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Contribution of agricultural systems to the bioeconomy in Poland: Integration of willow in the context of a stylised CAP diversification

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ABSTRACT

Synergies between the Common Agricultural Policy (CAP) and the deployment of bioeconomy that induces resource-efficient and sustainable biomass production patterns are in the core of discussion for the new CAP in Poland. Proactive greening mechanisms likely to enable a large-scale diffusion of willow plantation are investigated in this respect, including diversification schemes combined with incentives making willow plantation more attractive to farmers. A comprehensive approach to modelling farm diversification options is therefore provided by means of an integrated bioeconomic framework which relies on linking the agricultural supply model AROPAj with the crop model STICS. The economic and environmental impacts related to the gross margin, land use change, nitrogen (N) fertiliser use, and greenhouse gas emissions, i.e. methane (CH_4) and nitrous oxide (N_2O), are assessed at the regional scale according to the type of farming and the economic size. Under current crop diversification conditions only 9% of farm groups (FG) may opt for willow, benefiting solely from diversification support whereas subsidising willow increases this percentage up to 20% and 45%, for a received allocation amount equal to € 100 ha^{-1} and € 200 ha^{-1}, respectively. The uptake of willow is particularly high within small and middle-sized FG and within those specialising in grazing activities. Regarding the environmental impacts, the higher the number of required crops, the lower the N-fertiliser use, and in most cases, a coupled support policy (when willow plantation is subsidised) further reduces N-use, and consequently N_2O emissions. Unlike grazing-oriented FG, crop-oriented FG tend to significantly increase their CH_4 emissions due to the intensification of grazing activities. The countrywide coverage of the findings and their economic and spatial detail can support informed policies for sustainable bio-based activities development.

1. Introduction

Over the last decades, the interest towards bioeconomy has increased and new industrial prospects for biomass valorisation have been developed to fulfil the requirements of sustainable development. Public policies have therefore been aligned to define central and interconnected sectors covering agriculture, forestry, food, feed, bioenergy, and green chemistry. In this regard, the use of biomass as a substitute for fossil energy sources has benefited from a crossroads of incentive policies and binding Directives implemented in order to meet geopolitical, energy, economic, and environmental objectives. For instance, developing bioenergy production may reduce countries' dependence on fossil fuel, address oil supply issues, promote rural development, provide farmers with additional income, mitigate greenhouse gas (GHG) emissions, enhance natural carbon sinks, and limit erosion and biodiversity loss. However, the key problem lies within serious controversies over the economic and environmental impacts of a large-scale biomass expansion.

In Europe, bioeconomy is substantially inter-linked with the Common Agricultural Policy (CAP) since they address common goals related to food security and rural development. As a matter of fact, the production of non-food biomass from agriculture has gained considerable support from the CAP, in particular, since the Agenda 2000 reform, by means of which rural development policy has been introduced as a second pillar. In conjunction with the climate and energy policy framework and the Directives on renewable energy (2009/28/EC) and fuel quality (2009/30/EC), the CAP played a key role in fostering the supply of first-generation biofuel crops such as maize and rapeseed, leading to

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List of abbreviations

ArL	Arable land
CAP	Common Agricultural Policy
CH_4 emissions	Methane emissions
EFA	Ecological Focus Areas
ES1	Farm with an average size of 4 000 - < 15 000 €
ES2	Farm with an average size of < 25 000 €
ES3	Farm with an average size of < 50 000 €
ES4	Farm with an average size of < 100 000 €
ES5	Farm with an average size of < 750 000 €
EU	European Union
FADN	Farm Accountancy Data Network
FG	Farm groups
FT1	Farm specialised in cereals, oilseeds and protein crops
FT2	Farm specialised in general field and mixed cropping
FT3	Farm specialised in grazing livestock
FT4	Farm specialised in granivores
FT5	Farm specialised in field crops - grazing livestock combined
FT6	Farm specialised in various crops and livestock combined
GHG	Greenhouse Gas
ha	hectare
IA	Impact assessment
LP	Linear programming
MP	Mathematical programming
N	Nitrogen
N_2O emissions	Nitrous Oxide emissions
PEC	Perennial energy crops
SRC	Short rotation coppice
tdm	Tons dry matter
UAA	Utilised agricultural area
UnAA	Unutilised agricultural area

an ambiguous environmental and economic assessment. The food crisis in 2007/08 has questioned the legitimacy of incentives for crop-based energy and triggered a focused attention on the development of second-generation bioenergy from lignocellulosic plantations such as perennial herbaceous plants and short rotation coppice (SRC e.g. willow, birch and poplar), which offer a wide range of greener, more sustainable and more cost-efficient production routes than those of conventional crops. For instance, years of experiments and pilot plantations proved that, being harvested in SRC system (every 3–5 up to 25–30 years), willow represents high yields according to management practices (Stolarski et al., 2019) and can prevent nitrate leaching (Schmidt-Walter and Lamersdorf, 2012). Nevertheless, to meet the requirements of the development of a sustainable bioeconomy, willow must be sustainably grown with low or no nitrogen (N) fertilisers.

In the 2014-CAP reform, greening measures were established to mitigate climate change and conserve biodiversity, while diversifying the agriculture and supporting the development of rural areas. About 30% of greening direct payments are committed to favour crop diversification, the maintenance of permanent grasslands and the conversion of 5% of arable land (ArL) into Ecological Focus Areas (EFA). By controlling the number and land share of grown crops, farms are treated differently depending on their ArL area. Farms with ArL ranging between 10 and 30 ha are committed to cultivate at least two different crops and main crop area should not exceed 75% of ArL. For farms with Ar.L above 30 ha, at least three crops have to be cultivated and the area of two main crops should not exceed 95% of ArL. In addition to grassland, hedges, buffer-strips, and nitrogen-fixing crops, SRC can be considered eligible EFA since they provide wide variety of ecosystem services in terms of carbon storage and biodiversity (Emmerling and Pude, 2017). The main objective of this complex management practice is to reduce the consumption of pesticides, fertilisers and water as well as the environmental damage resulting from agricultural intensification. From the economic standpoint, it creates new opportunities and markets, reducing the risk common in monocultures.

Despite the growing interest in perennial energy crops (PEC), woody biomass from forest remains the main biomass energy source, representing more than 60% of the European domestic supply of energy from biomass (EC, 2016). Yet, PEC have real potential for decarbonisation of biorefinery and transport sector, when they are cultivated in a sustainable way. According to a recent statistical report (Bioenergy Europe, 2019), it is claimed that the production of renewable energy, of which biomass represents the largest share, continues to increase. This regular trend evokes unleashing the full potential of PEC by improving their uptake at the farm level. Despite the establishment of CAP greening measures, the adoption of perennial herbaceous plants and SRC is still slow, reflecting in particular the attitude of European farmers to establish these plantations. Various studies have focused on farm uptake of PEC in order to identify the barriers which hinder their large-scale deployment. The reluctance of farmers to adopt these new energy crops may be explained by several factors, namely the lack of expertise and technical equipment (Lewandowski et al., 2016), the long rotation period and low productivity on less fertile land (Ben Fradj and Jayet, 2018; Mola-Yudego et al., 2014; Ostwald et al., 2013), the high establishment cost and delayed cash-flows (Mola-Yudego and Aronsson, 2008), the absence of a structured market (Schweier and Becker, 2013) and the high risks related to energy market regulations (Sherrington and Moran, 2010).

Another inhibiting factor is the uncertainty associated with the CAP's regulations and their direct impact on the establishment of new crops (Mola-Yudego et al., 2014). The latter affects the supply of bioenergy and the projections for future agricultural and energy markets (Bartolini et al., 2010). CAP incentives are therefore of paramount importance for increasing innovation capacity and encouraging the take-off of green technologies (Bartolini and Viaggi, 2012). In particular, subsidies on PEC are necessary to overcome negative cash-flows in the first years after establishment as well as to limit the liquidity risks encountered throughout the life span of plantations (Mola-Yudego and Pelkonen, 2008). Recent PEC adoption studies, by using real options techniques (Spiegel et al., 2018), suggest that the most efficient instruments are EFA subsidy increase and guaranteed price, while the effect of an establishment subsidy is ambiguous. In addition, risk modelling of investments focuses on the financial and structural parameters that render feasible SRC establishment (Ridier, 2012). Furthermore, coupling CAP subsidies on PEC with environmental taxation instruments, for example tax on fossil fuels (Mola-Yudego and Pelkonen, 2008) and N fertilisation (Bourgeois et al., 2014), may increase the diffusion of PEC.

Besides incentive policy instruments, the economic size and type of farms are also important drivers of farmers' decision-making (Rozakis and Borek, 2018) regarding PEC adoption. For instance, Glithero et al. (2013) and Wilson et al. (2014) used questionnaires and interviews to identify the preferences of British farmers regarding the adoption of miscanthus and willow. They found that livestock farmers are more reluctant to convert land to PEC than arable farmers due to the requirements of fodder production. Using a revealed preferences framework, Konrad et al. (2018) by means of farm land use model, tried to assess the land replaced by willow and poplar as a function of the spatial variation and land characteristics in Denmark. Considering establishment and production subsidies, the authors showed that large farmers have strong propensity to allocate land to PEC because they can provide large and spatially consistent land use activities that are effectively managed and offer lucrative contracts with energy transformers. The aforementioned findings must be considered in the countrywide context of arable agriculture mathematical programming (MP) model, in order to estimate the potential of SRC taking into account competing crops in various conditions and farm heterogeneity.

In addition to their limited spatial extent, most studies on PEC uptake are based either on farm surveys or on economic modelling of farmers' decision-making land use without considering the adoption of such crops within new diversification scenarios to comply with greening requirements nor assessing the environmental impacts of their production. In terms of farm heterogeneity, the objective of this study is therefore to assess the potential adoption of willow as part of a stylised CAP greening model in which further restricted diversification schemes (in terms of number of eligible crops) are combined with incentives that make willow plantation more attractive to farmers. To this end, an integrated bioeconomic modelling approach using an MP model, namely AROPAj, is applied to approximate farmers' production choices under a set of diversification constraints. The model incorporates crop response functions on N inputs provided by the STICS crop model. By means of this modelling framework, the economic and environmental impacts related to the gross margin, land use change, N-fertiliser use and GHG emissions, i.e. methane (CH_4) and nitrous oxide (N_2O), are analysed at the regional scale, by farming type and economic size. For illustrative purposes, the used methodology is applied to Poland, a country with high biomass potential and large share of agriculture in the economy (Faber et al., 2012; Ignaciuk et al., 2006).

The paper is structured as follows: Section 2 introduces the modelling framework and tool used for assessing the economic and environmental impacts of sustainable supply potential of willow; Section 3 describes the case study country, i.e. Poland, as well as the scenarios and assumptions used to test the integration of willow within different crop diversification situations; Section 4 presents results regarding the economic and environmental impacts resulting from willow production. The impacts are declined into Polish FADN (Farm Accountancy Data Network) regions, farming type and economic size classes; Section 5 discusses and compares some of our findings to those found in the literature. Finally, Section 6 presents our conclusions.

2. Impact assessment of the sustainable supply potential of willow in the context of CAP diversification

Since its implementation in 1962, the EU's CAP has undergone successive reforms ranging from MacSharry (1992–2003), through Luxembourg agreement (2003–2013), to greening (2014–2020). Throughout these stages, CAP was increasingly focusing on shaping a multifunctional agriculture which can simultaneously support and protect EU farmers, cope with climate change, improve sustainable management of natural resources, maintain rural areas and landscapes, and promote jobs in agriculture and related sectors (EC, 2017). Several socio-economic and agri-environmental indicators have therefore been identified to monitor the integration of economic and environmental concerns into the CAP (EC, 2018). While the economic indicators depend mainly on farmers' income, the agri-environmental indicators concern, among others, the use of mineral fertilisers, the farming and animal husbandry, and the production of renewable energy and GHG emissions.

The introduction of greening payments has triggered the interest in PEC, especially willow SRC, thereby allowing an expansion of crop diversification (Bartolini et al., 2015). According to Monteleone et al. (2018), the integration of willow promotes the transition to a multifunctional agriculture reconciling agricultural economy with ecology. Despite the volume of published research, the technical and economic potential of willow at the regional level is often assessed without reference to the farm business context. Consequently, significant data gaps remain and information is still scarce on how much biomass is available and can be sustainably supplied. This can be done through farm-based models that represent cropping systems active in the region under study by taking into account soil, climate and socio-economic conditions of production as well as the policy context. Under the greening requirements, farm-based models can not only provide information on how willow would be integrated into the European farming systems, but also approximate and aggregate the economic and environmental impacts of crop diversification instruments. In this regard, the following section provides a short overview of farm-oriented models used so far for assessing CAP impacts and biomass supply.

2.1. Farm-based modelling

Several studies have been undertaken to assess the impacts of various policy instruments. In most cases, impact assessments (IA) on farm net benefit stem from calculations based on the observed crop mix neglecting farmers' response regarding the adjustment of cropping plans to cope with a potential decrease in their welfare. Appropriate models are therefore required to generate trustworthy estimates useful for policy analysis. For this purpose, bottom up models have been extensively used to replicate farmers' decisions and assess policy impacts, their specification depending on the modelling approach (Reidsma et al., 2018; Kremmydas et al., 2018). So far, MP models are widely applied for ex-ante and ex-post farm-level evaluation of farmers' choices, following a policy change (Reidsma et al., 2018; Espinosa et al., 2016; Galán-Martín, Á. et al., 2015; Arfini, 2012; Salvatici et al., 2000). Moreover, MP models have been proven particularly suitable to articulate agriculture to the downstream biomass processing. In fact, interactions among non-food crops at the national level (Sourie and Rozakis, 2001) and policy shift impact to the bioenergy production at the regional level (Bartoli et al., 2019) have been analysed by means of MP models that have explicitly included crop activities for energy purposes in the variable set of each individual decision making unit, namely farms.

Covering large part of crop and animal activities, farm-based models may reflect the behaviour of several farm types using different agricultural practices under different policy contexts. A wide range of MP models have been used to evaluate the effectiveness of CAP measures, thereby assessing changes in land use, input and economic performance of farms and to examine policy instruments. In the context of greening (2014–2020), most of IA have been applied at regional or country level cases (Solazzo and Pierangeli, 2016; Mahy et al., 2015; Solazzo et al., 2015; Czekaj et al., 2013), but only few of them provided a comprehensive farm-level analysis to capture the heterogeneity of EU farms in terms of farming systems, economic size and policy impacts (Louhichi et al., 2017; Espinosa et al., 2016).

Despite the large number of greening IA, to our best knowledge, no previous study went beyond simple assessment of the economic and environmental impacts of greening measures, in particular when two commands of crop diversification options, namely the number of eligible crops and the amount of support, change. In addition, these approaches do not take into account the scenarios which enable farmers not only to change their cropping plan but also to adopt new activities to comply with crop diversification requirements. The latter is made possible by the upgraded version of the agricultural supply model AROPAj, in which a new module of stylised CAP greening measures is integrated to provide information on the number and combination of eligible crops that can be efficiently cultivated. To be consistent with the EU strategies, for instance with the updated bioeconomy strategy, farmers can consider, through crop diversification options, adopting alternative PEC such as willow SRC to increase their sustainability, ecology and biodiversity performance.

2.2. The European agricultural supply model AROPAj

AROPAj model is a technical-economic optimisation tool of the European agricultural supply, describing numerous farming activities ranging from crop production to animal husbandry. Individual farmers are well represented as they are clustered into farm groups (FG) based on their technico-economic orientation, their economic size and their altitude class within regions. The model has been widely used to assess the interactions between agricultural activities and the environment by assessing climate change adaptation and mitigation (Leclère et al., 2013; De Cara and Jayet, 2011; Durandeau et al., 2010; De Cara et al., 2005), agro-environmental policies (Bourgeois et al., 2014; Jayet and Petsakos, 2013), and PEC supply (Ben Fradj and Jayet, 2018; Ben Fradj et al., 2016).

AROPAj is linked with the STICS crop model to take into account the heterogeneity in soil characteristics, climate conditions, agricultural practices, and crop N uptake. The approach relies on estimating non-linear production functions relating the input level to yield, for a better adaptation of N fertilisation according to physical and economic conditions (Godard et al., 2008). More recently, Humblot et al. (2017) extended this method to include water in the yield function. The integration of non-linear links between inputs and yields within a linear framework has been explicitly addressed in Aghajanzadeh-Darzi et al. (2017). The procedure relies on two-step process required, first, to calculate the optimal amount of nitrogen and yield for each crop activity that satisfy the first-order conditions. These variables are then called by the linear programming AROPAj model to return the optimal output for each activity at FG level. The modelled crop activities include only arable crops, particularly soft and durum wheat, barley, sugar beet, potatoes, rapeseed, sunflower and soya.

Furthermore, a module for computing GHG emissions from agriculture is integrated on the basis of the methodological framework developed within the International Panel for Climate Change (IPCC) guidelines (Jayet et al., 2020; De Cara and Jayet, 2011). The emissions are broken down into 20 items, thirteen of which concern CH_4 emissions from manure, enteric fermentation and rice cultivation, and seven relate to N_2O emissions, i.e direct and indirect emissions from agricultural soils as well as emissions from grazing livestock and manure application. While CH_4 emissions from enteric fermentation and manure are induced by the number of animals and the composition of their feed, N_2O emissions from agricultural soils are driven by N-fertiliser application dependent on either input and output prices or optimal crop area mix.

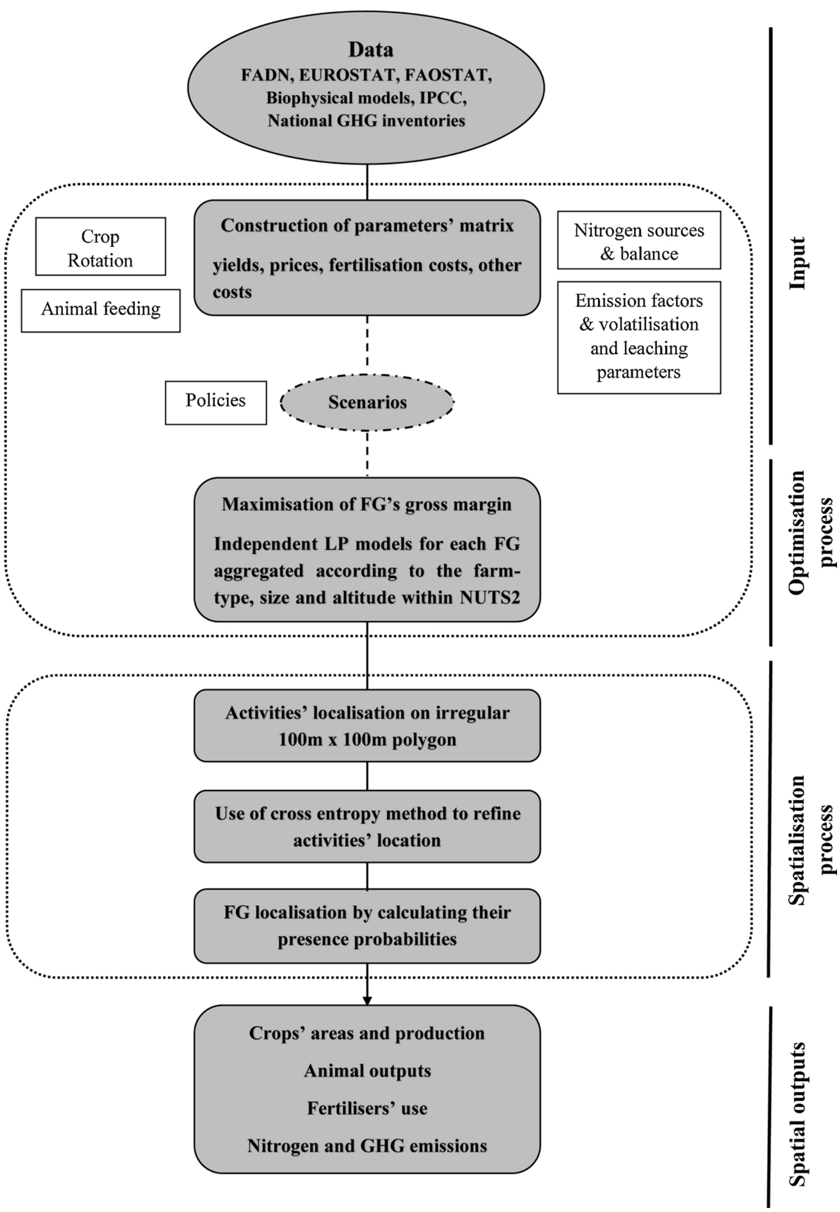


Fig. 1. Schematic representation of AROPAj modelling processes ranging from data collection and treatment, scenarios' construction, optimisation, to outputs' spatialisation.

One of the most important features of AROPAj model is its capacity to generate spatial outcomes at a fine geographical scale, which can be aggregated at regional level. To spatially locate FG and activities, Cantelaube et al. (2012) integrated a spatial distribution module, thereby expanding the micro-economic data by physical information on climate (Monitoring Agriculture from Remote Sensing project database), soils (JRC), land cover (CorineLandCover), land use (LUCAS) and terrain elevation (digital elevation model). The spatialisation process consists of a downscaling module which distributes the results at fine-resolution scale within a region. A description of the modelling process ranging from data collection to spatialisation is presented in Fig. 1.

2.2.1. Model structure

The architecture of AROPAj model has been explicitly described in numerous studies (De Cara et al., 2005; Godard et al., 2005; Galko and Jayet, 2011) as well as detailed in the manual from Jayet et al. (2020). The structure mainly accommodates the technico-economic farm profile designed according to the microeconomic approach (Arfini, 2012). It consists of independent, mixed integer and LP models, each of them describing a typical farming system of individual representative farm called farm group.

Defining the optimisation problem, each FG k is supposed to select the supply and input demand levels that maximise its total gross margin (π_k) under a set of economic, agronomic and environmental constraints. For the kth FG, the model is expressed as follows:

$$\max_{x_k} \ \pi_k(x_k) = \max \ g_k(\theta_k, \phi) \ . \ x_k$$

$$s.\ t.\ /A_{k_{mn}}(\theta_k, \phi) \ . \ x_k \ \leqslant B_k(\theta_k, \phi) \qquad x_k \ \geqslant 0$$

where x_k and g_k are respectively the $(n \times 1)$ vector of activities and the $(1 \times n)$ vector of gross margins for the kth FG. x_k refers to crop and animal activities that represent most of the European agriculture land and animal categories, thereby including crops' areas, livestock, production related to each crop and to each animal category and purchased feed. Regarding the gross margin g_k, it includes revenue per ton and subsidy per hectare minus variable expenses per hectare. Each FG is a price-taker and can either sell its crop production in the market or use it for livestock feed. The feasible production is constrained by the $(m \times n)$ matrix A_k referring to input–output coefficients and the $(m \times 1)$ vector b_k translating the endowments of m constraints encountered by farm group k. Those latter are about crop rotations, animal feeding and demography, livestock number, resource capacities, N balance, and CAP restrictions. Coefficients presented in g_k, A_k and B_k pertain to θ_k-parameters characterising the kth FG as well as to ϕ standing for the economic parameters related, *inter alia*, to CAP measures added in the form of sub-matrices which refer to the objective, right-hand side compounds, activities, constraints, and matrix elements.

2.2.2. Crop diversification mockup

The CAP crop diversification options were designed to account for three cases excluding one from the other and making the farm eligible for additional green payments:

1. the threshold defining small farms with ArL area less than 10 ha;
2. the threshold referring to medium farms with ArL ranging between 10 and 30 ha and committed to cultivate at least two different crops where main crop area should not exceed 75% of ArL;
3. the threshold specifying big farms with more than 30 ha and at least three crops cultivated, where the area of two main crops should not exceed 95% of ArL.

Many MP models designed for optimising farming system decisions, consider crop area (or land shares of a series of crops) as standard decision variable. However, considering the above-mentioned crop diversification requirements involves the integration of an additional decision variable representing the number of crop activities. This requires the insertion of integer variables (usually binary variables) in addition to a series of threshold conditions (e.g. limits for subsidy exclusion). Hereinafter, we explain how a part of CAP greening options was stylised and implemented in the model (full description in Jayet et al. (2020)), through adding series of parameters, real and binary variables and constraints. A comprehensive CAP greening block is detailed in Table 1. We denote j by the crop, most of parameters are k-indexed, depending on FG. The block calls for:

Parameters:

- area limits: sdmin(k), sdmax(k) (share of land in [0,1]);
- subsidy related to crop diversification: sudiv(k) (in € ha^{-1});
- numbers of crops delineating farm size categories: ndivb and ndivc;
- minimum area dedicated to crops accounting for the real number of crops: thrss(k) (in ha).

Table 1

The CAP greening module as integrated into AROPAj. The first line refers to labels of MP variables. The left column refers to labels of constraints. The cell contents refer to values, predefined or defined by parameters, or zero values by default. The k-index refers to a farm group and the j-index refers to a crop. The module is connected to the rest of the model through the objective function ("obj") and endogenous variables such as crop areas ("xtk(j,k)") and farm numbers ("zf(k)").

obj	xtk(j,k)	xdivb(k) sudiv(k)	xdivc(k) sudiv(k)	xdivd(k) sudiv(k)	xdive(k)	xarab(k)	idivc(k)	idivd(k)	idivb(k)	idive	itk(j,k)	nttjk(k)	zf(k)	=	RHS
eld(1,k)	−1 j eligible					1								<	
eld(2,k)		1	1	1	1	−1								<	
eld(13,k)		1											-sdmin(k)	<	
eld(3,k)			1										-sdmax(k)	<	
eld(4,k)			−1					−99999	−99999	−99999			sdmin(k)	<	
eld(10,k)				−1			−99999		−99999	−99999			sdmax(k)	<	
eld(5,k)			1				−99999							<	
eld(6,k)				1				−99999						<	
eld(11,k)		1							−99999					<	
eld(12,k)					1					−99999				<	
eld(9,k)							1	1	1	1				<	1
eld(7,k)											−1	1		<	
eld(8,k)											0.999999	−1		<	
eld(14,k)							ndivb					−1		<	
eld(15,k)								ndivc				−1		<	
ild(j,k,1)	1										−99999			<	
ild(j,k,2)	−1										thrss(k)			<	

Variables:

- crop areas (pre-existing variable): xtk(j, k) (in ha);
- number of farms in the FG: zf(k);
- binary variables of 1-value when xtk(j, k) is strictly positive: itk(j, k);
- number of crops cultivated in the MP solution, of value greater than thrss(k): nttjk(k);
- total amount of land accounting for agricultural activities: xarab(k) (in ha);
- total amount of land accounting for a one-size category: xdiv(b), xdivc(k), xdivd(k) eligible for green support and xdive(k) when the farm opts out of the green payment (in ha);
- binary variables related to diversification limits: idivb(k), idivc(k), idivd(k), idive(k).

Constraints:

- sub-block dedicated to n-constraints designed for the CAP greening: eld(n, k), e.g. eld(13, k): xdivb(k) $\leqslant$ sdmin(k); eld(13, k): xdivb(k) $\leqslant$ sdmin(k);
- specific constraints related to crops accounting for the number of crops: ild(j, k, n), e.g. ild(j, k, 2): xtk(j, k) $\geqslant$ thrss(k) zf(k).

Being an economic decision-taking unit, each FG may opt for one of the three farm categories eligible for the green payment or may opt out of this payment, given the modelled utilised agricultural area (UAA). The clustering of FADN-surveyed farms into FG as well as the number of crops cultivated by each FG depends on pre-existing crops referring to data sourced from sampled farms belonging to FADN surveys. This clustering implies that the potential number of crops in FG is greater (and usually much greater) than the number of crops in each of the sampled farms accounting for the FG (see an example in Table A1, Appendix A). The proposed modelling exercise is then tested on a large part of FG while assessing the additional cost of increasing the number of required crops through integrating a new crop in the model.

The right column of Table A1 gives the number of crops provided by FADN data. According to this example, each of the sampled individual farms has no more than 5 different crops, most frequently 3 crops. The FG is associated to 8 crops to which parameters are estimated (prices, costs, and yields). The reference point as the calibration AROPAj solution refers to 6 crops associated to strictly positive areas. The CAP diversification options may alter the LP solution when the limiting number of crops is of 7 or 8 (or indifferently greater than 8) and when the area threshold making a crop eligible for subsidy increases.

Although the above-mentioned methodology can be generalised over EU-24, we limit the study to Poland, to better capture and validate the economic output, land use allocation and environmental impacts following the adoption of willow.

3. Case study country – Poland

Poland is located in East-Central Europe bordered by the Baltic Sea to the north-west, and Carpathian Mountains to the south. In 2017, the total UAA in Poland constituted 14.6 million ha with nearly 74% of arable land, 22% of permanent meadows and pastures (Statistics Poland, 2018). The share of land used for agriculture is about 31.3 million ha representing 60% of the country's total surface. Formed on acidic rocks deposited by glaciers, dominant soils (46% of UAA) are of medium and poor quality and agricultural suitability. Large proportion of Polish soils are mostly characterised by sandy and light soils with low water content, thereby representing high risk of drought. In addition, 21% of UAA are threatened by water erosion, and consequently by mineral leaching (Krasowicz et al., 2012).

The viability of agricultural sector is highly dependent on the 1st pillar CAP entitlements. According to the Agency for Restructuring and Modernisation of Agriculture (ARMA), 1.3 million agricultural holdings benefited from € 3.39 billion of direct payments. Farms with land area between 1 and 10 ha are the major beneficiaries, representing 74% of the total number of Polish farms, but covering only 30% of the agricultural land (Statistics Poland, 2018). Since 2015, greening entitlements have been granted to almost all farmers complying with the direct payment scheme. To enhance crop diversification and climate change vulnerability, Poland applies a practice which requires a minimum of four eligible crops rather than of two or three (EEIG Alliance Environment, 2018). Despite this practice, the Polish agricultural production has intensified, resulting in an increased N fertilisation (+4.7%) and GHG emissions (+4.1%) in 2017 compared with 2015 (Eurostat, 2019; European Environment Agency, 2019).

Being one of the largest coal-mining countries in Europe, Poland is highly dependent on coal for energy production. In 2017, Poland had the largest share (55.5%) of solid fossil fuels, i.e. hard and brown coal, in the gross inland energy consumption (Statistics Poland, 2019), compared with other EU countries. During the 2018 United Nations Climate Change Conference (COP24, held in Katowice, Poland) pressure grew on Poland to decrease its reliance on fossil fuel and therefore to meet the EU climate policy targets. So far, biomass represents only 7% of the gross energy consumption, although it is claimed that the country represents a high biomass potential. Among PEC, willow SRC is the most suitable biomass crop for Polish soil and climate conditions. For instance, it can be grown either to reduce N leaching or to produce energy. Although it has the best developed network, willow is grown only on 8 000 ha in 2010. Current statistics on willow areas do not exist yet. Though many studies showed that large proportion of unutilised agricultural area (UnAA) can be used for non-food purposes in Poland. Pudełko et al. (2018) show that almost 2.03 million ha of UnAA can be allocated to non-food crops, more than half of which are of medium quality on arable land (39%) and permanent grasslands (23%). Low quality areas represent 20% of UnAA, 15 % of which are located on arable land and the remaining 5% on permanent grasslands.

3.1. Model description of the case study

In AROPAj model, individual Polish farmers are well represented as they are clustered into FG based on their technico-economic orientation, their economic size and their altitude class. 209 FG are created for Poland from 10343 individual 2012-FADN surveyed farms, representing 13.03 million hectares (Mha). FG are grouped into four Polish FADN regions, i.e. Pomorze & Mazury, Wielkopolska & Śląsk, Mazowsze & Podlasie, and Małopolska & Pogórze, according to 14 economic size and farming type classes. Horticulture and permanent fruit activities, e.g. vineyards and olives, are not included in AROPAj crop production.

If we are to test the consistency of some AROPAj outputs, Table 2 shows that they are in line with FAO and Eurostat data, although the latter are difficult to compare with FADN data. Results from V_5-AROPAj calibrated on 2012-FADN data confirm that Poland is characterised by an important and diversified agricultural activity with an intensive crop management dominated by cereal farming with more than 70% (Table B1, in Appendix B). As for animal rearing, it varies from one region to another. The greatest share is attributable to Wielkopolska and Śląsk (the highest livestock density per hectare of grasslands), and Mazowsze and Podlasie (the highest area of grasslands).

Simulation scenarios and assumptions – A wide range of perennial dedicated activities are integrated in AROPAj model, ranging from miscanthus, switchgrass, poplar, to willow. In this study, we consider only willow. As regards yields, we suggest to correlate data with those of a control plant, e.g oat, in a similar way to that in Mola-Yudego and Aronsson (2008). The authors estimated willow yields by combining crop management and climate data with local productivity of oats, based on more than 2000 commercial plantations in Northern Europe. Willow yields are then calculated through applying Eq.(1).

Table 2
Comparison between Statistic data and V5-AROPAj results for 2012. Statistics on cropland areas are provided by FAOSTAT, while those related to Agricultural GHG emissions and N fertilisation are provided by EUROSTAT

	2012 Statistic Data	2012 V5-AROPAj
Cropland (ha)		
Wheat	2 077 200	2 248 931
Barely	1 160 600	1 511 135
Maize	543 800	638 788
Oats	513 800	510 867
Rapeseed	720 308	943 524
Potatoes	373 000	420 883
Agricultural GHG emissions (tCO_2 equivalent)		
CH_4	13 683	12 707
N_2O	15 546	12 037
Consumption of inorganic fertilisers (tonnes)		
N fertilisation	1 094 673	758 200

Parameters (Table 3) are also used as benchmark. The estimation reveals an average yield of around 8 tdm ha^{-1} (Fig. 2).

$$\text{yield}_{\text{willow},k} = b_0 + b_1.\ \text{yield}_{\text{oats},k}.\ \text{pla}_k + \text{gro}_c.\ \text{pla}_k + b_2.\ \exp_k \tag{1}$$

To make farmers less reluctant to grow willow, incentives for its plantation are added. A wide range variation of willow subsidy amount is then proceeded, with the double aim of increasing the number of eligible crops and ensuring the multifunctionality of Polish agriculture. We propose to consider a subsidy value varying from 0 to € 250 ha^{-1} by increments of 10. We set the parameters related to the crop's threshold area and the maximum area limit to 1 ha and 95% of UAA, respectively. In addition, we consider that willow area is limited to 15% of UAA, its price is fixed at € 77 tdm^{-1} and the annual costs are about € 395 ha^{-1}. Those latter values reflect the guaranteed price and the establishment subsidy whose different levels may result in different values of annualised costs for the willow plantations. The area subsidy may identify to increasing levels due to the variation of EFA support levels, that represent the main policy parameters identified by field studies (Spiegel et al., 2018). The former parameters relate to energy policy and rural development measures whereas the latter to alternative provisions to consider in the frame of the CAP beyond 2020 allowing national priorities.

Based on De Cara et al. (2005), the livestock adjustment is limited to a range of -15 to 15% of the estimated level using FADN data. This interval pertains to the model constraints reflecting the inertia of the adjustment of FGs' livestock numbers for different animal categories (cattle, sheep, goats, swine, and poultry). A reference scenario in which the subsidy for crop diversification is set around the current level (i.e. € 75 ha^{-1}) is tested and then compared against other scenarios, representing lower and higher values of subsidy for crop diversification than that of the chosen level.

Since AROPAj FG represent higher number of crop activities than those of FADN sampled farms, we suggest to increase the number of eligible crops to more than what is assigned by the model calibration. A simple counting of number of crop activities per FG is proceeded in order to set the starting point of the scanning grid. From Fig. A1 (in Appendix A), one can notice that the lowest number of crop activities is about 2 recorded in Mazowsze & Podlasie and Małopolska & Pogórze, and the highest is 15 in Wielkopolska & Śląsk. Accordingly, the number of required crops is then varied from 2 to 16.

For better targeted measures and understanding the decision-making behaviours, it is required to consider the diversity of farming systems (Weltin et al., 2017). The impact analysis of the aforementioned scenarios is therefore distinguished according to regions, FG's technico-economic orientation and economic size, in order to analyse the behavioural differences and identify the FG's types that are the most sensitive to changes in CAP measures. For this study, we simplify the number of classification categories and thus consider that FG are distributed among only 6 types of farming (FT) and 5 economic sizes (ES), respectively ranging from crop production to livestock farming and from 4000 - < 15 000 to ⩽ 750 000 € (Table 4).

4. Results interpretation

In this section, the impacts of different scenarios regarding the number of eligible crops and the level of subsidy allocated for willow on FG's economic and environmental outputs, i.e. gross margin, land use change, N-fertiliser use and GHG emissions (N_2O and CH_4), are presented according to four Polish FADN regions, technico-economic orientation and economic size. The assessment is done against a baseline situation in which subsidies for crop diversification and willow plantation, and number of eligible crops are all set at 0. Since crop production varies widely from one region to another, depending on soil quality, the results regarding willow area are also spatially distributed at a fine geographical scale (FG level) to emphasize disparities between the different Polish regions.

4.1. Impacts on farm income

We consider the gross margin as an income indicator that includes the rent to the production factors, i.e. land, and received payments or paid taxes. In addition, we do not take price feedbacks into account and assume that farmers are price takers. Figs. 3 and 4 show the sensitivity of income and number of crop activities over FG to changes in the amount of crop diversification support, whether or not willow plantation is subsidised, and in the number of required crops.

One can notice, from Fig. 3, that an increase in crop diversification support leads to a clear upward variation in income, thereby displacing the curve towards higher values and reducing the income loss. For a support equal to € 75 ha^{-1}, the typical income per hectare stands between € 600 ha^{-1} and € 1200 ha^{-1}. Incomes between € 500 ha^{-1} and € 1400 ha^{-1} are frequent. High incomes are also recorded, ranging from € 1600 ha^{-1} to € 2500 ha^{-1}. Furthermore, an increase in the amount of subsidy for willow plantation results in a slight increase in incomes, since FG which opted for willow have already adjusted their cropping plan at the time of implementing crop diversification measures. However, if the latter are more binding in terms of number of crop activities, the income curve moves to lower values.

The adjustment of cropping plan may occur in two ways: either by increasing the number of grown crops up to the required level, or by decreasing the number of grown crops down to a number greater or equal to the required level. FG may also opt out of diversification obligations, and thus keep following the initial cropping plan. A closer look at the distribution of number of crop activities over FG (Fig. 4) reveals that the higher the amount of crop diversification support, the larger the number of FG which adjust their cropping systems to meet the requirements. Providing an additional support for willow plantation

Table 3
Parameter estimates of willow yield as cited in Mola-Yudego (2010). *pla* is the rotation period, *exp* refers to grower's management experience (no experience = 1), gro_c is a categorical parameter related to grower's performance (gro_{25} - 25% best growers, gro_{50} - 50% best growers). The index k refers to FG.

Parameter	Estimate	Parameter	Estimate	Parameter	Estimate
b_0	2.213	*b2*	−0.204	*exp*	1.5
b_1	0.075	*gro50**	−0.129	*pla*	30
b_2	−0.204	*gro25*	−0.039		

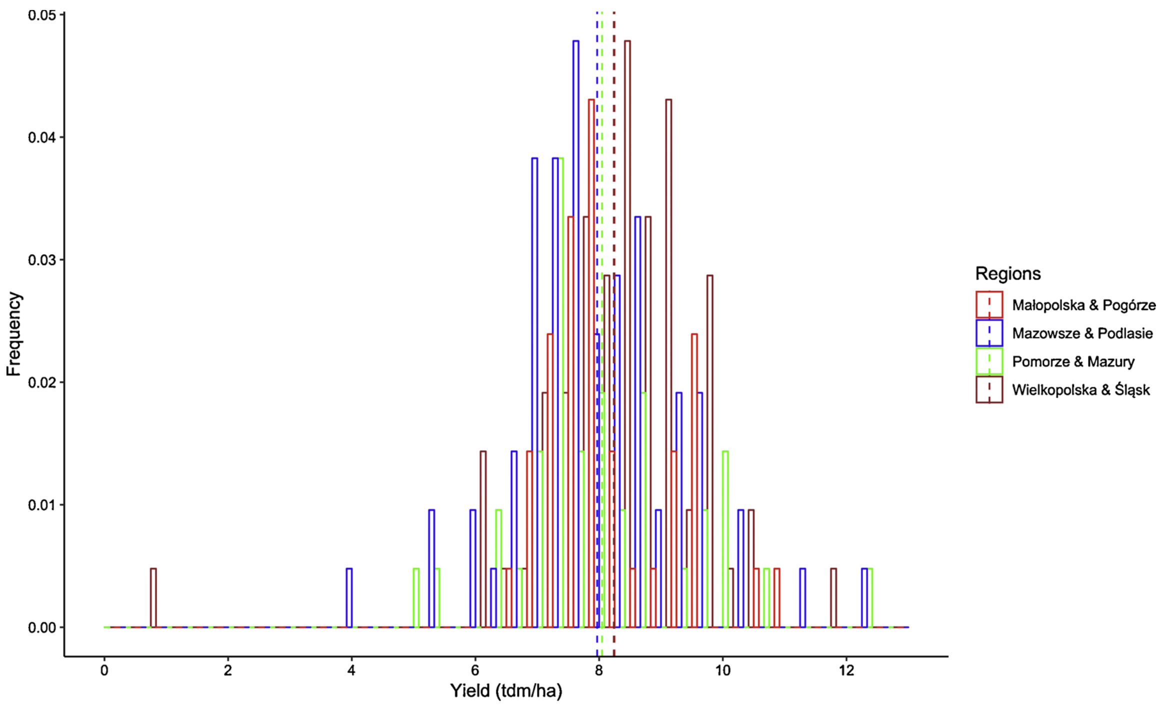


Fig. 2. Estimated willow yields according to Polish FADN regions. Vertical lines denote the averages.

Table 4
Simplified representation of farming type and economic size categories to which Polish farm groups belong

Type of farming	Designation	Number of FG
Specialist cereals, oilseeds and protein crops	FT1	29
General field & mixed cropping	FT2	38
Grazing livestock	FT3	51
Mainly granivores	FT4	36
Field crops - grazing livestock combined	FT5	24
Various crops and livestock combined	FT6	31

Average economic size (€)	Designation	Number of FG
4000 –< 15 000	ES1	42
< 25 000	ES2	43
< 50 000	ES3	50
< 100 000	ES4	34
< 750 000	ES5	40

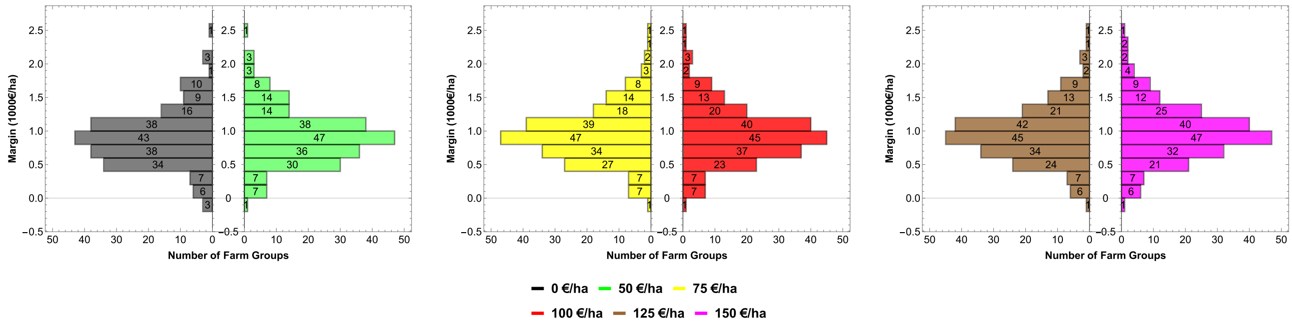
may also foster crop diversification. For instance, if the support exceeds € 125 ha^{-1}, 50% of FG increase the number of their activities up to the required level, compared to 40% of FG for a support of € 75 ha^{-1}. Nevertheless, as a result of an increased number of eligible crops, there are less FG complying with crop diversification measures (Fig. C1, in Appendix C). In this sense, while 47% of FG are compliant with 10 crop requirement, only 32% of FG comply with 14 crop requirement.

These results can be explained by the capacity of FG to comply with diversification requirements. According to Table 5, the measures result in different outcomes, depending not only on the number of eligible crops, but also on regions, farming types, and economic sizes. A subsidy allocated to willow plantation may slightly alleviate the loss in income or increase it. At the regional level, the crop diversification measures have positive impact in Pomorze & Mazury, unlike Małopolska & Pogórze in which the negative impact is the greatest. Regarding Mazowsze & Podlasie and Wielkopolska & Śląsk, mixed impacts are recorded being positive (or negative) for less (or more) binding requirements. This could be due to the farming structure (farm type and economic size) and specialisation defining each region. As a matter of fact, a substantial increase in income is marked in FG specialising in cereals, oilseeds and proteins (FT1), as well as FG specialising in animal production (mainly grazing livestock FT3). As the number of eligible crops increases, incomes decrease in FG specialising in granivores (FT4), in field crops and grazing livestock activities combined (FT5), and various crops and livestock combined (FT6). In the most binding cases, small-sized FG (ES1) record a consequent loss in their income, compared to middle and high-sized FG (ES3, ES4 and ES5). This could be explained by the specialisation of FG, according to their production factors. While small-sized FG are more likely specialised in capital intensive productions (e.g. cereals and oilseeds), middle and high-sized FG are more specialised in labour-intensive activities (e.g. livestock) (Gocht et al., 2017; Kancs and Ciaian, 2012).

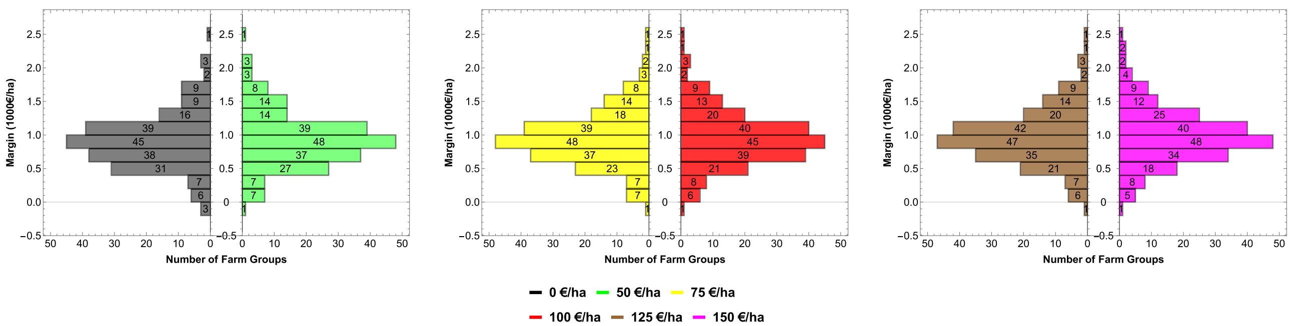
The increase in farmers' income is particularly important when the support for crop diversification is combined with another one, in this case, a support for willow plantation. However, an increase in required number of crops reduces gain from willow plantation. In this regard, increased subsidy levels for willow impact positively the income of all farmers. For instance, the highest positive impact is recorded in Mazowsze & Podlasie, with an increase between 1.5% and 2.2% for a subsidy level equal to € 200 ha^{-1}. The same holds true for Małopolska & Pogórze and Pomorze & Mazury, but to a lesser extent. Regarding farmers located in Wielkopolska & Śląsk, they are less sensitive to an increase in the amount of allocation for willow plantation, increase rates being between 0.1% and 0.6%. Assuming a gradual increase in the amount of allocation for willow plantation, FG belonging to FT3 and FT4 categories are the most sensitive. For instance, the income increase ranges from 0.6 to 1% for FT3, and from 1.8 to 3.5% for FT4 considering different number of eligible crops. As regards the economic size classes, FG belonging to ES1, ES2 and ES3 are the most sensitive, increase rates varying from 0.9 to 1.3%, from 0 to 0.8%, and from 1.8 to 2.1%, respectively.

4.2. Impacts on land allocation

Here, we consider that the agricultural land is shared between cropland, permanent grasslands and fallow land to examine the impacts of crop diversification constraints and willow plantation (Fig. 5).



(a) Subsidy_{willow} = €0 ha^{-1}

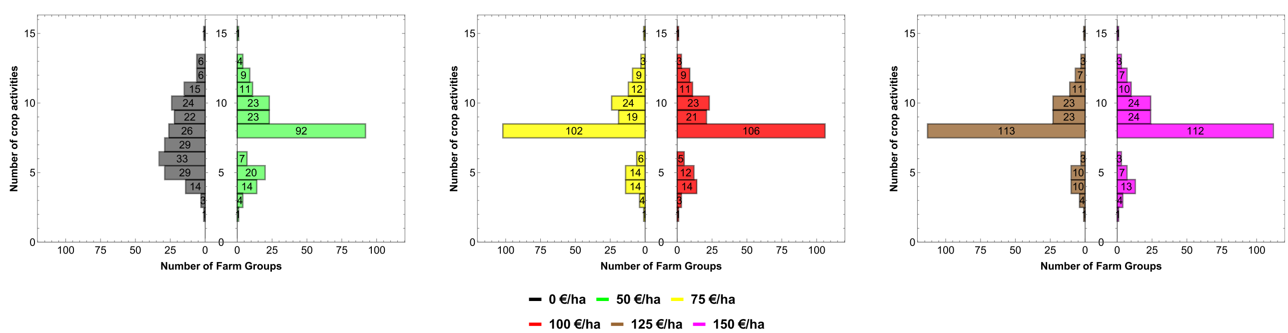


(b) Subsidy_{willow} = €200 ha^{-1}

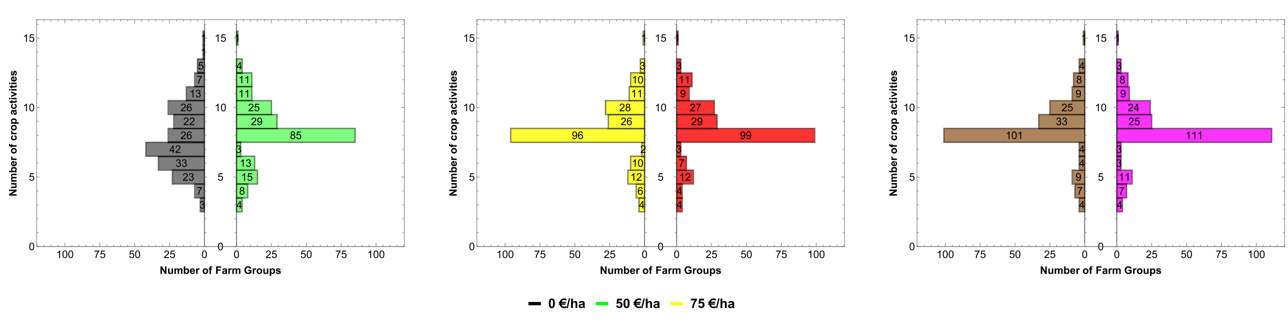
Fig. 3. Distribution of gross margin per hectare over AROPAj farm groups in case of 8 crop requirement and five subsidy levels for crop diversification € 0 ha^{-1} (Black), € 50 ha^{-1} (Green), € 75 ha^{-1} (Blue), € 100 ha^{-1} (Red), € 125 ha^{-1} (Brown), and € 150 ha^{-1} (Magenta).

Regarding arable land, it represents six aggregated uses, i.e. cereals, root crops, oilseeds, legumes and fodders, and willow. Cereals' category comprises wheat, maize, barely, oat, rye and other cereals. Sugar beet and potatoes are classified as root crops. Oilseeds include sunflower, rapeseed and soya. Finally, fodders refer to protein and vegetable fodders, fodder maize and other fodders.

At the regional level, it is observed that cropland decreases slightly with the number of eligible crops in all regions at the expense of



(a) Subsidy_{willow} = €0 ha^{-1}



(b) Subsidy_{willow} = €200 ha^{-1}

Fig. 4. Distribution of number of crop activities over AROPAj farm groups in case of 8 crop requirement and five subsidy levels for crop diversification € 0 ha^{-1} (Black), € 50 ha^{-1} (Green), € 75 ha^{-1} (Blue), € 100 ha^{-1} (Red), € 125 ha^{-1} (Brown), and € 150 ha^{-1} (Magenta).

Table 5
Variation in percent of gross margin per hectare for the Polish FADN regions, types of farm specialisation and economic size classes depending on number of eligible crops and levels of willow subsidy. The rates are assessed against a baseline situation in which crop diversification measures are not considered.

	Margin (€ 1000 ha^{-1})	Variation rate (%)												
	Baseline Scenario	Eligible crops	6			8			10			12		
		Willow subsidy (€ ha^{-1})	0	100	200	0	100	200	0	100	200	0	100	200
Regions														
Pomorze & Mazury	0.8		19.8	19.9	20.2	18.1	18.3	18.8	16.7	16.8	17.2	15.3	15.6	16.0
Wielkopolska & Śląsk	0.9		0.2	0.1	0.1	−0.8	−0.6	−0.4	−0.7	−0.6	−0.3	−1.4	−1.3	−1.0
Mazowsze & Podlasie	1.0		7.4	8.0	9.2	0.5	1.5	2.7	−4.3	−4.2	−2.8	−4.9	−4.8	−3.4
Małopolska & Pogórze	0.9		−3.3	−3.0	−2.6	−4.9	−4.8	−4.4	−5.8	−5.7	−5.4	−6.8	−6.7	−6.3
Farming Type														
FT1	0.9		9.9	9.9	9.9	8.8	8.9	9.0	7.2	7.2	7.4	6.0	6.1	6.2
FT2	1.1		−2.9	−2.8	−2.6	−4.0	−3.8	−3.5	−5.4	−5.2	−4.9	−6.3	−6.2	−5.8
FT3	1.2		5.4	5.6	5.9	4.4	4.6	5.0	3.1	3.3	3.8	2.3	2.5	3.2
FT4	0.4		12.8	13.4	15.2	0.5	2.2	4.0	−4.0	−4.0	−2.2	−4.0	−4.0	−2.1
FT5	1.0		3.1	3.2	3.5	1.9	1.9	2.3	0.4	0.5	1.1	−0.5	−0.4	0.2
FT6	0.7		3.5	3.6	4.0	1.7	1.9	2.2	0.1	0.3	0.6	−1.5	−1.3	−0.8
Economic size														
ES1	0.8		−6.9	−6.5	−5.8	−10.0	−9.6	−8.7	−11.7	−11.4	−10.6	−12.1	−11.9	−11.1
ES2	0.8		2.2	2.1	2.2	0.2	0.4	0.9	−2.4	−2.2	−1.6	−3.6	−3.4	−2.8
ES3	0.9		23.0	23.6	25.1	13.6	14.9	16.4	6.7	6.9	8.4	5.2	5.4	7.0
ES4	1.0		−1.6	−1.6	−1.5	−0.5	−0.6	−0.7	2.0	2.0	2.2	0.3	0.5	0.6
ES5	0.9		4.7	4.7	4.7	4.6	4.6	4.6	5.4	5.4	5.3	6.1	6.0	6.0

grasslands and fallow land. However, land use allocation depends also on the subsidy amount for cropping system diversification. For instance, as willow subsidy increases, one can notice a decrease pattern in fallow areas independently of required number of crops, in all regions, farming types, and economic size categories. As regards grasslands area, it tends to increase slightly with increased number of crops and subsidy levels as well, especially in Małopolska & Pogórze, region representing the highest share of grasslands (17% of agricultural land). FG specialising in grazing livestock and those combining field cropping and grazing livestock activities (FT3 and FT5) are the most affected by crop diversification, impacts on cropland being most noteworthy. In fact, having large share of grassland, these FG convert higher proportion of cropland than others to comply with diversification requirements, thereby planting willow and/or increasing slightly grassland area. Regarding the economic size, middle and high-sized (ES4 and ES5) FG tend to adjust their grassland (including fodders) and fallow land area, while small-sized FG tend to re-allocate their cropland area in favour of willow.

Furthermore, as the number of eligible crops increases, willow area increases mainly at the expense of cereals, in all regions, particularly in small and middle-sized FG (ES1, ES2, ES3) specialising in mixed cropping (FT2) and in animal activities (FT3, FT4, and FT5). The same holds true for high levels of subsidy for willow plantation. However, FG specialising in cereals, oilseeds and protein crops (FT1) allocate lesser area for willow independently of the subsidy level. It is likewise for FG belonging to ES4 and ES5, willow being integrated more for higher number of crops required for diversification. The remaining land allocated for other crop activities is also about to decrease but with insignificant magnitudes.

At FG level, land re-allocation resulting from diversification measures is heterogeneous, with respect to the initial number of crop activities and land use patterns. In fact, among 89 FG (out of 209) that comply with the 8 crop requirement, only 9% of FG opt for willow when its plantation is not supported (Table D1, Appendix D). FG having less than 8 activities in their cropping systems tend to increase the number of activities, whereas FG with more than 8 activities tend to remove some activities. On the one hand, fodders' and fallow areas are re-allocated to other uses mainly in FG specialising in general field and mixed cropping (FT2), in grazing livestock (FT3) and those combining field cropping and grazing livestock activities (FT5). However, grasslands are mainly displaced in middle and high-sized FG specialising in granivores, and in various crops and livestock combined (FT4, FT6). On the other hand, cereals (mainly wheat and oat) and oilseed crops (sunflower) are integrated in most of FG that comply with the requirement. 13% of FG, mostly specialising in animal activities (grazing livestock, i.e. FT3 and granivores, i.e. FT4), tend to re-allocate land in favour of fodders and grassland, independently of their economic size.

4.3. *Impacts on willow production*

Here, we attempt to locate the FG which opt for willow plantation. Potential areas allocated for willow are spatially identified using AROPAj downscaling module aiming at estimating the presence probabilities of willow activity in irregular 100mx100m polygons (Cantelaube et al., 2012). Fig. 6 shows the change in willow area per percent of AROPAj UAA (equal to 13.03 million ha) according to different number of eligible crops and levels of subsidy for willow plantation.

One can notice that willow area is sensitive to changes in required number of crops and support on willow. The greater the subsidy amount, the more likely willow is to be planted, depending on regions' profiles and economic characteristics. In Mazowsze & Podlasie, willow is more likely to be adopted than in other regions regardless of the amount of subsidy. As matter of fact, the crop may be grown without subsidy up to 1% of UAA in the most binding case. The land share may reach 5.3%, 5.4%, and 7.1% of UAA for a number of crops constrained to 6, 8 and 10, respectively and for a subsidy amount equal to € 200 ha^{-1}. In the case of Pomorze & Mazury, willow areas are ranging from 0.08-0.3%, 0.1-0.5%, to 0.4-1.1% of UAA for a number of crops constrained to 6, 8 and 10, respectively and for a subsidy level set at 0. For a higher level of subsidy equal to € 200 ha^{-1}, the land share of willow increases threefold, i.e. 3.5% of UAA in some areas. In Wielkopolska & Śląsk, the crop may be grown on lesser share of land, compared to Pomorze & Mazury. Without subsidy, willow area may reach 0.1%, 0.2%, and 1% of UAA for an increasing number of crops. Subsidsing the crop up to € 200 ha^{-1} may spread willow plantation within the region to 2.8% of UAA. As regards Małopolska & Pogórze, if willow is not subsidised, its area declines (from 1.2% to 0) instead of expanding as the number of eligible crops increases. For a subsidy amount equal to € 200 ha^{-1}, willow may be grown up to 5% of UAA in the most binding case (10 eligible crops).

Table 6 provides the reader with estimates of willow production at national and regional scales for different scenarios, according to model assumptions and optimisation. As previously shown, Mazowsze & Podlasie represents the highest production level. If willow plantation is

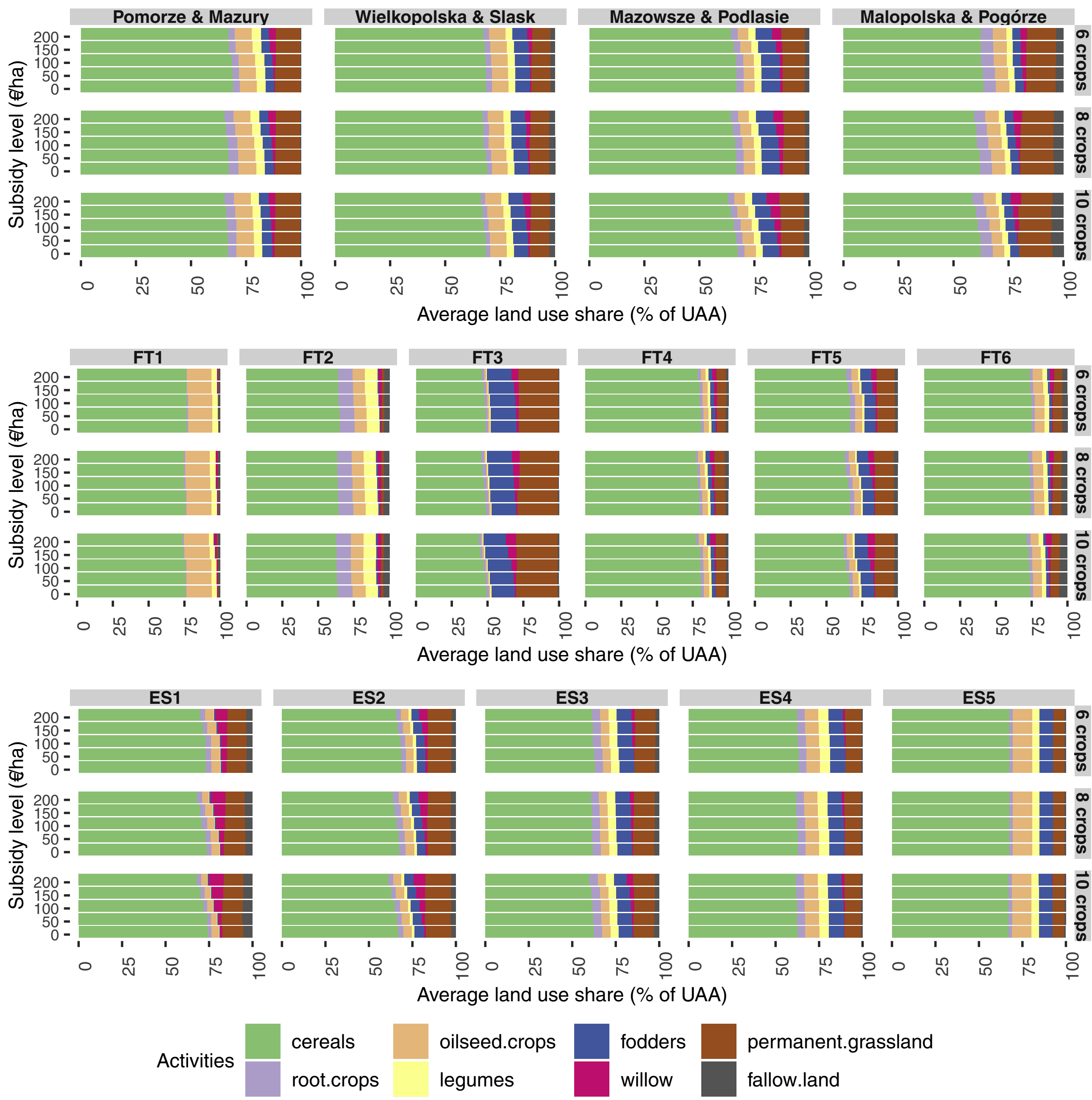


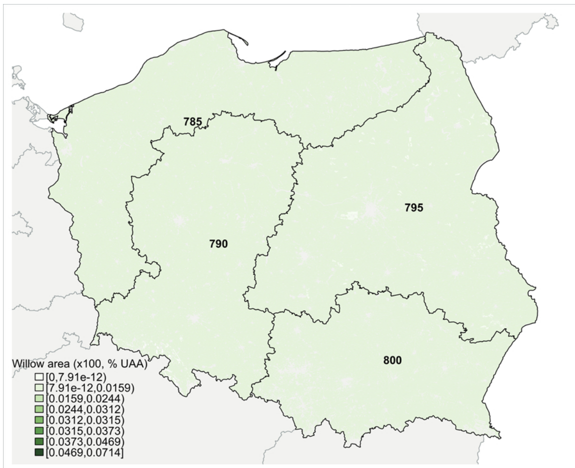
Fig. 5. Changes in land use allocation in percent of arable land for different number of eligible crops and according to Polish FADN regions, farming type and economic size classes.

not subsidised, the production drops by almost 50% from 0.7 million tons to 0.3 million tons for 6 and 10 crop requirements, respectively. Subsidising the crop up to € 100 ha^{-1} (or € 200 ha^{-1}) may increase the production level even in the most binding cases (number of crops set at 10), up to 1.7 million tons (3.6 million tons), thereby representing more than 55% (approximately 60%) of total national production. The same figure is also observed in the remaining regions but with lower levels, production reaching 1 million tons in Wielkopolska & Śląsk, and 0.7 million tons in Pomorze & Mazury and Małopolska & Pogórze, for a subsidy level of € 200ha^{-1}. The reader can also notice that willow production increases with crop diversification options, when increasing both the support for willow plantation and the number of eligible crops. This is not the case for Wielkopolska & Śląsk in which a policy increasing the number of eligible crops outweighs the benefit from the support of willow plantation, thereby decreasing the number of FG that opt for willow.

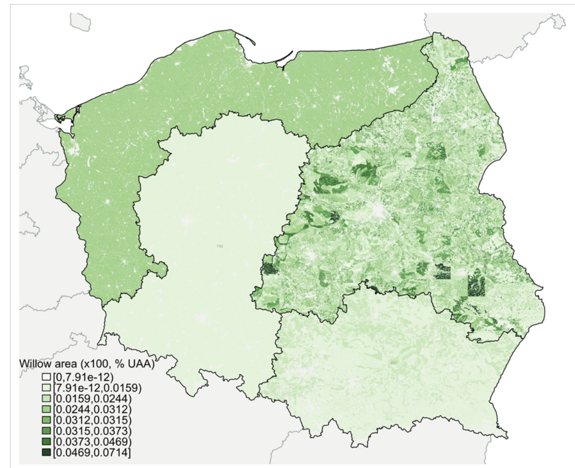
4.4. Environmental impacts

In addition to economic indicators, environmental impacts are also taken into account to assess the sustainability and the friendliness to the environment of Polish agriculture when considering the integration of a new crop. Based on AROPAj-STICS framework, N-fertiliser use, methane (CH_4) and nitrous oxide (N_2O) emissions are assessed against a baseline situation in which crop diversification measures are not considered.

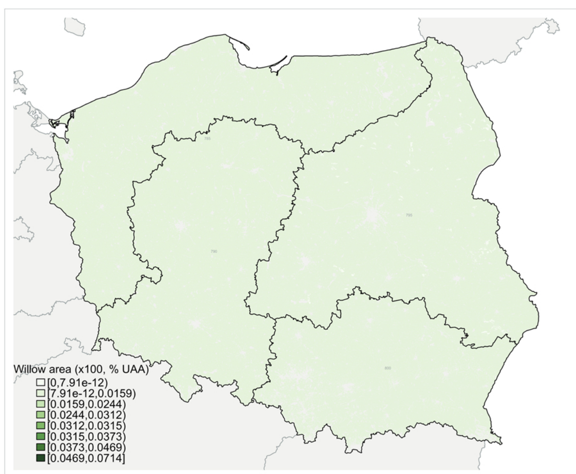
As shown in Fig. 7, the crop diversification measures have a double effect on agricultural production, thereby varying the N-fertiliser use among regions, farming types, and economic size categories. Firstly, unlike Pomorze & Mazury and Wielkopolska & Śląsk, the implementation of crop diversification measures increases the N-fertiliser use in Mazowsze & Podlasie and Małopolska & Pogórze (by 5% and 4% respectively in the case of 6 required crops). This holds true especially



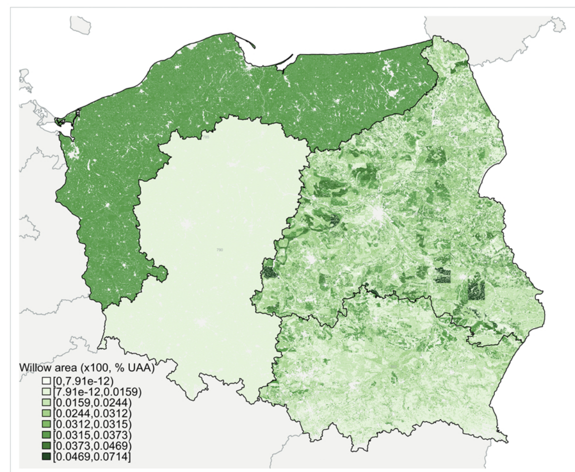
(a) 6 crop requirement - Subsidy$_{willow}$ = €0 ha^{-1}



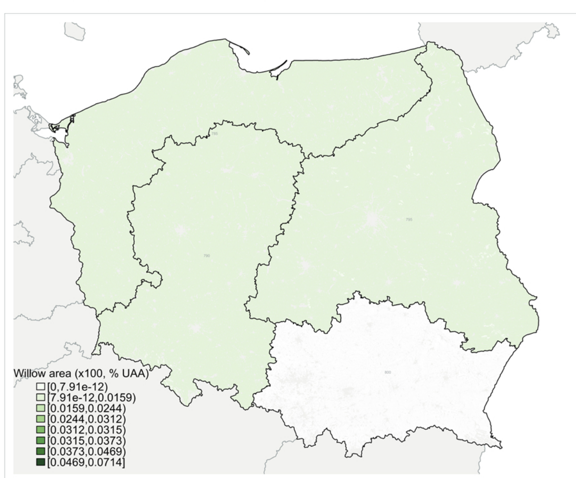
(b) 6 crop requirement - Subsidy$_{willow}$ = €200 ha^{-1}



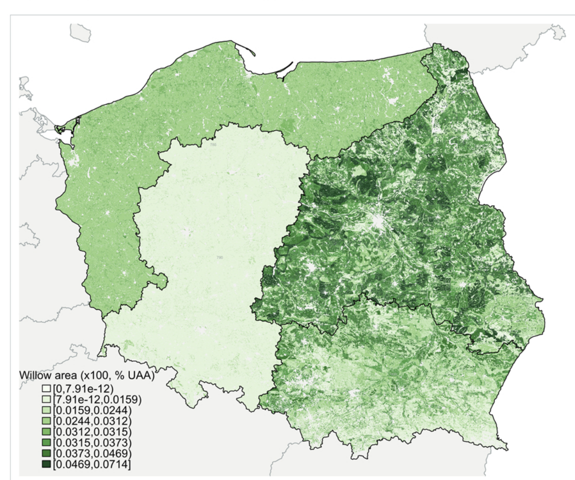
(c) 8 crop requirement - Subsidy$_{willow}$ = €0 ha^{-1}



(d) 8 crop requirement - Subsidy$_{willow}$ = €200 ha^{-1}



(e) 10 crop requirement - Subsidy$_{willow}$ = €0 ha^{-1}



(f) 10 crop requirement - Subsidy$_{willow}$ = €200 ha^{-1}

Fig. 6. Regional distribution of willow area in Poland according to different crop number requirements and levels of subsidy on willow plantation. (a) refers to 6 crop requirement and subsidy level equal to € 0 ha^{-1}, (b) refers to 6 crop requirement and subsidy level equal to € 200 ha^{-1}, (c) refers to 8 crop requirement and subsidy level equal to € 0 ha^{-1}, (d) refers to 8 crop requirement and subsidy level equal to € 200 ha^{-1}, (e) refers to 10 crop requirement and subsidy level equal to € 0 ha^{-1}, and (f) refers to 10 crop requirement and subsidy level equal to € 200 ha^{-1}. The IDs of FADN regions: 785, 790, 795 and 800 refer to Pomorze & Mazury, Wielkopolska & Śląsk, Mazowsze & Podlasie, and Małopolska & Pogórze, respectively. Data geoprocessing: INRA - JRU Public economics, Grignon, France.

within middle and high-sized FG, for instance ES3 and ES4 (by 2% and 6% respectively) and within those specialising in grazing livestock, i.e. FT3 and FT5 (by nearly 10% and 7% respectively). As a matter of fact, to comply with crop diversification requirements, FG decrease their cropland area at the expense of willow, but in return, they use more fertilisers to increase cropland yields (intensive effect) and add to their cropping plans high N-demanding crops, i.e. cereals, oilseeds and root crops. Secondly, the higher the number of required crops, the lower the

Table 6
Willow production (in thousand tons and in percent of total production) in Polish FADN regions according to different number of eligible crops and levels of subsidy for willow plantation - Assessment resulted from AROPAj model assumptions and optimisation.

Number of crops	Willow subsidy	% FG producing willow (%)	Willow Production (million tons)	Share of production (%) Pomorze & Mazury	Wielkopolska & Śląsk	Mazowsze & Podlasie	Małopolska & Pogórze
	0	11	1.0	7	13	72	8
6	100	25	2.4	16	25	44	15
	200	38	4.6	18	17	50	14
	0	12	0.8	32	31	37	0
8	100	27	2.5	18	21	46	14
	200	49	5.5	13	18	56	13
	0	19	0.7	37	20	41	3
10	100	36	3.1	21	12	55	12
	200	56	6.2	13	18	58	11

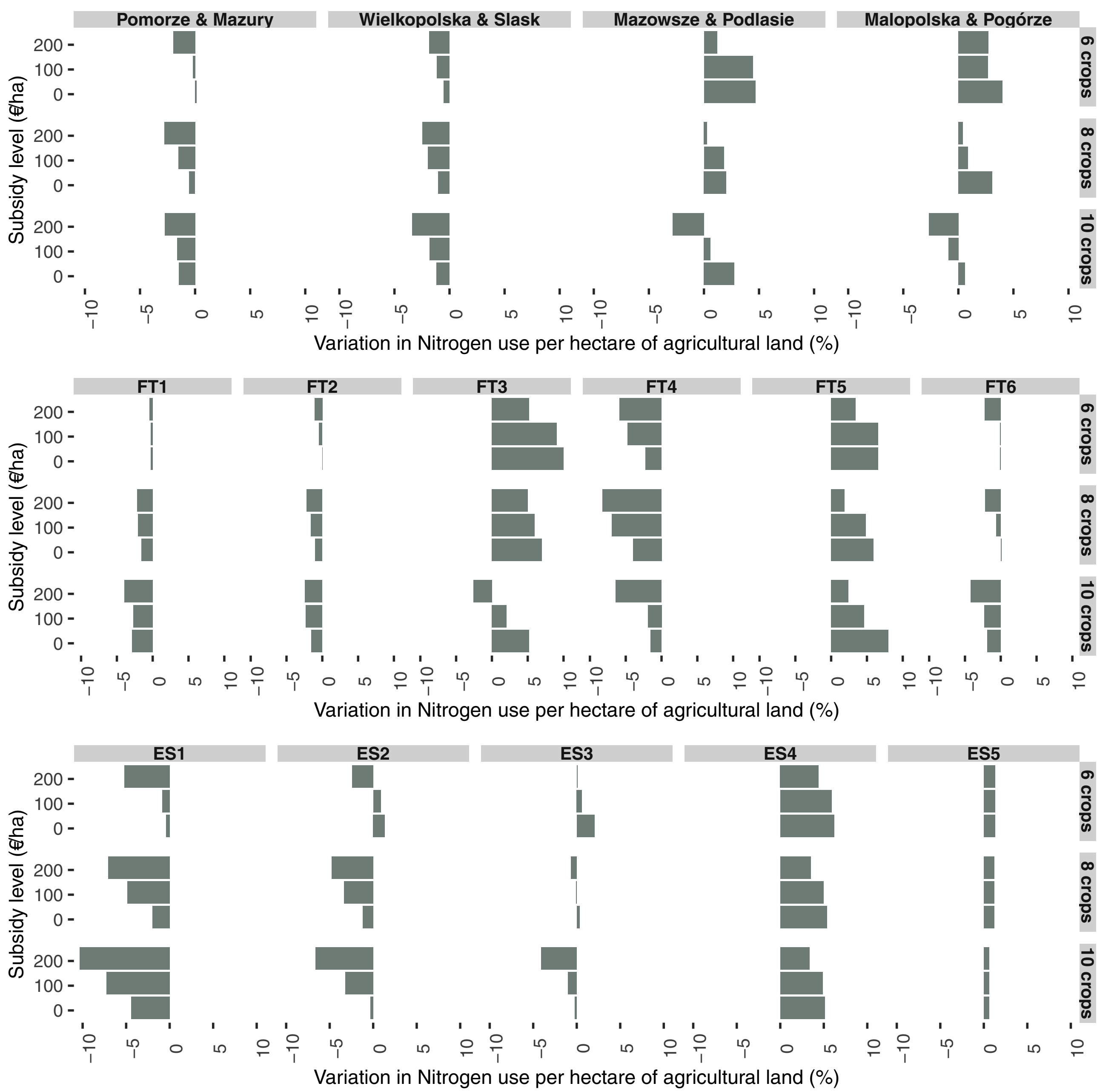


Fig. 7. Variation in Nitrogen use per hectare of agricultural land (in %) for different number of eligible crops and according to Polish FADN regions, farming type and economic size classes. Values assessed against a baseline situation in which subsidies for crop diversification and willow plantation, and number of eligible crops are all set at 0.

N-fertiliser use. In most cases, a coupled support policy (when willow plantation is subsidised) further reduces N-use. For instance, if willow is subsidised up to € 200 ha^{-1} and 10 eligible crops are required, the N-demand may be reduced down to 3.4% in Wielkopolska & Śląsk, to 6% within granivores-oriented FG (FT4), and to 10% within small sized FG (ES1). Increasing the number of eligible crops results not only in an increase in areas already allocated for willow, a crop with low N demand, but also in a decrease in areas allocated for high N-demanding crops (extensive effect) in favour of willow and fallow. This is recorded in all regions and FG categories, except for FG combining field crops and grazing livestock (FT5) in which N-fertiliser use increases by nearly 8%.

Regarding GHG emissions, Fig. 8 shows the variation in N_2O and CH_4 emissions (in %) for different number of eligible crops and according to Polish FADN regions, farming types, and economic size categories. While the former are directly related to agricultural soils and depend on per hectare N-fertiliser application (Fig. 7), the latter are mainly linked to livestock activities and manure management (Fig. E1, in Appendix E). An intensification of N-fertiliser use and livestock rearing leads therefore to an increase in N_2O and CH_4 emissions, respectively. On the one hand, as crop diversification measures increase N-demand in Mazowsze & Podlasie and Małopolska & Pogórze, especially within middle and high-sized FG specialising in grazing livestock, N_2O emission levels are significantly higher than those estimated in the baseline scenario (without crop diversification measures). For instance, if willow plantation is not subsidised and low number of eligible crops is required, N_2O emissions increase by 2% within Mazowsze & Podlasie, by 3% within grazing-oriented FG (FT3), and by 7% within FG with incomes higher than € 100 000 (ES4). However, due to a decrease in N-demand, N_2O emissions decline in Pomorze & Mazury and Wielkopolska & Śląsk, within small-sized FG mainly specialising in cereals, oilseeds and proteins, general field and mixed cropping, granivores, and

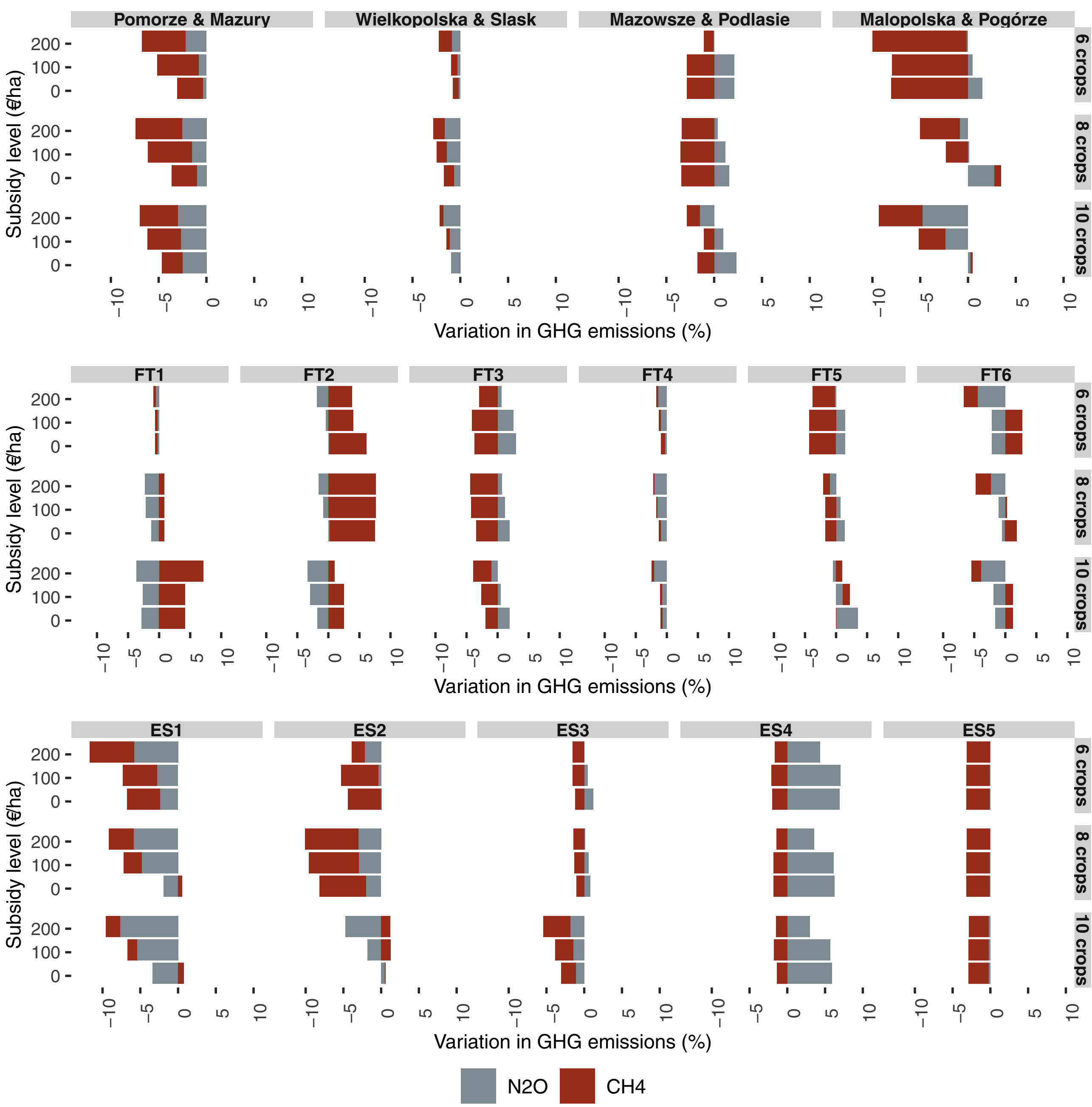


Fig. 8. Variation in N_2O and CH_4 emissions (in %) for different number of eligible crops and according to Polish FADN regions, farming type and economic size classes. Values assessed against a baseline situation in which subsidies for crop diversification and willow plantation, and number of eligible crops are all set at 0.

various crops and livestock combined. Though the reduction is insignificant unless crop diversification measures become more binding (increase in number of eligible crops) and willow plantation is subsidised. In this regard, N_2O emissions decrease by almost 3% in Pomorze & Mazury, by 4% within FG specialising in various crops and livestock combined (FT6), and by almost 8% within small-sized FG (ES1).

On the other hand, the highest CH_4 emission decrease is recorded in regions with small areas of agricultural land, and more particularly, of grasslands (Table B1, in Appendix B), such as Pomorze & Mazury and Małopolska & Pogórze. For instance, if willow plantation is not subsidised and low number of eligible crops is required, CH_4 emissions decrease down to 3% and 8%, respectively. The reduction is also particularly high (down to 4%) in small and middle-sized FG (ES1 and ES2), which opted for willow plantation (see Fig. 5). Integrating willow with a subsidy may further heighten the decrease in CH_4 emissions. However, the more binding crop diversification measures (high number of eligible crops and no subsidy on willow), the lower CH_4 emission decrease. This is mainly due to an increase in livestock activities resulting from the expansion of areas allocated for grassland and fodders. Regarding farming type categories, FG specialising in grazing activities, i.e FT3 and FT5, significantly reduce their CH_4 emissions down to 4% as they grow willow at the expense of grazing activities, thereby limiting the intensification of livestock rearing. However, within FG specialising in crop activities, i.e FT1 and FT2, the diversification measures are in favour of grassland and fodders instead of willow. That explains the increase in CH_4 emissions within these FG.

5. Discussion

The upgraded version of AROPAj model was used to inform policy makers to make prudent choices regarding the number and mix of eligible crops that may be cultivated at a low cost. Firstly, we were able to assess the cost of crop diversification for farmers, by testing on all Polish related FG the impacts of various scenarios and assumptions of 2014-CAP commands, namely number of eligible crops and subsidy amount for crop diversification. Then, we showed how promising candidates for the development of bio-based economy, such as willow, could have been integrated into the Polish farming systems through this CAP option.

Stemming from the modelling approach, our findings differ from those of the existing literature assuming that small-sized and livestock farms have low propensity to allocate land to PEC. To assess farmers' motivation for PEC adoption under different scenarios of CAP crop diversification, the current study is based on a tool for farm-specific policy analysis rather than land use share models (Konrad et al., 2018) and farm surveys (Wilson et al., 2014; Glithero et al., 2013). According to Konrad et al. (2018), small-sized farms cannot provide large and effectively managed land use activities neither can they negotiate advantageous contracts with biomass transformers. As regards livestock farms, they cannot sacrifice a land that is already used to satisfy fodder production requirements (Wilson et al., 2014). However, our result reflects farmers' choices to comply with crop diversification requirements, considering that small-sized and grazing farms have less diversified cropping systems than those of other farm categories. As a matter of fact, middle and high-sized FG tend to adjust their fallow land, grassland, and fodder areas, while small-sized FG tend to adjust their cropland area in favour of willow. FG specialising in grazing livestock and those combining field cropping and grazing livestock activities convert higher proportion of cropland than others to comply with diversification requirements and integrate willow, since they have large share of grassland. This is noteworthy for an increased amount of subsidy allocated for willow plantation.

Regarding the environmental impacts, it has so far been reported that current crop diversification measure has limited environmental impacts since the positive trends resulting from the decrease in arable areas are generally reversed, considering market feedback and increasing UAA (Gocht et al., 2017). In this study, feedback from food market is not taken into account since prices are exogenous. However, optimal N requirements and yields of arable crops are estimated through linking AROPAj with STICS. This allowed us to identify a rather complex double effect of crop diversification: 1) an intensive effect reflecting an increase in yields of arable crops and 2) an extensive effect reflecting a decrease in areas of conventional crops at the expenses of willow. The first effect is further heightened by the integration of high N-demanding crops. According to our estimates, the total N-fertiliser use per hectare slightly increases by 0.9% relative to the baseline scenario. This situation is reversed when subsidy on willow amounts to € 200 ha^{-1} and a -1.1% decrease recorded in the case of 8 eligible crop requirement. In this scenario, average regional levels vary between -2.8% and 0.39%. Differences within FT and ES categories are between -7.9% and 2.7%, and -7.2% and 4.6%, respectively.

To our knowledge, the impacts of crop diversification on GHG emissions have been assessed only in Gocht et al. (2017) with a focus on fertilisation-related ammonia emissions (NH_3). No change in NH_3 emission level was reported by the authors, while highlighting the insignificant impacts of crop diversification on N-fertiliser use. However, our results suggest that the decrease in cereals' areas, mainly within FG with high livestock-rearing, leads to an increase in N fertilisation (for yield improvement) to nearly 10% especially when willow plantation is not subsidised, thereby significantly increasing N_2O emissions up to 3%. Furthermore, unlike crop-oriented FG, livestock-oriented FG tend to significantly reduce their CH_4 emissions (down to 4%) since they integrate willow at the expense of grassland, among other activities, thereby limiting the intensification of livestock rearing. However the more binding crop number requirement the lower CH_4 emission decrease. In almost all cases, subsidising willow may slightly decrease CH_4 emissions.

According to our estimates, the Polish agriculture presents high production potential of willow, the supply varying between 1 and 6.2 million tons with respect to the diversification measures and the amount of support on willow. This is contrary to what is actually observed, few farmers opting for willow plantation. Several barriers can explain this gap, in particular, the lack of support. As a matter of fact, only 9% of FG, i.e. small and middle-sized FG specialising in cereals, oilseeds and protein crops, and in grazing livestock, opt for willow, benefiting from a basic diversification support (€ 75 ha^{-1}). In addition to this payment, subsidising willow plantation up to € 100 ha^{-1} and € 200 ha^{-1} results in an increase of 20% and 45% of FG opting for willow, respectively. The latter support option constitutes a proactive approach to promoting PEC cultivation within Polish farmers thereby coping with liquidity risks and uncertainties associated with agricultural and energy policies.

Considering Polish soil conditions, willow SRC currently eligible for EFA could have also been identified as an option for diversification schemes to manage the agricultural areas threatened by water erosion as well as to take advantage of the available large amounts of unutilised land dedicated to non-food crops. In the most binding case, i.e high number of eligible crops and without subsidy, willow area barely reaches 0.1 million ha (0.74% of AROPAj UAA), representing only 6% of the potential acreage that can be allocated for PEC, i.e. 1.59 million ha, estimated in Pudełko et al. (2012). Assuming a higher amount of subsidy for willow plantation (i.e. € 200 ha^{-1}), the surface area may increase up to 0.68 million ha (5% of the total UAA) mainly located in Pomorze & Mazury and Mazowsze & Podlasie regions. This spatial distribution stems from urbanisation and historical factors, the former region being highly urbanised and the latter belonging to past Russian partition. While the first case induces high PEC profitability due to low production costs and market proximity, the second case reflects low agricultural productivity and strongly fragmented arable land (Jezierska-Thöle et al., 2016).

To accelerate the establishment of a sustainable bioeconomy in Europe, post-2020 CAP has to be highly inter-connected with the updated bioeconomy strategy, while maximising their respective contribution to the Sustainable Development Goals and the Paris

Agreement on climate change. Furthermore, future CAP instruments have to be consistent with the current European policies, for instance Nitrates and Water Framework Directives, and respect the new *'good agricultural and environmental conditions'* and cross compliance requirements. For more effective and efficient application, crop diversification will be upgraded to crop rotation depending upon regions, soil and climate conditions, and farming structures as well. In this regard, the new CAP model should enhance the implementation of innovative and sustainable cropping and agroforestry systems combining arable crops and SR woody plantations for better valuation of the agricultural production and efficient management of the environment. An increased support towards SRC and, in general, to PEC is therefore required to ensure an effective large-scale deployment of these promising bioeconomy careers. As a matter of fact, in Poland, willow SRC, among other PEC, could be integrated either as part of first pillar eco-schemes *'for care for the environment and the climate'*, or as part of second pillar *'agri-environment-climate commitments'* without jeopardising food security. Considered as an environmentally-friendly crop with a deep root system, willow is more likely to be grown on areas representing high risk of organic matter decline, water erosion and drought as well as on areas of protected water resources under the Nitrate and Water Directives. Nevertheless, the above CAP schemes should be backed up with an enhanced support from regional authorities and a better articulation between industry and biomass producers in order to make farmers less reluctant to adopt this relatively new and economically unattractive crop, characterised by a long lifespan and involving regulatory risk deriving from agricultural and energy policies (Sherrington and Moran, 2010). In this regard, long-term support mechanisms to improve the profitability in the establishment stage and small-scale innovation projects using already established technologies are then required to enhance the competitiveness of local biomass supply as well as to share the risk between actors (Adams and Lindegaard, 2016).

6. Conclusion

In this study, we attempted to assess the potential integration of a promising non-food crop, i.e. willow SRC, into cropping systems in Poland. Having a large potential for the bioeconomy, willow can be produced sustainably and efficiently in order to supply bio-based industries, while improving agro-ecosystems and providing additional income for farmers. We examined the adoption of willow by means of a stylised CAP crop diversification allowing Polish farmers to enhance their sustainability and increase their agro-ecological performance. Diversification schemes were combined with incentives making willow plantation more attractive to farmers, and hence increasing its diffusion at a large scale. An integrated bioeconomic modelling approach using AROPAj LP tool, was therefore applied to approximate production choices of Polish farmers under a set of diversification constraints. The economic and environmental impacts related to the gross margin, land use change, N-fertiliser use, and GHG emissions, i.e. methane (CH_4) and nitrous oxide (N_2O), were therefore analysed at the regional scale, depending on the type of farming and economic size. Accordingly, we provided an analysis on how and where willow can be optimally integrated into farming systems through several diversification options.

The article presents a stylised framework of CAP diversification, in which complex aspects, e.g. number of eligible crops, are taken into account. So far, under the current diversification measures, the number of crops grown on the farm and their share of land are controlled, and farmers must comply with the requirements to receive payments. However, the methodology used in this study involves considering the number and combination of crops as decision variables. This means that farmers decide which and how many crops to grow while respecting the greening rules. Rather than evaluating a constantly evolving CAP, the objective is therefore to stylise some of its measures, recently abandoned or under modification, which are particularly complex to integrate into agro-economic modelling. Even if the CAP always evolves by oscillating between a complicated multi-objective targeting, economic efficiency and a requirement of simplicity and parsimony in tool implementation, it is important that researchers progress in exploring complex instruments for assessing the impacts of their application.

Declarations of interest

None.

Author contributions

Ben Fradj N.: Conceptualisation, Methodology, Formal analysis, Investigation, Software, Validation, Visualisation, Writing-Reviewing-Editing; **Jayet P.-A.:** Conceptualisation, Methodology, Resources, Software, Validation, Reviewing-Editing; **Rozakis S.**: Conceptualisation, Investigation, Resources, Reviewing-Editing; **Georganta E.:** Contribution in writing - original draft, Investigation, Software; **JędrejekA.:** Contribution in writing the case study section, Resources;

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Appendix A. Clustering and distribution of AROPAj crop activities

Table A1
Fig. A1

Table A1
A hypothetical example of crop distribution in individual farms to constitute a farm group in AROPAj (source FADN)

FADN Individual farm	Crop1	Crop2	Crop3	Crop4	Crop5	Crop6	Crop7	Crop8	**Total**
1	x		x		x				**3**
2	x	x		x		x			**4**
3		x					x		**2**
4	x	x	x	x	x				**5**
5	x							x	**3**
6	x		x					x	**3**
FarmGroup	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**8**
After calibration	**x**	**x**	**x**		**x**	**x**		**x**	**6**

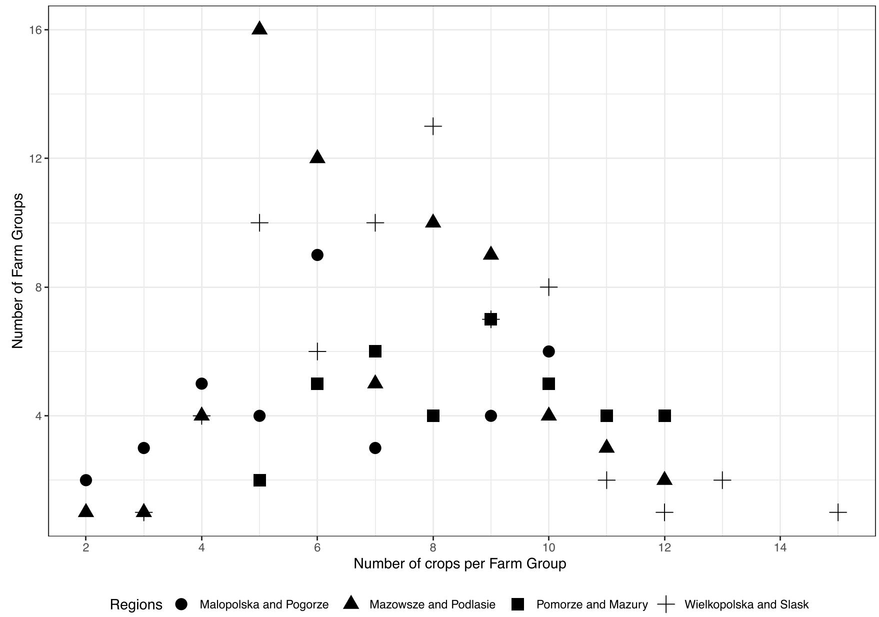


Fig. A1. Distribution of the number of crop activities as calibrated for AROPAj FG according to the Polish FADN regions.

Appendix B. Agricultural characteristics of Poland

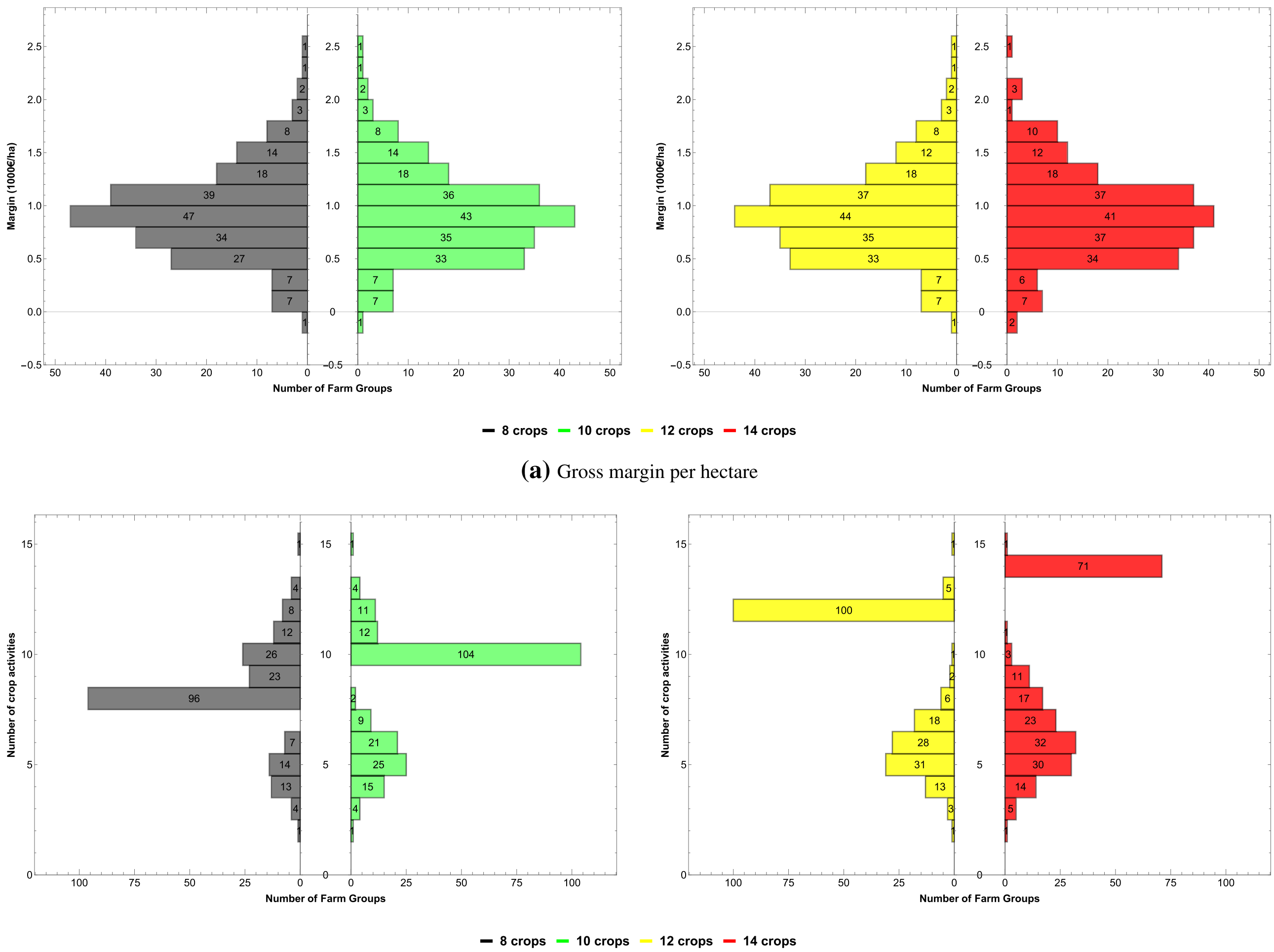
Table B1

Table B1
Agricultural characteristics of Polish FADN regions - Results aggregated at regional level as estimated by V_5-AROPAj model calibrated on 2012-FADN data

	Regions			
	Pomorze & Mazury	Wielkopolska & Śląsk	Mazowsze & Podlasie	Małopolska & Pogórze
Number of farm groups	37	65	67	40
Agricultural land (Ag.L, ha)	2910.3	4143.3	4633.9	1343.2
Arable land (ArL, % of Ag.L)	87.9	90.1	82.3	83.0
Permanent grasslands (% of Ag.L)	11.6	8.5	17.5	16.4
Fallow land (% of Ag.L)	0.5	1.5	0.2	0.6
Economic factor				
Gross margin (1000 €/ha of Ag.L)	0.88	0.89	1.00	0.89
Crop diversification (% of ArL)				
Cereals	74.1	76.4	76.5	64.1
Root crops	2.8	2.8	4.2	5.9
Oilseed crops	13.2	10.3	3.7	4.6
Industrial crops	0.2	0.1	0.6	0.4
Legumes	5.3	4.0	4.4	5.5
Fodders	4.4	6.3	10.7	6.4
Livestock Unit (LU)				
Livestock Density (LU/ha of P.Grass)	3.1	6.0	3.4	3.4

Appendix C. Impacts of crop diversification on economic margin and number of crop activities

Fig. C1



(a) Gross margin per hectare

(b) Number of eligible crops

Fig. C1. Distribution of gross margin per hectare and number of eligible crops over AROPAj farm groups for four numbers of required crops: 8 crops (Black), 10 crops (Green), 12 crops (Blue), and 14 crops (Red) when subsidies for crop diversification and willow plantation are set at € 75 ha^{-1} and € 0 ha^{-1}, respectively.

Appendix D. Impact of crop diversification measure on cropping plan

Table D1

Table D1

Changes in cropping plan among AROPAj farm groups that opted for crop diversification measures, according to two crop diversification scenarios: 1) 0 crop requirement & subsidy for crop diversification = € 0 ha^{-1}, and 2) 8 crop requirement & subsidy for crop diversification = € 75 ha^{-1}. The subsidy for willow plantation is set at € 0 ha^{-1}. The results are broken down into Polish FADN regions, farming type categories and economic size classes. ** d.wheat and s. wheat refer to durum wheat and soft wheat, respectively.

			0 crop requirement			8 crop requirement			
			Crop diversification subsidy € 0 ha^{-1}			Crop diversification subsidy € 75 ha^{-1}			
FADN region	Farming type	Economic size	Cropping plan	Gross margin (€ 1000 ha^{-1})	Number of activities	Removed activities	Added activities	Gross margin (€ 1000 ha^{-1})	Number of activities
Pomorze & Mazury	FT1	ES2	Cereals (wheat, barley, oat, rye and others), oilseed crops (rapeseed), proteins	0.902	7		Cereals (maize), grass	0.975	9
	FT1	ES3	Cereals (wheat, barley, rye and others), oilseed crops (rapeseed), proteins	0.800	6		Cereals (oat, maize)	0.873	8
	FT1	ES4	Cereals (wheat, barley, rye and others), oilseed crops (rapeseed), proteins	0.893	6		Cereals (d. wheat, maize)	0.965	8
	FT2	ES1	Cereals (wheat, barley, oat, rye, maize and others)	0.676	6		Oilseed crops (sunflower), root crops (sugar beet)	0.743	8
	FT3	ES2	Cereals (wheat, maize and others), fodders, willow, grass	1.087	6		Cereals (d. wheat), willow	1.106	8
	FT3	ES2	Cereals (barley, maize, rye and others), willow, grass	0.811	6		Root crops (sugar beet), fodder	0.841	8
	FT4	ES3	Cereals (wheat, barley, rye, maize and others), grass	0.220	6		Cereals (d. wheat), willow	0.228	8
	FT4	ES4	Cereals (barley, maize and others), oilseed crops (rapeseed), proteins, root crops (potatoes)	0.472	6		Cereals (oat), root crops (sugar beet)	0.531	8
	FT3	ES2	Cereals (barley, oat, rye and others), fodders, grass	0.662	6		Cereals (d. wheat, maize)	0.712	8
	FT4	ES2	Cereals (wheat, barley, maize and others), grass	0.596	6		Root crops (sugar beet), oilseed crops (rapeseed)	0.604	8
	FT4	ES3	Cereals (barley, rye, maize and others), proteins, root crops (potatoes), grass	0.751	7		Root crops (potatoes), fodder	0.816	8
	FT5	ES1	Cereals (wheat, barley,rye and others), root crops (potatoes)	0.816	6		Cereals (oat), root crops (sugar beet), grass	0.882	9
	FT6	ES1	Cereals (wheat, barley, oat, rye, maize and others)	0.563	6		Root crops (sugar beet), grass	0.623	8
	FT6	ES2	Cereals (wheat, barley, oat, rye and others), oilseed crops (rapeseed), proteins, root crops (potatoes), grass, fallow	0.714	10	Proteins	Oilseed crops (sunflower)	0.775	10
Wielkopolska & Śląsk	FT1	ES1	Cereals (wheat, barley, rye, maize and others), oilseed crops (rapeseed), fallow	0.854	7	Fallow	Cereals (d. wheat), oilseed crops (sunflower)	0.913	8
	FT1	ES2	Cereals (wheat, barley, oat, rye and others), oilseed crops (rapeseed)	0.799	5		Cereals (d. wheat), oilseed crops (sunflower), willow	0.825	8
	FT1	ES3	Cereals (wheat, barley, rye, maize and others), oilseed crops (rapeseed), proteins	0.902	7		Cereals (oat), fodder, grass	0.977	10
	FT2	ES1	Cereals (wheat, barley,rye and others), root crops (potatoes), fallow	0.798	6		Cereals (d. wheat), oilseed crops (sunflower)	0.838	8
	FT2	ES3	Cereals (wheat, barley, rye, maize and others), oilseed crops (rapeseed), legumes, root crops (potatoes), grass, fallow	1.019	11	Cereals (d. wheat), grass		1.088	9
	ft2	es4	Cereals (wheat, barley, rye, maize and others), legumes, root crops (potatoes)	1.653	7		Fallow	1.708	8
	ft3	es3	Cereals (barley, oat, rye and others), fodders, grass	1.427	7		Cereals (s. wheat)	1.479	8
	ft3	es4	Cereals (barley, rye, maize and others), fodders, grass	1.702	7		Cereals (s. wheat)	1.756	8
	FT3	ES2	Cereals (wheat, oat, rye and others), root crops (potatoes), fodders, grass	0.881	7		Fodder	0.931	8
	FT3	ES4	Cereals (wheat, oat, rye and others), fodders, grass, fallow	0.975	9	Fallow		1.004	8
	FT3	ES3	Cereals (wheat, barley, oat, rye and others), fodders, grass	1.006	7		Fallow	1.048	8

(*continued on next page*)

Table D1 (*continued*)

			0 crop requirement			8 crop requirement			
			Crop diversification subsidy € 0 ha^{-1}			Crop diversification subsidy € 75 ha^{-1}			
	FT4	ES4	Cereals (barley, rye and others), proteins, fallow	0.074	5		Cereals (s. wheat, d. wheat), grass	0.128	8
	FT2	ES3	Cereals (wheat, barley, rye and others), oilseed crops (rapeseed), fallow	0.682	7		Oilseed crops (sunflower)	0.746	8
	FT3	ES2	Cereals (wheat, barley, rye and others), grass, fallow	0.887	6		Fodder, willow	0.911	8
	FT3	ES3	Cereals (wheat, barley, rye and others), fodders, grass	0.781	7		Fallow	0.839	8
	FT3	ES3	Cereals (wheat, barley, rye and others), fodders, grass	0.784	6		Fallow, willow	0.826	8
	FT3	ES5	Cereals (wheat, barley, oat, rye, maize and others), oilseed crops (rapeseed), root crops (potatoes), fodders, grass	1.370	11		Proteins	1.432	12
	FT4	ES1	Cereals (oat, rye, maize and others), grass	0.680	5	Cereals (oat)		0.672	4
	FT4	ES3	Cereals (barley, oat and others), proteins, fodders, grass	0.614	6		Cereals (s. wheat), fallow	0.671	8
	FT4	ES4	Cereals (barley, maize and others), proteins, root crops (potatoes), fodders, grass	0.457	7		Cereals (oat)	0.522	8
	FT4	ES4	Cereals (barley and others), oilseed crops (rapeseed), proteins, fodders, grass, fallow	0.416	7		Fodder	0.477	8
	FT5	ES1	Cereals (wheat, barley, rye, maize and others)	0.784	5		Grass	0.784	6
	FT6	ES1	Cereals (wheat, barley, rye and others), fallow	0.541	5		Cereals (d. wheat), root crops (sugar beet), willow	0.548	8
	FT6	ES2	Cereals (wheat, barley, rye and others), oilseed crops (sunflower), grass	0.565	6		Cereals (d. wheat), fodder	0.620	8
	FT6	ES4	Cereals (barley, maize and others), oilseed crops (rapeseed), root crops (sugar beet and potatoes), proteins, legumes, fodders, grass	0.746	9	Grass		0.819	8
Mazowsze & Podlasie	FT1	ES1	Cereals (wheat, barley, rye and others), oilseed crops (sunflower)	0.721	5		Cereals (oat), root crops (sugar beet), willow	0.759	8
	FT1	ES1	Cereals (wheat, barley, rye, maize and others), oilseed crops (rapeseed), grass	0.759	7		Willow	0.818	8
	FT1	ES1	Cereals (wheat, barley and others), oilseed crops (rapeseed), fallow	1.081	5		Cereals (oat), oilseed crops (sunflower), willow	1.114	8
	FT2	ES1	Cereals (wheat, barley, oat, rye and others), root crops (potatoes)	0.544	7		Oilseed crops (sunflower)	0.612	8
	FT2	ES3	Cereals (wheat, barley, oat, rye and others), oilseed crops (rapeseed), root crops (potatoes), legumes, fodders, fallow	1.389	9		Proteins	1.457	10
	FT2	ES2	Cereals (wheat, barley and others), oilseed crops (rapeseed), root crops (potatoes), fallow	0.668	6		Cereals (oat), oilseed crops (sunflower)	0.730	8
	FT2	ES3	Cereals (wheat, oat, rye and others), proteins, legumes, root crops (potatoes), fodders	1.651	7		Cereals (d. wheat)	1.716	8
	FT2	ES3	Cereals (wheat, barley, oat, rye, maize and others), oilseed crops (rapeseed), industrial crops (tobacco), legumes, fodders, grass	1.031	13	Cereals (d. wheat), fodder		1.102	11
	FT3	ES2	Cereals (rye and others), fodders, grass	1.347	5		Cereals (d. wheat, oat), fodder	1.359	8
	FT3	ES2	Cereals (rye and others), fodders, grass	1.309	5		Cereals (oat), root crops (sugar beet), willow	1.342	8
	FT3	ES3	Cereals (rye and others), fodders, grass	1.462	6		Cereals (s. wheat, oat)	1.510	8
	FT3	ES3	Cereals (barley, rye and others), fodders, grass	1.645	6		Cereals (s. wheat, oat)	1.684	8
	FT3	ES4	Cereals (others), fodders, grass, fallow	1.796	6		Cereals (s. wheat), willow	1.834	8
	FT3	ES5	Cereals (wheat, barley, oat, rye, maize and others), oilseed crops (rapeseed), fodders, grass	2.145	11	Fodder		2.207	10

(*continued on next page*)

Table D1 (*continued*)

			0 crop requirement			8 crop requirement			
			Crop diversification subsidy € 0 ha^{-1}			Crop diversification subsidy € 75 ha^{-1}			
	FT3	ES1	Cereals (rye, maize and others), grass	0.890	4		Cereals (d. wheat), root crops (sugar beet), fodder, willow	0.903	9
	FT3	ES3	Cereals (barley and others), root crops (potatoes), fodders, grass, fallow	1.052	7	Fallow	Root crops (sugar beet), fodder	1.092	8
	FT4	ES3	Cereals (wheat, barley and others), root crops (sugar beet)	0.021	5		Grass, fallow, willow	0.048	8
	FT4	ES4	Cereals (wheat, barley, maize and others), oilseed crops (rapeseed)	0.011	5		cereals (d. wheat, oat), willow	0.042	8
	FT4	ES5	Cereals (wheat, barley, oat, rye, maize and others), proteins	0.452	7		cereals (d. wheat)	0.521	8
	FT2	ES3	Cereals (wheat, barley, oat, rye and others), fallow	0.558	6		Cereals (d. wheat), willow	0.586	8
	FT3	ES2	Cereals (barley, oat, rye and others), oilseed crops (rapeseed), grass, fallow	1.091	7		Cereals (d. wheat)	1.137	8
	FT3	ES3	Cereals (wheat, barley, oat, rye and others), fodders, grass	1.060	9		Oilseed crops (sunflower)	1.117	10
	FT3	ES5	Cereals (wheat, barley, maize and others), oilseed crops (sunflower), root crops (potatoes), fodders, grass, fallow	1.243	12	Oilseed crops (sunflower), fallow		1.303	10
	FT4	ES2	Cereals (barley, oat and others), fodders, grass	0.670	5		Cereals (rye, maize), willow	0.686	8
	FT4	ES3	Cereals (wheat, barley, rye and others), fodders, grass	0.556	6		Cereals (d. wheat), willow	0.590	8
	FT4	ES5	Cereals (barley and others), fodders, grass	0.682	5		Cereals (s. wheat), oilseed crops (sunflower), proteins	0.732	8
	FT5	ES1	Cereals (wheat, barley, rye and others), fodders, grass, fallow	0.645	7		Cereals (oat), oilseed crops (sunflower)	0.691	8
	FT5	ES1	Cereals (wheat, barley, oat, maize and others), grass	0.748	6		Cereals (d. wheat), willow	0.784	8
	FT5	ES2	Cereals (wheat, barley, rye and others), root crops (potatoes), fodders, grass	1.043	7		Cereals (oat)	1.095	8
	FT5	ES2	Cereals (wheat, barley, oat and others), oilseed crops (rapeseed), fodders, grass	0.807	7		Fodder	0.865	8
	FT5	ES3	Cereals (wheat, barley, rye, maize and others), oilseed crops (rapeseed), proteins, legumes, root crops (potatoes), fodders, grass, fallow	1.073	13	Fallow		1.137	12
	FT6	ES1	Cereals (wheat, barley, rye and others), oilseed crops (sunflower), grass, fallow	0.587	7		Willow	0.632	8
	FT6	ES2	Cereals (wheat, barley, maize and others), root crops (potatoes), grass	0.637	6		Cereals (rye), oilseed crops (sunflower)	0.702	8
Malopolska & Pogorze	FT1	ES2	Cereals (wheat, barley, oat and others), proteins	0.605	6		Cereals (oat), oilseed crops (sunflower)	0.663	8
	FT1	ES5	Cereals (wheat, barley, oat and others), proteins	1.055	6		Cereals (s. wheat, oat)	1.126	8
	FT2	ES1	Cereals (barley and others), grass, fallow	0.471	4		Cereals (s. wheat, oat), oilseed crops (sunflower), grass, willow	0.473	8
	FT2	ES2	Cereals (wheat, barley, maize and others), proteins, root crops (potatoes)	0.901	6		Cereals (d. wheat), fodder, grass	0.961	9
	FT2	ES4	Cereals (wheat, barley, maize and others), oilseed crops (rapeseed), root crops (sugar beet and potatoes), fodders, grass	0.840	10	Fodder	Fodder	0.910	9
	FT3	ES2	Cereals (wheat, barley, maize and others), fodders, grass	1.441	7		Root crops (sugar beet)	1.481	8
	FT3	ES3	Cereals (wheat, oat and others), root crops (sugar beet and potatoes), fodders, grass	1.434	7		Fallow	1.469	8

(*continued on next page*)

Table D1 (*continued*)

		0 crop requirement			8 crop requirement			
		Crop diversification subsidy € 0 ha^{-1}			Crop diversification subsidy € 75 ha^{-1}			
FT3	ES5	Cereals (wheat, barley, maize and others), oilseed crops (rapeseed), fodders, grass	1.550	10	Fodder		1.587	9
FT4	ES5	Cereals (wheat, barley, oat, rye, maize and others), oilseed crops (rapeseed), grass, fallow	2.431	9	Grass, fallow	oilseed crops (sunflower)	2.506	8
FT2	ES1	Cereals (wheat and rye), legumes, grass, fallow	0.555	5	Legumes, fallow		0.551	3
FT4	ES2	Cereals (barley, rye and others), root crops (sugar beet), fodders, grass	0.893	6		Cereals (s. wheat), fallow	0.922	8
FT4	ES4	Cereals (barley, oat, maize and others), root crops (sugar beet and potatoes), grass	1.034	7		Fodder	1.101	8
FT5	ES1	Cereals (wheat, rye and others), fodders, grass, fallow	0.647	7	Fodder		0.647	6
FT5	ES4	Cereals (barley, rye, maize and others), oilseed crops (rapeseed), root crops (sugar beet and potatoes), fodders, grass, fallow	1.211	10		Fodder	1.264	11
FT6	ES2	Cereals (barley and others), fodders, grass, fallow	0.559	5		Cereals (s. wheat, oat), oilseed crops (sunflower)	0.597	8
FT6	ES3	Cereals (barley, maize and others), oilseed crops (rapeseed), proteins, grass, fallow	0.649	7		Cereals (oat)	0.714	8
FT6	ES5	Cereals (wheat, barley, oat, rye, maize and others), oilseed crops (rapeseed), proteins, grass	0.474	9	Grass		0.548	8

Appendix E. Impacts of crop diversification on livestock breeding

Fig. E1

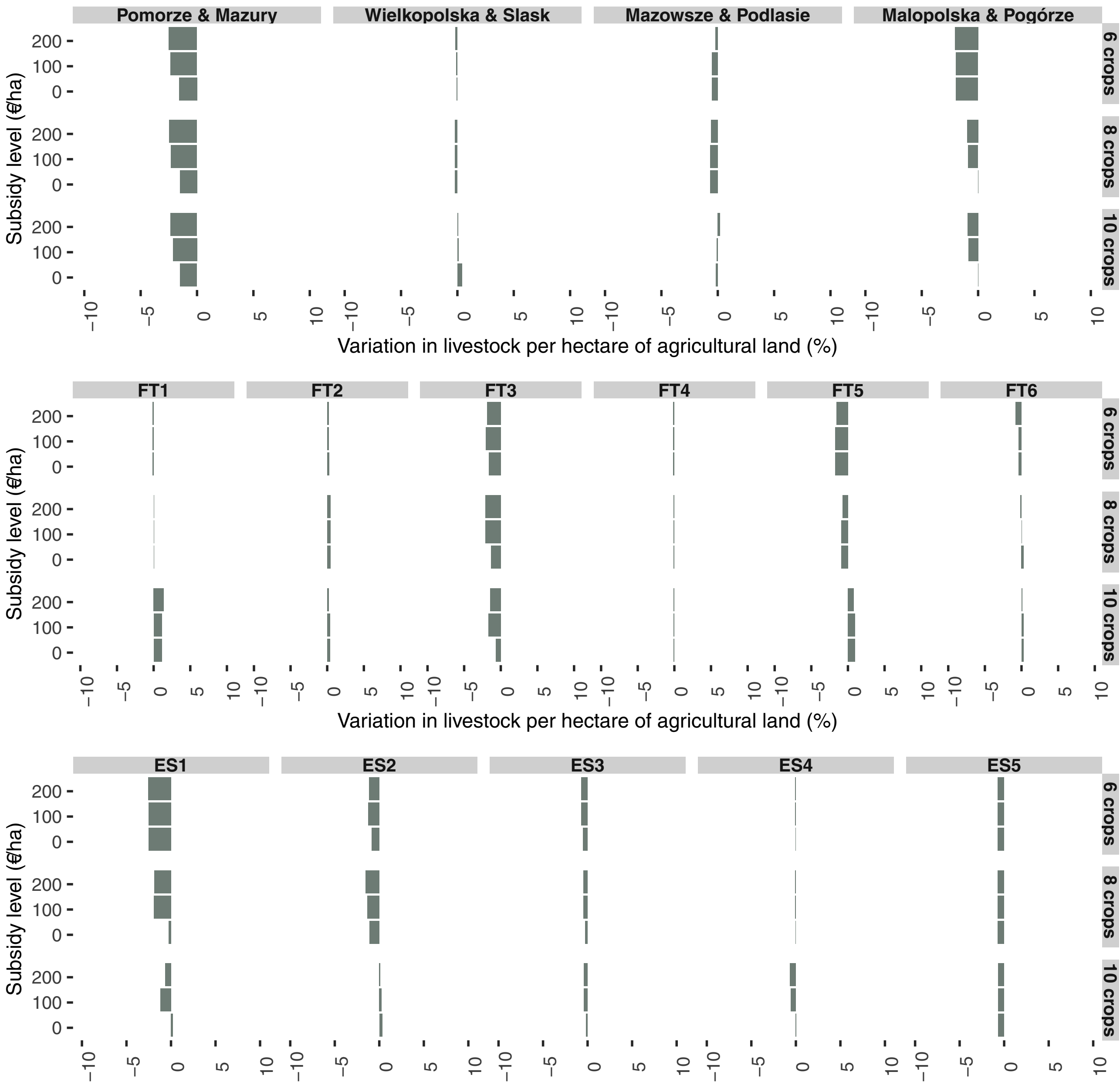


Fig. E1. Variation in livestock unit per hectare of agricultural land (in %) for different number of eligible crops and according to Polish FADN regions, farming types, and economic size classes. Values assessed against a baseline situation in which subsidies for crop diversification and willow plantation, and number of eligible crops are all set at 0.

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