important questions for policymakers: how does the competition between food, bioenergy plantations, and wetland reserves for scarce land affect the competitive economic potential of these environmental goals? EUFASOM is well suited to address this question. The following scenario setup is used. First, bioenergy policies are represented by biomass targets up to 300 million wet tons. This amount of biomass would roughly be required to generate about 20% of the current total electricity consumption in the European Union. Second, to avoid negative ecological spillovers, existing wetlands and forests are protected and cannot be used for agriculture or bioenergy plantations.

Aggregated economic potentials of wetland restoration are displayed in Figure 1. The 100% biomass target corresponds to a European wide requirement of 300 million wet tons. As shown, with such a constraint, wetland subsidies as high as 800 Euro per ha are insufficient to induce restoration. For reduced biomass targets, restoration potentials are higher. In all cases, increasing opportunity costs lead to increased marginal costs of restoration. Figure 1 also illustrates that the competition between bioenergy production and wetland restoration does not increase linearly. While the difference between no and a 25% biomass target is small, a relative large gap exists between the 25% and 50% targets.

The interaction between food production and environmental goals is shown in Figure 2. The line labeled "EU25wide" shows the wetland restoration potential for wetland subsidies established in all European countries. The second line, labeled "national" forms the sum of 23 independent assessments. In each of these national assessments, the wetland subsidy is only established in the respective nation. For both setups, a 50% biomass constraint is enforced jointly over all countries. Figure 2 shows that starting from a subsidy level of 300 Euro per ha, the two lines drift apart. The sum of national assessments gives a higher restoration potential because bioenergy and agricultural production simply shift to those countries without wetland subsidy. At the highest shown subsidy level, the sum of national assessments overestimates the economic potential by almost 10 million ha.

Conclusions

This paper describes the mathematical structure of the European Forest and Agricultural Sector Optimization Model. The model has been developed to assess the economic and environmental impacts of political, technological, and environmental change on European land use. EUFASOM goes beyond existing approaches in portraying the interdependencies between food, water, bioenergy, climate, wildlife preservation, and soils. Despite a huge amount of data, variables, and equations, the model is built on simple principles. These principles are captured through 14 fundamental equations. The large model size results from repeated implementations of these equations over space, time, commodities, technologies, and environmental qualities.

The strength of EUFASOM lies in its simultaneous representation of observed resource and technological heterogeneity, global commodity markets, and multiple environmental qualities. Land scarcity and land competition between traditional agriculture, timber production, nature reserves, livestock pastures, and bioenergy plantations is explicitly captured. Environmental change, technological progress, and policies can be investigated in parallel. Consequently, EUFASOM is well-suited to a) examine the competitive economic potential of agricultural and forestry based mitigation of environmental problems and contrast these to technical or economic potentials without market feedbacks, b) estimate leakage, i.e. how European environmental policies affect non-European land use and c) analyze synergies and trade-offs between different environmental objectives.

Finally, several limitations should be noted. First, EUFASOM is a partial equilibrium model and does not adequately account for income effects. Second, EUFASOM does not value benefits and damages from different environmental qualities but considers only exogenous values, i.e. carbon prices or ecosystem values. Third, due to data constraints, validation of EUFASOM is limited to comparisons between the base period solution and observations. Fourth, the quality of the model reflects the quality of the input data and the quality of linked models. Fifth, EUFASOM results are derived from the optimal solution of a mathematical program and as such constitute point estimates without probability distribution.

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Table 1 Major indexes in EUFASOM

Index	Symbol[1]	Elements
Time Periods	t	2005-2010, 2010-2015, …, 2145-2150
Regions	r	25 EU member states, 11 Non-EU international regions
Species	s	All individual and aggregate species categories
Crops	c(s)	Soft wheat, hard wheat, barley, oats, rye, rice, corn, soybeans, sugar beet, potatoes, rapeseed, sunflower, cotton, flax, hemp, pulse
Trees	f(s)	Spruce, larch, douglas fir, fir, scottish pine, pinus pinaster, poplar, oak, beech, birch, maple, hornbeam, alnus, ash, chestnut, cedar, eucalyptus, ilex locust, 4 mixed forest types
Perennials	b(s)	Miscanthus, Switchgrass, Reed Canary Grass, Poplar, Willow, Arundo, Cardoon, Eucalyptus
Livestock	l(s)	Dairy, beef cattle, hogs, goats, sheep, poultry
Wildlife	w(s)	43 Birds, 9 mammals, 16 amphibians, 4 reptiles
Products	y	17 crop, 8 forest industry, 5 bioenergy, 10 livestock
Resources/Inputs	i	Soil types, hired and family labor, gasoline, diesel, electricity, natural gas, water, nutrients
Soil types	j(i)	Sand, loam, clay, bog, fen, 7 slope, 4 soil depth classes
Nutrients	n(i)	Dry matter, protein, fat, fiber, metabolizable energy, Lysine and
Technologies	m	alternative tillage, irrigation, fertilization, thinning, animal housing and manure management choices
Site quality	q	Age and suitability differences
Ecosystem state	x(q)	Existing, suitable, marginal
Age cohorts	a(q)	0-5, 5-10, …, 295-300 [years]
Soil state	v	Soil organic classes
Structures	u	FADN classifications (European Commission 2008)
Size classes	z(u)	< 4, 4 - < 8, 8 - < 16, 16 - < 40, 40- < 100, >= 100 all in ESU (European Commission 2008)
Farm specialty	o(u)	Field crops, horticulture, wine yards, permanent crops, dairy farms, grazing livestock, pigs and or poultry, mixed farms
Altitude levels	h(u)	< 300, 300 – 600, 600 – 1100, > 1100 meters
Environmental qualities	e	16 Greenhouse gas accounts, wind and water erosion, 6 nutrient emissions, 5 wetland types
Policies	p	Alternative policies

[1] Parent indexes are given in brackets

Table 2 Major variables in EUFASOM

Variable	Unit	Type	Description
CROP	1E3 ha	≥ 0	Crop production
PAST	1E3 ha	≥ 0	Pasture
LIVE	mixed	≥ 0	Livestock raising
FEED	mixed	≥ 0	Animal feeding
TREE	1E3 ha	≥ 0	Standing forests
HARV	1E3 ha	≥ 0	Forest harvesting
BIOM	1E3 ha	≥ 0	Biomass crop plantations for bioenergy
ECOL	1E3 ha	≥ 0	Wetland ecosystem reserves
LUCH	1E3 ha	≥ 0	Land use changes
RESR	mixed	≥ 0	Factor and resource usage
PROC	mixed	≥ 0	Processing activities
SUPP	1E3 t	≥ 0	Supply
DEMD	1E3 t	≥ 0	Demand
TRAD	1E3 t	≥ 0	Trade
EMIT	mixed	Free	Net emissions
STCK	mixed	≥ 0	Environmental and product stocks
WELF	1E6 €	Free	Economic Surplus

Table 3 Major parameters in EUFASOM

Symbol	Description
α	Technical coefficients (yields, requirements, emissions)
τ	Objective function coefficients
φ	Supply and demand functions
∂	Discount rate, product depreciation, dead wood decomposition
β	Resource endowments
ϑ	Soil state transition probabilities
η	Land use change limits
ϕ	Initial land allocation
ψ	Sign switch ($\psi_{+} = 1$, $\psi_{-} = -1$)
θ	Alternative objective function parameters

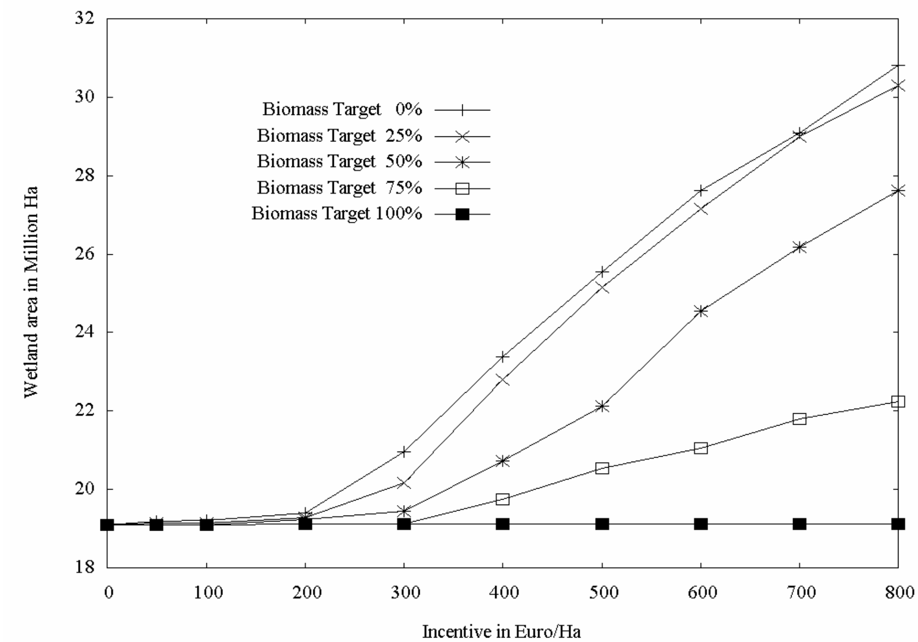

Figure 1 **Competitive economic wetland restoration potentials for different biomass targets and different wetland subsidies (horizontal axis)**

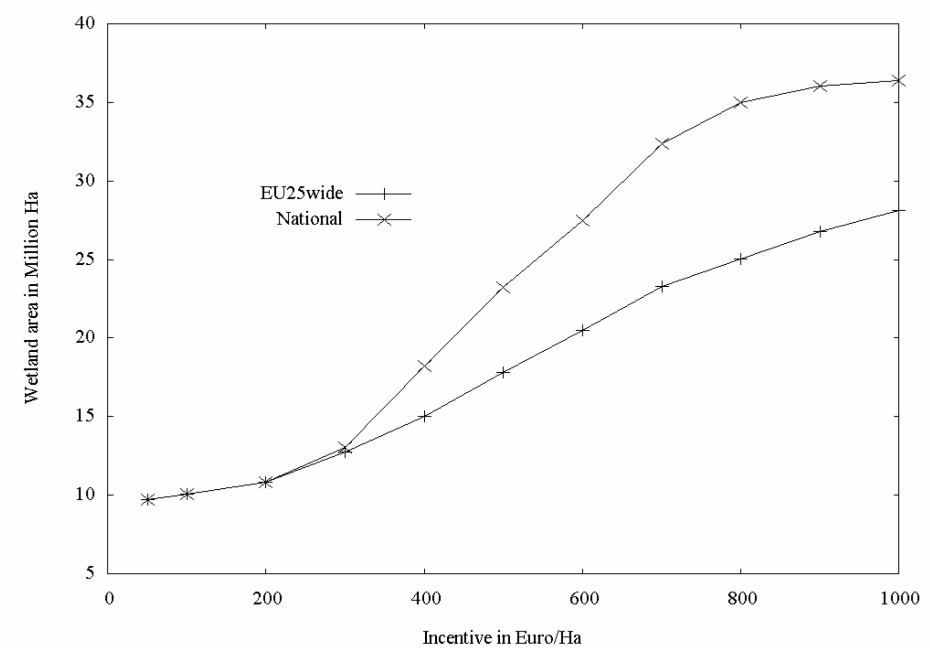

Figure 2 **Economic wetland potentials for a) simultaneous wetland subsidies in all EU countries and b) sum of independently obtained national potentials assuming that subsidy is only established in the respective country**

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