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Dynamic simulation of sustainable farm development scenarios using cognitive modeling

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Abstract: *Dynamic simulation of sustainable farm development scenarios using cognitive modeling.* The paper presents a dynamic simulation system of sustainable development scenarios on farms using cognitive modeling. The system incorporates relevant variables which affect the sustainable development of farms. Its user provides answers to strategic issues connected with the level of farm sustainability over a long-term perspective of dynamic development. The work contains a description of the model structure as well as the results of simulations carried out on 16 farms in northern Ukraine. The results show that the process of sustainability is based mainly on the potential for innovation in agricultural production and biodiversity. The user is able to simulate various scenarios for the sustainable development of a farm and visualize the influence of factors on the economic and social situation, as well as on environmental aspects. Upon carrying out a series of simulations, it was determined that the development of farms characterized by sustainable development is based on additional profit, which serves as the main motivation for transforming a conventional farm into a sustainable one. Nevertheless, additional profit is not the only driving force in the system of sustainable development. The standard of living, market condition, and legal regulations as well as government support also play a significant motivational role.

Key words: agro-ecosystem, decision-making tool, farm production systems, renewable energy, sustainable agriculture

INTRODUCTION

The challenges faced by agriculture in the 21st century require the systemic integration of the environmental, social and economic pillars of development to meet the needs of present generations without sacrificing those of generations to come (Fischer et al. 2002). Great emphasis has been placed on the suitability and sustainability of business undertakings, the assessment of which requires appropriate methods. Both the theory behind and the practical application of impact assessment are expanding rapidly. There are many different types of impact assessment methods, related to: environmental, social, and economic levels, as well as local, national and regional aims (Bond, et al. 2012, Schindler et al. 2015). Sustainable development has become a principle which all governments seemingly aspire to abide by; its roots at the level of international policy are commonly believed to lie in the Brundtland Report (1987), which, in itself, was a culmination of acknowledging public concerns over poorly planned resource use, popularized by reports such as that produced by the Club of Rome (Meadows et al. 1972). The Brundtland Report (1987) coined a frequently quoted definition of sustainable development, though, by no means, the sole definition (Bell and Morse 2008): "…development that meets the needs of current generations without compromising the ability of future generations to meet their needs".

Sustainable agriculture is socially just, ecologically sound, economically viable, and a paradigm that aims to produce the food needed to achieve food security (McIntyre 2009, Cavatassi et al. 2011, FAO 2013). An individual element of the agricultural system is a farm, which is an open system with constant flows of resources from the environment. Farmers manage about 50% of the Earth's surface, excluding boreal lands, desert, rock and ice (Tilman et al. 2001). The increase in agriculture production over the past 20 years at an average rate of 3.2% is due to an increase in land under cultivation rather than an increase in productivity. For example, a 229% increase in cultivated farmland accounted for a 70% increase of productivity in regional production (Garrity et al. 2010). This intensification of agriculture has led to the strong homogenization of agricultural landscapes and loss of natural and semi-natural habitats (Foley et al. 2005), as well as soil biodiversity, which is dependent on the above (Tsiafouli et al. 2015). Faced with these, now well-documented, negative impacts of agriculture as well as global changes requires developing more sustainable agricultural systems, i.e., less dependent on anthropogenic activities and petroleum, characterized by the efficient use of resources and low environmental impacts, resilient to climate change, and producing sufficiently abundant and healthy food (Duru et al. 2015). Studies concerning the influence of impact factors on the sustainable development of farms have been conducted previously, including vulnerability assessment and modeling (Sauer and Fischer 2010, McCown 2012, Yearworth and White 2013, Tanure et al. 2013, van Winsen et al. 2013, Altieri et al. 2015, Chen and Zhang 2015, Ciegis et al. 2015, Schindler et al. 2015).

Among the greatest current challenges in building models, we can mention the correction of the aforementioned limitations and the usage of dynamic models. Almost all models applied in agricultural and livestock production (or even in the broad context of agribusiness) employ static criteria and variables for creating spreadsheets and describing the interconnections between key elements (Tanure et al. 2013). Agricultural scientists are introduced to the concept of probability during their training in experimental design and statistical analysis, while agricultural economists learn about probability in formal decision analysis. Both, however, are of limited value when assisting farmers in contemplating and managing uncertainty (McCown 2012).

Therefore, in the present study, we propose a novel cognitive model to be used as a decision-making tool in farm production systems aiming to convert to sustainable development. The current research attempts to answer the following questions: How can we model sustainable development? What impact factors should we select for modeling? How does the framework of conditions of the internal and external environment affect a farm's sustainability? The aim of this paper is to evaluate the influence of different factors on the sustainable development of farms using cognitive modeling.

MATERIAL AND METHODS

Agriculture in Ukraine secures approximately 10–11% of national GDP and employs a quarter of the working population (State Statistic Service of Ukraine 2015). Ukraine has 42.8 million ha of agricultural land, comprising 71% of the country's total area, of which 32.5 million ha are arable (excluding pastures, grasslands, permanent plantings). Ukraine has a favorable climate for large-scale agriculture, rich agricultural soils and access to abundant land and water resources. Black soil, which contains a very high percentage of humus (3 to 15%) along with phosphoric acids, phosphorus and ammonia, occupies 41% of Ukraine's total area and even higher shares of its agricultural land (54%), and arable land (58%). Crops constitute about 55% of the total agricultural output. Among the leading crops are wheat, oil crops, sunflowers and sugar beets. Livestock farming includes cattle, pigs, sheep and horses (State Statistic Service of Ukraine 2015). Most Ukrainian farms are recognized as large farms, in which the average number of employees for the accounting (fiscal) year exceeds 250 people, and gross revenue from the sale of goods (work, services) for the year exceeds 100 million USD (State Fiscal Service of Ukraine 2011). Accordingly, the land area of the majority of farms is more than 1,000 ha.

The study area covered 16 farms from the Chernigov region (north-eastern part of Ukraine). The farms are geographically located in a region of steppes with similar agro-climatic conditions. The main crops grown by the farms are: grains and legumes, open-soil vegetables and potatoes. In terms of livestock – dairy cattle and pigs dominate.

The methodology of cognitive modeling (cognitive map) is aimed at analyses and decision-making in uncertain situations. The concept was introduced by Edward Tolman (Tolman 1948). A cognitive map is a graphical representation, or visual picture, of the contents and structure of a chosen system (Eden et al. 1992). The process of cognitive mapping was introduced to the field of scientific management by Axelrod in 1976 (Markoczy and Goldberg 1995). Cognitive modeling encounters two major challenges. The first is to identify and select the impact factors of the sustainable development of farms. The second is to visualize the level of the factors' influence on farm sustainability.

In this section, we will present some of the key methodological choices in creating and analyzing cognitive maps, with an emphasis on techniques that are most likely to be of practical use in the context of human factors in manufacturing environments. This section will include: methods of eliciting information, the role of the facilitator, mapping methods (software), and methods for the analysis and interpretation of maps (Village et al. 2013). Eleven diagnostic variables were selected for the dynamic simulation of sustainable farm development scenarios. The variables were included in the following thematic groups (using available data):

1. Environmental indicators

- X_1 – *innovative capacity* – the level of implementation and use of energy, saving technologies in the enterprise;
- X_2 – *biodiversity* – pesticide use (kg/ /ha), total nitrogen input (kg/ha), total direct and indirect energy input (kg fuel equivalents), average size of farm size (ha);
- X_3 – *availability of natural resources* – potential of solar energy (kW), total amount of organic fertilizers (t), water resources (km^3);

2. Social indicators

- X_4 – *level of professional development of labor force* – participation rate in education and training (%);
- X_5 – *social climate of farm* – the ratio of the average salary in farm to the average salary in industry (+/–), level of automation and standardization of farm manufacturing (proportion), level of satisfaction of the personnel with working conditions;
- X_6 – *social climate* – survey different group of society;
- X_7 – *society's standard of living* – GDP aggregates per capita (USD), income quintile share ratio (%), long-term unemployment (% of active population), expenditure on education (% of GDP), expenditure on medicine service (% of GDP), total fertility rate (%);

3. Economic indicators

- X_8 – *financial capacity of the farm* – profit margin (%), profitability (%), coefficient of reinvestment of net profit to farm equity (%);
- X_9 – *management capacity of farm* – ratio of management staff constancy, profitability management costs (%), the share of administrative staff who has worked in farm for more than five years (%);
- X_{10} – government support and regulation – nominal protection coefficient, nominal protection rate, effective protection coefficient, effective protection rate, level of total government support of farm (%);
- X_{11} – *market condition* – increase of market share (%), availability of own distributing markets (amount), experience in the market sales (years),

effectiveness of participation in public events (%), sales and profits from new products (USD), customer satisfaction (amount of reclamations).

The cognitive model of farm sustainability has been presented as the graph:

$$G = (x, e)$$

$$x = \{X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11}\} \quad (1)$$

where:

x – a set of vertices that show the parameters of the external and internal environment comprising the system of the sustainable development of farms;

e – a set of curves reflecting the direct influence of parameters on each other.

The definition of scenarios for each situation is carried out by the impulsive impact on some vertices. Considering that U_i, $i = 1, 2, \ldots, n - 1$, the numeric value of vertices equals 1, and $p_j(t)$ – is the change in vertex V_j at moment t, then the impact of this change in V_i at moment t describes the function $\pm p_j(t)$ depending on the sign of the lines connecting V_i and V_j and equal to 1. Using the rule of the distribution of disturbances on the graph, numerical values $Q_i = 1$ of perturbation were determined according to formula (2) (Zinoviev et al. 2009):

$$U_i(t+1) = U_i(t) + \sum_{j=1}^{n} f(V_i V_j) \cdot p_j(t) \quad (2)$$

Calculation of the matrix of initial data was carried out in MathCad.

RESULTS AND DISCUSSION

Strong ecological modernization of agriculture, hereafter referred to as biodiversity-based agriculture, is similar to “ecologically intensive agriculture” or “eco-functional intensification” (Levidow et al. 2012) and “the sustainable intensification of agriculture” (Pretty et al. 2011, Garnett and Godfray 2012). It refers to an ecocentric approach (Hill 1998) that relies on the high biological diversification of farming systems (Karmen and Miles 2012, Kremen et al. 2012) and the intensification of ecological interactions between biophysical system components that promote fertility, productivity, and resilience to external perturbations (Bellon and Hemptinne 2012, Malézieux 2012).

Odum (1971) established ecology as a systemic approach and gave credentials to the concept of ecosystems through which matters and energy circulate and introduced the properties of agroecosystems (Odum 1984, 1997), their specificitions as compared with ecosystems. Agroecology, as seen by Altieri (1987, 2015) and Gliessman (2007), fits well in Odum’s framework.

Based on the sensitivity analysis of literature, three types of factors were identified:

- target factors – the change or stabilization of which is the aim of system management;

- controlling factors – the potential for influencing and controlling the process of the sustainable development of a farm;
- factor indicators – reflecting and explaining the development process in a problematic situation.

The links between selected impact factors of a farm's sustainable development were analysed and are presented in Figure 1, as a novel cognitive model. Each type of arrow shows how one factor impacts the others. A continuous (solid) arrow in one direction demonstrates the impact of one factor on the others as being "the more..., the more", whereas a dotted arrow means that the factor affects other factors according to the relationship "the more…, the less"; an arrow with double ends means that the both factors are interrelated.

Based on the cognitive mapping of the sustainable development of farms, we constructed several scenarios of farm development with different influences of factors. Examples of some cognitive maps have been provided in Figures 2–4.

The analysis of the results of the forecast of a farm's sustainable development shows that as the people's standard of living increases, factors of both the external and internal environment are improved

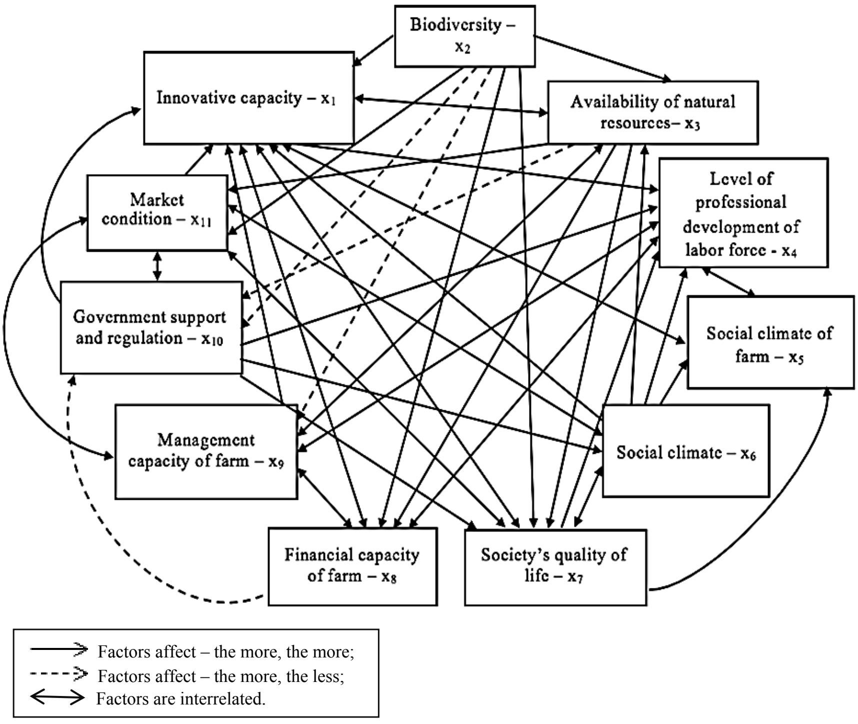

FIGURE 1. Cognitive map of impact factors on the sustainable development of farms

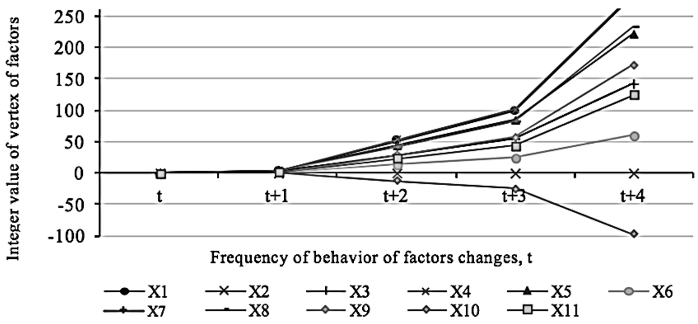

FIGURE 2. Impulse process – graph of the impulse changes in X_1–X_{11} causing disturbance $q = +1$ on X_7 (the standard of living)

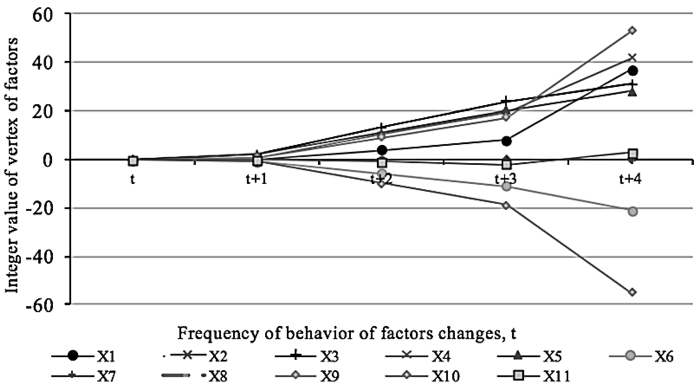

FIGURE 3. Impulse process – graph of the impulse changes in X_1–X_{11} causing disturbance $q = +1$ on X_8 (financial capacity)

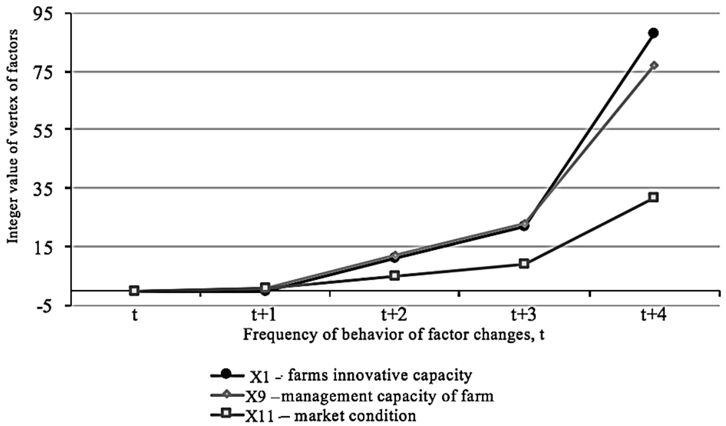

FIGURE 4. Impulse process – graph of the impulse changes in X_1, X_9, X_{11} causing disturbance $q = +1$ on X_{10} (government support and regulation)

after the second cycle of modeling. Biodiversity remains unchanged, while government support deteriorates rapidly.

The forecast data for an increase in the financial capacity of a farm (Fig. 3) in comparison with the standard of living (Fig. 2) is slightly worse. This allows us to conclude that the profit of a farm is not the main factor behind its efficient development.

Scenario analysis is aimed at modeling the sustainable development of farms with a specific number of impulses in vertices on an active cognitive map and determining changes in the values of vertices in respective cycles of modeling. Vertices ought to be understood as the factors which have a potential stimulating effect on the system of sustainable development: X_7 – society's standard of living; X_8 – financial capacity of the farm; X_{10} – government support and regulation; and further recommended X_3 – natural resources.

In order to limit the number of the possible disturbances on the vertices of graphs, a following experiment focused on building scenarios of the sustainable development of farms aimed at targeting individual factors was conducted (Fig. 4).

Natural resources and improvement of the financial capacity of farms increases the trust factors after the second simulation of the measure. However, natural resources are not always in available in adequate quantities, so it is worth developing innovative production based on energy-saving technologies.

Cognitive mapping provides a tool to compose a comprehensive overview from the fragmented information in the farmer's mind. Cognitive maps can help to focus on one part while not losing track of the context and the bigger picture. They provide a useful method for facilitating understanding and communication about complex problems (Wood et al. 2012).

Cognitive maps can be useful tools to guide and improve bi-directional learning between the farming community and policy, industry and research. The boundaries previously described are important, but not exclusive in this regard (van Winsen 2013).

CONCLUSIONS

This paper presents a methodology for understanding the sustainable development of farms and modelling the interactions between its components. Unlike frameworks which are available to assess the sustainability of farm-ecosystems based on predefined hierarchical guidelines placing the responsibility of proper understanding of the system on specialists, the approach presented in this paper emphasizes the importance of local knowledge in capturing the key components of sustainability and the interactions between its components, as per the local experience, values and perceptions. Furthermore, the usefulness of a fuzzy inference system to model these interactions based on qualitative knowledge as presented in this paper is a promising step towards the formal capture and analysis of information which is ignored by conventional techniques relying on quantitative data.

The approach has the potential to be universal in its applicability, as it does not attempt to force preconceived notions about a system. It facilitates holistic understanding through actors who are actually living and participating in the sustainability interactions. The proposed approach to model the sustainability interactions is also cost-effective, with minimal requirements in terms of trained manpower and resources, and suitable for widespread application in developing nations until sufficient capacity is developed to adopt more rigorous methods which demand higher expertise and more resources. The combination of cognitive mapping and a fuzzy inference system can be used to develop expert systems for understanding the sustainability of agro-ecosystems with similar profiles/key components, which can aid decision makers in developing initiatives in the policy of social development, and for assessing the impact of projects, plans, policies and programs, as well as enhancing the quality of decisions arrived at.

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Streszczenie: *Dynamiczna symulacja scenariuszy zrównoważonego rozwoju gospodarstw rolnych z wykorzystaniem modelowania poznawczego.* W niniejszym opracowaniu przedstawiono system dynamicznej symulacji dla scenariuszy zrównoważonego rozwoju gospodarstw rolnych z wykorzystaniem modelowania poznawczego. System zawiera istotne zmienne, które wpływają na zrównoważony rozwój w gospodarstwach. Użytkownik udziela odpowiedzi w strategicznych kwestiach związanych z poziomem zrównoważenia gospodarstwa w długoterminowej perspektywie dynamicznego rozwoju. Praca zawiera opis struktury modelu i wyniki symulacji przeprowadzonych na przykładzie 16 gospodarstw północnej Ukrainy. Wyniki pokazują, że podstawą procesu zrównoważenia jest potencjał innowacyjny w produkcji rolnej i bioróżnorodności. Użytkownik jest w stanie symulować różne scenariusze dla zrównoważonego rozwoju gospodarstwa i wizualizować wpływ czynników na sytuację gospodarczą, społeczną i aspekty środowiskowe. Po wykonaniu serii symulacji ustalono, że rozwój w gospodarstwach o zrównoważonym rozwoju możliwy jest tylko wtedy, gdy generuje dodatkowy zysk, który stanowi główną motywację przekształcenia gospodarstwa z konwencjonalnego na rzecz zrównoważonego. Dodatkowy zysk nie jest jednak jedyną siłą napędową w systemie zrównoważonego rozwoju. Istotną funkcję motywującą pełnią również jakość życia, warunki rynkowe oraz regulacje prawne i wsparcie ze strony rządu.

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