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Review

Sustainable Agriculture – the Potential to Increase Wheat and Rapeseed Yields in Poland

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Abstract

Poland represents a country with relatively low agricultural productivity but high potential, particularly for certain crops. The aim of our study was to:

(i) Show the potential to increase crop yields to sustainable levels of wheat and rapeseed in Poland based on simulations in the Global Agro-Ecological Zones (GAEZ v3.0) model

(ii) Show the yield gap for wheat and rapeseed for Poland

(iii) Compare yield gaps in Poland with yield gaps of neighbouring counties: Germany, Czech Republic, and Slovakia

(iv) Discuss the potential of agricultural productivity increase along with challenges and pragmatic requirements associated with increasing agricultural productivity in Poland

To our knowledge, this is the first study that discusses spatially sustainable intensification of agriculture in Poland and critically assesses opportunities pertinent to such intensification. The results show that Polish agriculture can play an important role in contributing to sustainable agricultural productivity increase in a resource-constrained world. The results presented here also demonstrate that yields can even be doubled, yet significant investment and relevant know-how for agriculture must be provided.

Keywords: sustainable agriculture, wheat, rapeseed, increasing productivity, yield gap

Introduction

Concomitant with worldwide trends to sustainably increase agricultural productivity, developing sustainable agriculture within the European Union (EU) has been highlighted as one of the priorities of the Common Agricultural Policy [1]. Indeed, the need to protect the environment while simultaneously increasing agricultural production can be found in political and research agendas worldwide [2-4]. Sustainable agriculture is one of the European Commission's key objectives aimed at supplying sufficient food, feed, biomass, and raw materials while safeguarding natural resources and mitigating climate change. According to the report on setting priorities for research and development in the EU [1], sustainable agriculture should be developed based on research and innovation, with the bioeconomy strategy action plan (promoting sustainable production of renewable biological resources and their conversion into food, bio-based products, biofuels, and bioenergy) and the research should be focused on how to increase productivity

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in a sustainable way and to eliminate food waste [1]. Those principles are also included in 'Horizon 2020 – the Framework Program for Research and Innovation,' introduced in the beginning of 2014 [2]. One of the objectives of the Horizon 2020 program is to provide the basis to secure sufficient supplies of safe and high-quality food and other bio-based products by developing productive and resource efficient primary production systems, fostering related ecosystem services, alongside with competitive and low carbon supply chains [2].

Notwithstanding differences in interpretation, 'sustainable' approach also plays an increasingly important role in research, not only agricultural and environmental [5] but also within 'sustainable production' or 'sustainable manufacture' [6-10]. Sustainable agriculture can be described as the management and utilization of the agricultural ecosystems in a way that maintains its biological diversity, productivity, regeneration capacity, vitality and ability to function, to fulfil ecological, economic and social functions at the local, national and global levels, and that does not harm other ecosystems [11] or, in other words, 'achieve more and better from less' [12].

The role of innovation and sustainably increasing agricultural productivity is now more important than ever because of steadily growing world population and increasing consumption fuelled by increasing per capita income [13]. Humanity is faced with the problem of 'how to feed 9 billion people in the near future?' [13]. FAO estimates that food production increase by 70% (including 1,000 million tons of grain and 200 million tons of meat), will be required to adequately feed a population of approximately 9 billion compared to the current 7 billion [14]. In that respect, sustainable intensive agriculture has been highlighted as a key solution to reconcile growing demand on one side and the need to protect natural resources that the agricultural systems ultimately depend on, on the other. Sustainable intensification has been defined as a form of production wherein 'yields are increased without adverse environmental impact and without the cultivation of more land' [15]. In this context, sustainable intensification 'denotes an aspiration of what needs to be achieved, rather than a description of existing production systems, whether this be conventional high-input farming, or smallholder agriculture, or approaches based on organic methods' [16]. The expansion of agriculture into new land is not a sustainable solution not only because the remaining unconverted natural land provides a variety of ecosystem services [17], but also because given land scarcity [18] there is also competition with other land uses, such as for fuel [19]. In addition, under the new European Commission regulations, 7% of farm area will have to be transformed under the protection of biodiversity, which further diminishes the available area for future crops. In 2011 the European Commission introduced systems to ensure greater environmental protection and management, known as ´greening measures´ [20].

Agriculture and its expansion is one of the major causes of global environmental change [17], driving land clearing and habitat fragmentation [22, 23], harming ecosystems, polluting marine and freshwater through pesticides and fertilizer excess [17]. About one-quarter of global greenhouse gas emissions result from crop production, fertilization, and land clearing [18]. Others also showed [24] that the loss of tropical forests ensued agricultural expansion. Although research shows that environmental impacts of global agriculture development until 2050 would have lower impacts than past business-as-usual [25-27], if significant investment in appropriate spatial planning and other measures (such as incentives, legislation, extension) are not in place, agriculture can have a range of adverse impacts over the coming decades [26].

Consequently, because increasing yields per hectare is indicated as a sustainable solution to meet growing demands and sparing land for nature and other land uses, here we explore this concept for Poland. Increasing agricultural productivity should be focused in the areas of high bio-physical potential (yet low current productivity) and best edaphoclimatic conditions, if benefits of improving agricultural productivity are to be maximized, and in order to diminish the use of agro-chemicals. We use the model of global agro-ecological zones (GAEZ) developed by the International Institute for Applied Systems Analysis (IIASA) and Food and Agriculture Organization of the United Nations (FAO), which allows us to spatially present agricultural production, weather conditions, potential yield, and yield predictions for 2050 on a global scale [28]. This model also allows identifying areas with the largest yield gaps, and thus facilitates the prioritization of areas where sustainable increases of agricultural productivity could be pursued.

The aim of the study was to:

(i) Show the potential to increase crop yields to sustainable levels of wheat and rapeseed in Poland based on the simulation in program Global Agro-Ecological Zones (GAEZ v3.0)
(ii) Show the yield gap for wheat and rapeseed for Poland
(iii) Compare yield gaps in Poland with yield gaps of neighbouring counties: Germany, Czech Republic, and Slovakia
(iv) Discuss the potential of agricultural productivity increase along with challenges and pragmatic requirements associated with increasing agricultural productivity in Poland

To our knowledge this is the first study that comprehensively discusses different databases on agricultural outputs, analyzes its roots and consequences, and proposes a sustainable increase of agricultural productivity as a pragmatic way forward for the country to develop a greener and a more efficient agricultural sector. Furthermore, this research shows how Polish agriculture can play an important role in fulfilling sustainable food production in a resource-constrained world. Given the EU's key objective: 'sustainable agriculture,' the results presented here may be a valuable contribution to the current scientific and political discussions related to sustainable resource management and food security.

Materials and Methods

This paper presents an analysis for two crops: wheat and rapeseed. These crops belong to the group of the most important plants cultivated mainly for food and feed [29-33]. Moreover, the production of rapeseed is increasing because of growing demand for biodiesel [19, 30, 34].

We performed a series of computer simulations based on the GAEZ (v3.0) model. FAO and IIASA have been continuously developing the Agro-Ecological Zones (AEZ) methodology over the past 30 years for assessing agricultural resources. The GAEZ database provides the agronomic backbone for various applications and includes data on land resources, agro-climatic resources or suitability, and potential yields, to mention just a few. GAEZ simulations for potential production and yield gap enable rational land-use planning based on an inventory of land resources (e.g. all relevant components of climate, soils, and landform, which are basic for the supply of water, energy, nutrients, and physical support to plants) and evaluation of their biophysical limitations and potentials for crop production [28].

The methodology for data modeling in this study is as follows:

1. First, the spatial distribution for actual yield of wheat and rapeseed is presented.
2. Then data on yields over the last 30 years is shown graphically to observe production trends.
3. The next steps provide an estimate of potential production capacity, taking into account agro-ecological suitability and productivity model for current cultivated land for wheat and rapeseed. Results are presented both in maps and as statistical values (minimum, maximum, range, and mean). Among three basic available levels of inputs generated by GAEZ, here two of them are presented: high and intermediate as the most preferable, taking into account the growing demand for food. In order to be consistent with current agricultural practices and for clarity of discussion, intermediate-input levels will hereafter be referred to as 'improved management,' while the high-input level will hereafter be named as 'advanced management.' Intermediate-input level assumes improved varieties used in agriculture, some level of mechanization with hand tools and/or animal traction, select fertilizer and chemical pests, disease and weed control. This system is partly market-oriented [28]. High-level agriculture is mainly market-oriented and the production is based on improved high-yield varieties. It is fully mechanized with low labour intensity and optimum applications of nutrients, while chemical pest, disease, and weed control are also used [28]. These variables of the model were chosen because they are best aligned with the assumptions and goals of sustainably increasing agricultural productivity.
4. The last step of the simulation was the assessment of a crop-yield ratio (actual over potential) and the production gap for select crops. Yield gaps and production gaps also have been estimated in GAEZ v3.0 by comparing potential attainable yields and estimated production (from downscaling year 2000 statistics of main food products, derived mainly from FAOSTAT [35] and the FAO study 'Agriculture. Towards 2010/30' [36]). The yield gap represents the difference between the potential yield and actual yield achieved in percentage or, alternatively, the difference between potential yield and actual yield in t/ha [28]. Yield gaps provide important information that can be used, for example, for identifying causes and addressing rural poverty and local food security.

We also reviewed the most up-to-date literature on causes of spatial patterns of agricultural productivity in Poland, and we discuss opportunities and constraints for diminishing the existing productivity gap. The results presented here are therefore also discussed in light of the existing body of knowledge and validated within a number of consultations with agricultural experts in Poland.

Results and Discussion

Current and Past Production

Spatial distribution of yield for wheat and rapeseed obtained from the model is presented in Figs. 1 and 2, respectively. All figures are shown for 5 arc-minute resolutions. For wheat, yield values can be observed as follows: mean of 3 t/ha with a range 0-8.3 t/ha, and for rapeseed: mean of 2 t/ha, range 0-4.9 t/ha. The actual production was assessed using data from GAEZ.

According to the Polish Central Statistical Office, the yield for wheat is estimated at the level of 4.14 t/ha and for rapeseed 2.59 t/ha [29]. Current yields of wheat and rapeseed, (including turnip rapeseed) based on data from the Polish Central Statistical Office, are presented in Fig. 3 [29]. The average value for the last 30 years is 3.6 t/ha for wheat and 2.28 t/ha for rapeseed and turnip rapeseed [29, 37]. It can be observed that actual production obtained from the GAEZ model (Figs. 1 and 2) differ from values pre-

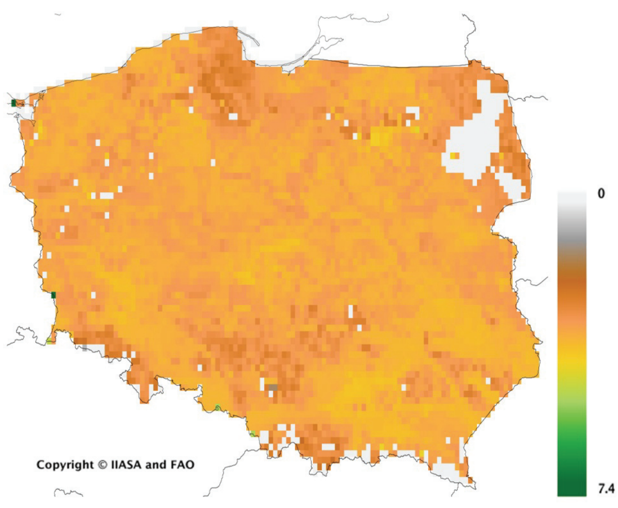

Fig. 1. Spatial distribution of yield for rain-fed and irrigated wheat (t/ha) [based on IIASA/FAO, 2010. Global Agro-ecological Zones (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy].

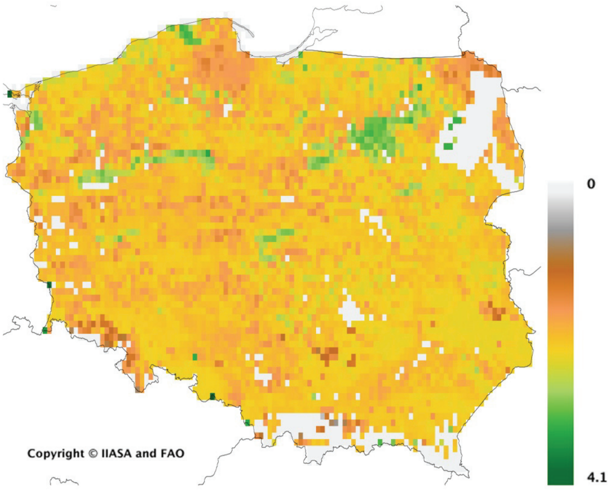

Fig. 2. Spatial distribution of yield for rain-fed and irrigated rapeseed (t/ha) [based on IIASA/FAO, 2010. Global Agro-ecological Zones (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy].

sented obtained from the Polish Central Statistical Office for 2012 (Fig. 3). Although there are differences in average current yields for wheat and rapeseed between the national and GAEZ estimates, the yield gap is still high, hence the potential possibilities for increasing yield are high. Differences between both estimates, therefore, do not undermine the results of this study; rather, they both reinforce the high-yield gap for select crops in Poland (see also analysis below). For consistency, our further assessment for agro-ecological suitability, productivity, and yield gap presented in Figs. 5-9 was calculated using production values based on the GAEZ database.

The highest wheat yield was observed in Opolskie and Pomorskie provinces (5.97 t/ha and 4.82 t/ha, respectively; Fig. 3) [29]. Yields above 4.2 t/ha were also registered in provinces: Zachodniopomorskie (4.57 t/ha), Dolnoslaskie (4.48 t/ha), Warminsko-mazurskie (4.4 t/ha), and Lubuskie (4.32 t/ha) [29]. Values for the share in production are similar. All above-mentioned provinces are at the same time the largest producers of wheat in Poland (Opolskie: 8,658,082 dt, Pomorskie 6,573,055 dt, Zachodniopomorskie: 7,199,648 dt, Dolnoslaskie: 10,699,128 dt, Warminsko-mazurskie: 6,617,804 dt, and Lubelskie: 10,018,211 dt).

The highest yield values for rapeseed and turnip rapeseed (Fig. 3) were observed for the following Provinces: Malopolskie (3.08 t/ha), Opolskie (3.05 t/ha), Pomorskie (2.92 t/ha), Zachodniopomorskie (2.89 t/ha), and Lubuskie (2.87 t/ha), while the highest production for these crops was observed in provinces: Zachodniopomorskie (3,084,587 dt), Dolnoslaskie (2,535,984 dt), Wielkopolskie (2,038,399 dt), Warminsko-mazurskie (1,823,304 dt), and Opolskie (1,657,186 dt). Spatial differences in the extent of production of both wheat and rapeseed in Poland are primarily due to the type of soil, but also the climate and the level of fertilization and mechanization of agriculture. For instance in Opolskie, Pomorskie, and Zachodniopomorskie provinces, where the agrarian structure (size of the farm) is much better than in other regions (bigger farms), yields are much higher than in southern Poland. Fragmentation of the farms in the south of Poland and steep areas are not conducive to the introduction of mechanization at a high level, which is crucial for high-productivity agriculture.

Notwithstanding periods with lower yields (e.g. 1993-1994, 1996-1997, and 2003), over the last 30 years the yields have been steadily growing both for wheat and for rapeseed, owing to technological progress and improved technical performance (see the regression line; Fig. 4).

Growing production of major oils and fats industry products is predicted for Poland and indeed a slow upward trend of rapeseed yield will likely continue in the future [30]. In Poland, production of rapeseed crops stabilized in 2011 and 2012, but it is expected to grow in 2013 by ca. 16% (to 2.2 million tons) due to a large increase in acreage (by 14%). In the 2013/14 season a further increase of rapeseed crops is expected at the level of 3-6% [30].

Worldwide wheat production is growing as well and in 2010/11 it amounted to 652.3 million tons [31]. In 2013, global wheat harvest may reach 683 million tons, which is about 4% more than in the previous year. The increase is a result of higher yields and a slightly larger area of crops,

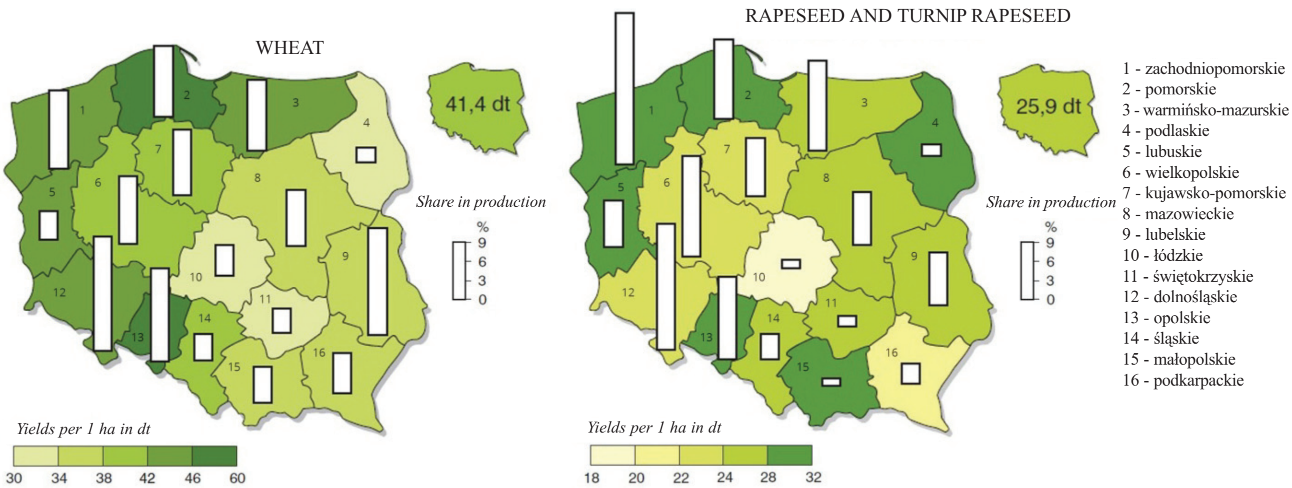

Fig. 3. Spatial distribution of yield for rapeseed and wheat in 2012 (dt/ha) [29].

Table 1. Statistical values of potential production in agroecological model GAEZ [based on IIASA/FAO, 2010. Global Agro-ecological Zones (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy].

	Potential production for wheat (t/ha)				Potential production for rapeseed (t/ha)			
	Min.	Max.	Range	Mean	Min.	Max.	Range	Mean
Intermediate input level – improved management	0.2	6.5	6.3	4	0.3	2.6	2.3	2
High level – advanced management	0.4	10.4	10	8	0.1	4.4	4.3	4

which may reach 222.3 million hectares, which is the highest value in four years [38]. Production raised 2.8 million tons for the European Union with the biggest increases for Spain, France, and Germany, and smaller increases for Romania, Bulgaria, and Hungary [39].

Agro-Ecological Suitability and Productivity

A potential production capacity taking into account agro-ecological suitability and productivity for current cultivated land for wheat and rapeseed is showed in Figs. 5-8.

Table 1 presents select statistical values for potential production for wheat and rapeseed in improved management model and advanced management model.

For the model of intermediate input level the potential production for wheat is between 0.2 t/ha and 6.5 t/ha with a mean of 4 t/ha. For the model of high input level the potential production for wheat is between 0.4 t/ha and 10.4 t/ha with a mean of 8 t/ha. While for rapeseed potential production ranges from 0.3 t/ha to 2.6 t/ha with a mean of 2 t/ha (for intermediate input level), and for high input level it ranges from 0.1 t/ha to 4.4 t/ha with a mean of 4 t/ha. Both for wheat and rapeseed, for advanced management, yield doubling could be achieved as compared with the improved management model. In other words, up to 8 t/ha for wheat and 4 t/ha for rapeseed could be harvested in the future (harvest values in 2012 were at levels of 4.14 t/ha for wheat and 2.59 t/ha for rapeseed).

The feasibility of increasing yields and sustainably increasing agricultural productivity in Poland is determined primarily by natural conditions (agro-ecological suitability), but also by financial inputs and organizational specificity of Polish agriculture. Sustainable increase of agricultural productivity depends also largely on technical and technological progress, and the rational and ecologically adequate intensification of production. An important aspect is also to limit degradation of the productive potential of soils.

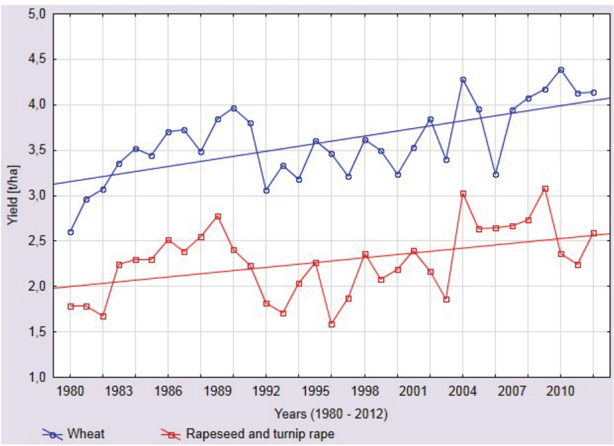

Fig. 4. Yield for wheat and rapeseed and turnip rapeseed over the years 1980-2012 with a linear trend line [29, 37].

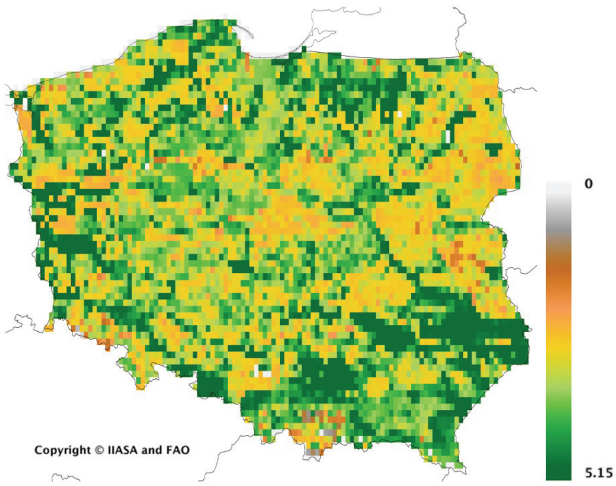

Fig. 5. Agro-ecological suitability and productivity - potential production capacity (t/ha) for current cultivated land of (intermediate input level) wheat [based on IIASA/FAO, 2010. Global Agro-ecological Zones (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy].

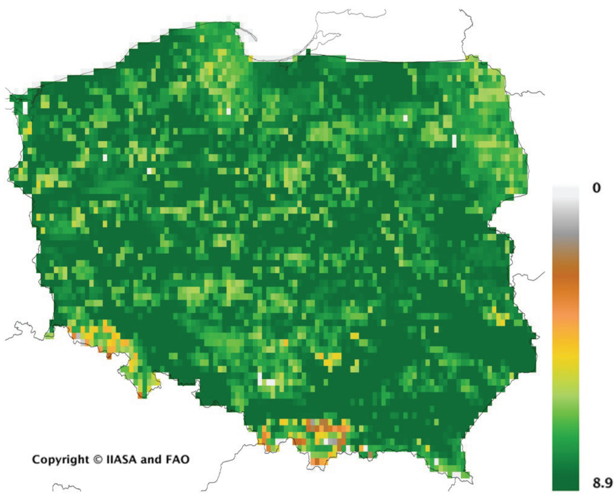

Fig. 6. Agro-ecological suitability and productivity - potential production capacity (t/ha) for current cultivated land of (high input level) wheat [based on IIASA/FAO, 2010. Global Agro-ecological Zones (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy].

Furthermore, expansion and modernization of technical infrastructure in rural areas and the farms are also paramount. Indeed, without adequate technical infrastructure modern, higher-yield agriculture is unlikely to develop. The current unfavorable economic situation of agriculture indicates the need to financially support (from the state as well as from the EU) any action that underpins development of sustainable agriculture and promotes changes in the agrarian structure. Action is also needed to improve the income situation of agriculture, as this is the main reason for limiting the opportunities for efficient investing in agriculture.

Yield Gap

The difference between current productivity and the maximum sustainable productivity that can be achieved using current genetic material and available technologies and management is termed the 'yield gap' [13]. In addition to factors discussed above, the maximum sustainable yields as estimated in the GAEZ model can be obtained depending on capacity of farmers to access and use seeds, water, nutrients, pest management, soils, biodiversity, and knowledge, among others [13]. Based on GAEZ program simulation we assessed that the majority of crop yield ratio (actual over potential) and production gap for rain-fed wheat is between 25- 40% (for 94.5% of total area), and only 0.1% ratio of actual over potential yield is in the range 40-55% (Table 2). A slightly better situation is for rapeseed because a production gap is smaller: 55-70% of crop yield ratio amounts to 91.6% of total land and 0.1% is a range over 85% (Table 2).

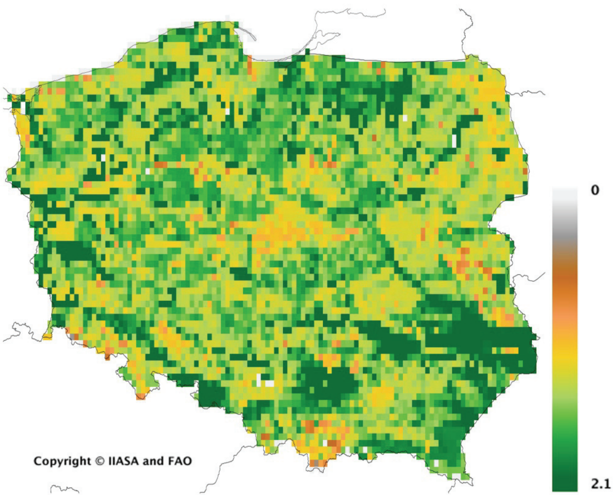

Fig. 7. Agro-ecological suitability and productivity – potential production capacity (t/ha) for current cultivated land of (intermediate input level) rapeseed [based on IIASA/FAO, 2010. Global Agro-ecological Zones (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy].

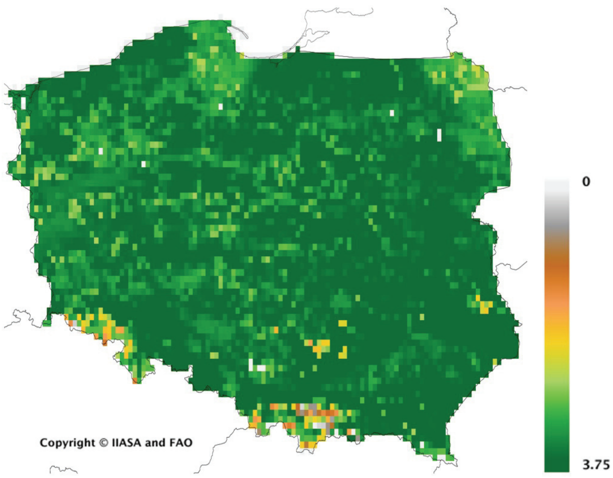

Fig. 8. Agro-ecological suitability and productivity – potential production capacity (t/ha) for current cultivated land of (high input level) rapeseed [based on IIASA/FAO, 2010. Global Agro-ecological Zones (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy].

Table 2. Ratio of actual over potential yield for rain-fed wheat/rapeseed [based on IIASA/FAO, 2010. Global Agro-ecological Zones (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy].

	Crop yield ratio (wheat/rapeseed)				
Country	25-40%	40-55%	55-70%	70-85%	>85%
Czech Republic	0/0	94.8/0	0.1/0	0.1/0	0/96.8
Poland	94.5/0	0.1/91.6	0/0	0/0	0/0.1
Slovakia	84.7/0	0/0.3	0/83.0	0/0	0/0
Germany	0/0	0/0	0/0	93.6/0	0/92.9

In 2020, area planted with wheat in Poland is expected to reach 2.15 million hectares, and an average cereal yield may reach 3.4 t/ha [32]. Research shows that it is indeed possible to achieve average yields in the range 3.8-3.9 t/ha and that production in Poland at the level of 29-30 million tons is possible, but it is necessary to increase investment in economically justifiable intensification of production and to improve soil fertility and pH [40, 41]. On the other hand are predictions that acreage of wheat in Poland will be smaller due to the increase in the competitiveness of other cereals relative to wheat [13]. Current acreage of wheat is related to easy sale of this grain. It is expected that when wheat area decreases and at the same time soil fertility increases, it may result in increasing of the national harvest by about 10% [33]. In Poland grain surpluses will likely not be used for fodder purposes, because the increase in livestock production is not expected, in fact, opposite – livestock production will likely diminish as the country's population decreases [33, 42].

In conclusion, these simulations show a remarkable opportunity for Poland to improve agricultural production. Owing to agro-meteorological conditions in Poland it is possible to obtain average yield of wheat of 4 t/ha and 8 t/ha, while yield of rapeseed could reach 2 t/ha and 4 t/ha, for improved (intermediate input level) and advanced (high-input level) scenarios, respectively (Figs. 5-8). Given that our estimates assumed rain-fed production, it may be anticipated that if irrigation is used the yields may be higher.

In the case of rapeseed, 91.6% of land is represented by a 55-70% ratio, which means that the yields of rapeseed in some places still have potential to double.

However, to achieve such an increase in productivity, the management of current agricultural lands will have to improve, for example, by the use of optimal applications of nutrient and chemical pest, better disease, and weed control. Because low yields are often associated with technical and economic constraints preventing local producers from increasing productivity, these aspects should be prioritized when considering productivity increases in Poland. In order to achieve higher yields, it is also necessary to use high-quality seeds, increase NPK fertilization and protection from diseases and pests, as well as the use of appropriate technology. This is the only way for Poland to increase yields and to be competitive in Europe in terms of productivity.

Compared with Other Countries

The crop yield ratio and production gap for wheat for neighbouring countries such as the Czech Republic, Slovakia, and Germany is shown in Fig. 9. Obtained values of the ratio of actual over potential yield for wheat and rapeseed are presented numerically in Table 2.

Comparing data for wheat (Table 2) for Germany, the Czech Republic, Poland, and Slovakia, it can be observed that Germany has the smallest production gap (Fig. 9). Because farming in Germany is mostly fully mechanized, low-labour intense, and involves optimal applications of nutrients and chemical pesticides, disease and weed control, in many places it already has achieved its maximum sustainable yields given edaphoclimatic conditions. Almost the entire area of the country (93.6%) presents high crop-yield ratios corresponding to a range between 70-85%. Poland and Slovakia are similar with respect to the ratio. The majority of land (94.5% for Poland and 84.7% Slovakia, respectively) is characterized with a crop yield ratio between 25-40% for wheat. Similarly, in the Czech Republic the majority of production of wheat could still be doubled, because 94.8% of the area is represented by the crop yield ratio 40-55%.

On the other hand, the Czech Republic and Germany have high values for rapeseed ratio (over 85%) of 96.8% and 92.9%, respectively. Overall, Slovakia also presents a better ratio than Poland. For Slovakia the ratio is higher and the majority of land (83%) is characterized by a crop yield ratio between 55% and 70%. Poland has 91.6% of land with a crop yield ratio between 40-55%, thus significant improvements can be done to increase productivity. In simulations for both wheat and rapeseed, Poland has the lowest ratio and the highest yield gap of all countries analyzed here.

Poland is already among the four key European rapeseed producers. The growth in rapeseed oil production in the future will be favored by increasing demand for that raw product in the European biofuels industry [30]. Taking into account results of this investigation – the majority of land in Poland has a crop yield ratio between 40-55% (high yield gap) – Poland may significantly increase its role as a producer in the European market. Although improving agricultural productivity in Poland may be a formidable challenge, it also presents a great opportunity for the country to improve agricultural productivity in a sustainable manner. Furthermore, because sustainably increasing agricultural productivity is on political agendas worldwide due to increasing demands for agricultural products and land scarcity, the stakes are high and sustainable production increases, while minimizing environmental impacts can be an opportunity for a country to follow a better development path.

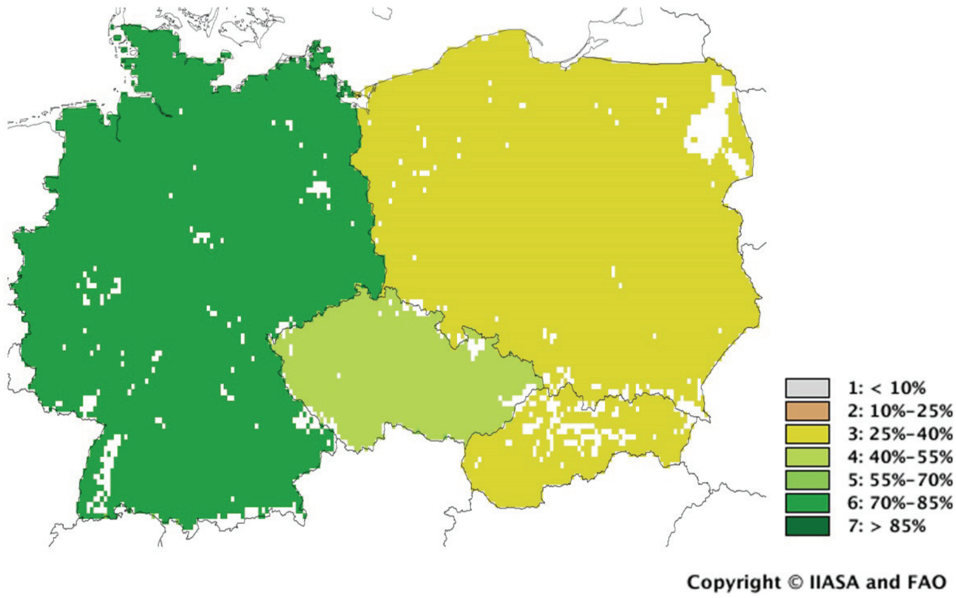

Fig. 9. Crop yield ratio (actual over potential) and production gap for rain-fed wheat in Czech Republic, Poland, Slovakia and Germany [based on IIASA/FAO, 2010. Global Agro-ecological Zones (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy].

Sustainably Increasing Agricultural Productivity

The results presented in this paper are concurrent with other authors. For example, Licker et al. [43] in their global analysis also demonstrate a 'yield gap' in agriculture by accessing 'climatic potential yield' as the 90th percentile yield achieved for a given crop in a given climate zone. In that, yield gaps for most crops (maize, wheat, rapeseed, and sunflower) are high for Eastern Europe, and approximately 60% more wheat could be produced if the top 95% of crop-harvested areas met the current climatic potential [43]. While their study was performed on a global scale, here we complement this analysis with more intricate downscaling to local circumstances. Our results are therefore congruent with Licker et al. and in this paper we additionally analyze in more detail factors pertinent specifically to sustainable increases of agricultural yields in Poland.

Our results along with the discussion relating to the current production may contribute to future considerations of the agricultural development in Poland. The simulations presented here may, for example, be directly useful within spatial planning and when considering setting priority areas for agricultural development. In recent years in Poland, changes in agricultural structure of farms can be observed, which has resulted in a range of environmental impacts. It is expected that the yields will further increase, keyed to increasing total farmed area. In fact, the number of farms is decreasing, but their average size is increasing. Significant changes in the structure of farms have been reported: over a 34% increase in the largest farms of 50 hectares or more, 25% decrease in the smallest farms 0-5 ha of agricultural land, 17% decrease of farms of 5-20 ha of agricultural land, farms of 20-50 ha area maintained their numbers [44].

Moreover, as a result of increasing yields and a lack of opportunities to increase animal production in Poland, surplus grain production can in the future be used for industrial use for the production of bioenergy. Grzybek [45] showed that the total demand for land for biofuel production, according to legal regulations, would amount to 787,900 ha in 2010 and 1,511,500 ha in 2020. According to Grzybek [45], maintaining the current level of consumption and allocation of crops for energy purposes may cause competition for land. This further emphasizes the importance of our results as sustainable yield increase can be a strategy to mitigate (or indeed to avoid) competition for land [3]. Increase in yield can be reconciled with increase in production for energy purposes while maintaining the increased demands of 7% under the protection of biodiversity ('greening').

Polish agriculture can play an important role in fulfilling sustainable food production in a resource-constrained world. Given growing competition for natural resources, increasing food consumption and new regulations concerning protection of the environment, a global competition for land is predicted to escalate. One of the key entities within the European Commission, the Standing Committee on Agriculture Research, states that 'research, innovation and agricultural knowledge systems must be fundamentally reorganized' [4]. Sustainable agriculture can be a way to compromise multiple demands with profit for the future. Greater yield is a key to greater production [46]. Greater yield of agriculture has been proposed as paramount to saving land for nature, also known as the 'land sparing' effect [47]. Agricultural intensification and land sparing indeed have been suggested to result in larger areas dedicated to nature conservation [48] provided that intensification leads to lower demand for new land clearance and do not cause a so-called 'rebound effect' [18]. Although land sparing has been proposed to best reconcile agriculture and biodiversity, others propose coexistence of biodiversity and agriculture on the same area within agro-ecological matrixes as the best strategy, the so-called 'land sharing' approach [49]. There are currently ongoing debates on which approach is better, while some authors show that this apparent dichotomy is context-dependent and both approaches may lead to positive benefits depending on local circumstances [50].

To sum up, in Poland further technological progress and technical performance is necessary [51-53] through better use of natural conditions and rational use of mineral fertilizers and liming, improved natural and organic fertilizer management, optimizing the use of soils for agricultural purposes, and optimal selection of crop species and varieties to conditions. Owing to these activities, land and labour productivity can be increased, which represents a unique opportunity for the country agricultural sector for a better way forward. Indeed, Poland is already often brought into scientific discussions regarding biodiversity management because of the hallmark Białowieża forest, and this paper demonstrates Poland as a country where reconciliation of biodiversity protection and agricultural development can be possible. In that respect, we show opportunities for Poland to take a different route than some already developed countries with highly intensive (yet not necessarily sustainable) agriculture.

Conclusions

Although increasing agricultural productivity in Poland may be a formidable challenge, it also presents a great opportunity for the country to improve yields in a sustainable manner. Poland has a large yield gap for wheat in the majority of the land (94.5%), meaning that Poland has a high potential to increase yield per hectare of wheat. A potential to increase yield was found also for rapeseed, but the gap was smaller than for wheat. The yield for wheat as well as for rapeseed could potentially be doubled. Indeed, it may be possible in the future to harvest even 8 t/ha of wheat and 4 t/ha of rapeseed compared with the harvests in 2012 at the levels of 4.14 t/ha for wheat and 2.59 t/ha for rapeseed. Improvements in productivity can be achieved through technological progress and technical performance, through rational use of mineral fertilizers and liming, improved natural and organic fertilizer management, optimizing the use of soils for agricultural purposes, and optimal selection of crop species and varieties adapted to certain conditions.

Comparing data for wheat for different countries: Poland, Slovakia, the Czech Republic, and Germany, we observed that Germany has the smallest yield gap. Poland and Slovakia present similar levels of yield gap. The majority of land (94.5% for Poland and 84.7% for Slovakia) has a crop yield ratio between 25-40%, while in the Czech Republic, 94.8% of the area has a wheat yield ratio between 40-55%. In the Czech Republic majority of production of wheat could potentially be doubled, because 94.8% of area has the crop yield ratio of 40-55%. Comparing data for rapeseed for Poland, Slovakia, the Czech Republic, and Germany, we observed that the highest values for ratio (over 85%) are in the Czech Republic and Germany (96.8% and 92.9%, respectively).

Sustainable intensification of agriculture in Poland could avoid, or at least contribute to, mitigating possible future competition for land between different crops (for example between crops for food and fuels). Increases in agricultural yields can also be reconciled with increasing demands for nature protection (for example 7% under the protection for biodiversity, so-called 'greening'). Consequently, Polish agriculture can play an important role in fulfilling sustainable food production in a resource-constrained world. In that the country faces an opportunity to follow development of high-yield agriculture while minimizing adverse impacts on the environment. Poland therefore is in an extraordinary position not only to demonstrate sustainable increase in agricultural productivity within the European Union, but also in the international context, especially for countries with agricultural productivity still below potential.

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References

1. Report 'Priorities for research and development in EU agriculture – How do we develop Sustainable Intensive Agriculture.' Brussels, March, **2012**.
2. European Commission Brussels. Communication from the Commission to the European Parliament, the Council, the European economic and social committee and the committee of the regions. Horizon 2020 – The Framework Programme for Research and Innovation, COM(2011) 808 final, 30. 11. **2011**.
3. Foresight. The Future of Food and Farming. Final Project Report. The Government Office for Science, London, **2011**.
4. European Commission – Standing Committee on Agricultural Research (SCAR). The 3rd SCAR Foresight Exercise. Sustainable food consumption and production in a resource-constrained world. February **2011**.
5. HEŁDAK M., RASZKA B. Evaluation of the local spatial policy in Poland with regard to sustainable development. Pol. J. Environ. Stud. **22**, (2), 395, **2013**.
6. FRATILA D. Evaluation of near-dry machining effects on gear milling process efficiency. Journal of Cleaner Production. **17**, (9), 839, **2009**.
7. KROLCZYK G., GAJEK M., LEGUTKO S. Predicting the tool life in the dry machining of duplex stainless steel. Eksploatacja i Niezawodnosc – Maintenance and Reliability; **15**, (1), 62, **2013**.
8. KROLCZYK G., LEGUTKO S., RAOS P. Cutting wedge wear examination during turning of duplex stainless steel, Tehnički Vjesnik - Technical Gazette, **20**, (3), 413, **2013**.
9. PUŠAVEC F., STOIĆ A ., KOPAČ J. The role of cryogenics in machining processes, Tehnički Vjesnik – Technical Gazette, **16**, (4), 3, **2009**.
10. PUSAVEC F., KRAJNIK P., KOPAČ J. Transitioning to sustainable production – Part I: application on machining technologies. Journal of Cleaner Production, **18**, (2), 174, **2010**.
11. LEWANDOWSKI I., HARDTLEIN M., KALTSCHMITT M. Sustainable crop production: definition and methodological approach for assessing and implementing sustainability. Crop Sci. **39**, 184, **1999**.
12. European Innovation Partnership 'Agricultural Productivity and Sustainability.' Available on: http://ec.europa.eu/agriculture/eip/
13. GODFRAY H.C., BEDDINGTON J.R., CRUTE I.R., HADDAD L., LAWRENCE D., MUIR J.F., PRETTY J., ROBINSON S., THOMAS S.M., TOULMIN C. Food security: The challenge of feeding 9 billion people. Science **327**, 812, **2010**.
14. BRUINSMA J. The Resource Outlook to 2050. By How Much Do Land, Waterand Crop Yields Need to Increase by 2050? FAO Expert Meeting on How to Feed the World in 2050. FAO, Rome, pp. 33, **2009**.
15. The Royal Society. Reaping the benefits: science and the sustainable intensification of global agriculture, London, **2009**.
16. GARNETT T., GODFRAY C. Sustainable intensification in agriculture. Navigating a course through competing food system priorities, Food Climate Research Network and the Oxford Martin Programme on the Future of Food, University of Oxford, UK, **2012**.
17. DAILY G. C. Nature's services: societal dependence on natural ecosystems. Island Press, Washington, D.C., USA. **1997**.
18. LAMBIN E.F., MEYFROIDT P. Global land use change, economic globalization, and the looming land scarcity. Proceedings of National Academy of Sciences **108**, (9), 3465, **2011**.
19. SMITH P., GREGORY P.J., VAN VUUREN D., OBERSTEINER M., HAVLIK P., ROUNSEVELL M., WOODS J., STEHFEST E., BELLARBY J. Competition for land. Philos. T. Roy. Soc. B. **365**, 2941, **2010**.
20. Greening the Common Agricultural Policy: MEPs vote on environmental measures. The British Ecological Society. Available on: http://www.britishecologicalsociety.org/blog/2013/03/21/greening-the-cap/#sthash.TPDrkO4t.dpuf http://www.britishecologicalsociety.org/blog/2013/03/21/greening-the-cap/, 21 March **2013**.
21. A few words about the agreement on the reform of the CAP. Agricultural portal Gospodarz.pl based on FAMMU/FAPA/Reuters, Available on: http://www.gospodarz.pl/aktualnosci/finanse/dotacje-i-doplaty/jest-porozumienie-w-kwestii-reformy-wpr.html, 3 July **2013** [In Polish].
22. DIRZO R., RAVEN P.H. Global state of biodiversity and loss. Annu Rev Environ Resour **28**, 137, **2003**.
23. STRASSBURG B.B.N., LATAWIEC A.E., CREED A., NGUYEN N., SUNNENBERG G., LOVETT A., JOPPA L., ASHTON R., SCHARLEMANN J.P.W., CRONENBERG-

ER F.J., IRRIBAREM A. Biophysical suitability, economic pressure and land-cover change: a global probabilistic approach and insights for REDD+. DOI: 10.1007/s11625-013-0209-5, Sustainability Science, pp 1-13, **2013** [In Press].
24. GIBBS H.K., RUESCH A.S., ACHARD F., CLAYTON M.K., HOLMGREN P., RAMANKUTTY N., FOLEY J.A. Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. P. Natl. Acad. Sci. USA., **107**, 16732, **2010**.
25. TILMAN D., BALZER C., HILL J., BEFORT B.L. Global food demand and the sustainable intensification of agriculture. December 13, PNAS, **108**, (50), **2011**.
26. TILMAN D., FARGIONE J., WOLFF B., D'ANTONIO C., DOBSON A., HOWARTH R., SCHINDLER D., SCHLESINGER W.H., SIMBERLOFF D., SWACKHAMER D. Forecasting agriculturally driven global environmental change. Science **292**, 281, **2001**.
27. LAMBIN E.F., GEIST H. (Eds). Land-Use and Land-Cover Change: Local processes and global impacts, Springer, Berlin, **2006**.
28. IIASA/FAO. Global Agro-ecological Zones (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy, **2012**.
29. Concise Statistical Yearbook of Poland. Central Statistical Office, Statistical Publishing Estabishment, Warsaw, **2013** [In Polish].
30. SEREMAK-BULGE J. (Ed.). Rapeseed market. State and perspectives. Instytut Ekonomiki Rolnictwa i Gospodarki Żywnościowej – Państwowy Instytut Badawczy, Agencja Rynku Rolnego, Ministerstwo Rolnictwa i Rozwoju Wsi. Nr 43, ISSN 1231-269X, June **2013** [In Polish].
31. FAS USDA: Grain: World Markets and Trade, May **2013**.
32. HARASIM A. (Ed.). Trends in the plant production in Poland until 2020. Instytut Uprawy Nawożenia i Gleboznawstwa Państwowy Instytut Badawczy. Studia i Raporty IUNG-PIB, 14, ISBN 978-83-7562-030-6, Puławy, **2009** [In Polish].
33. GRABIŃSKI J. Production of cereals in Poland-present condition and perspectives. IUNG Puławy. Available on: http://iung.pulawy.pl/pszenica/Produkcja%20zboz%20w%20Polsce-stan%20obecny%20i%20perspektywy.pdf [In Polish].
34. ROSIAK E., BODYŁ M., WIEGIER M., ZDZIARSKA T. Cereals market: state and perspectives. Instytut Ekonomiki Rolnictwa i Gospodarki Żywnościowej – Państwowy Instytut Badawczy. Nr 42, ISSN 1231-3149, October **2012** [In Polish].
35. Food and Agriculture Organization of the United Nations (FAOSTAT). Available on: http://faostat.fao.org/site/567/default.aspx#ancor (accessed, March **2011**).
36. Food and Agriculture Organization (FAO) (2000); agriculture towards 2010/30 technical interim report, Rome. April **2000**.
37. Concise Statistical Yearbook of Poland. Central Statistical Office, Statistical Publishing Estabishment, Warsaw, years: **1980-2012** [In Polish].
38. ZWOLIŃSKA M., KOWALSKI A., SEREMAK-BULGE J., SZAJNER P., TRAJER M. , MACHOWINA E. Cereals market: state and perspectives. Instytut Ekonomiki Rolnictwa i Gospodarki Żywnościowej – Państwowy Instytut Badawczy. Nr 44, ISSN 1231-3149, May **2013** [In Polish].
39. World Agricultural Supply and Demand Estimates. ISSN: 1554-9089 United States Department of Agriculture, August 12, **2013**.
40. KRASOWICZ S. Possibilities to increase cereal production in Poland. In: Is the cereal crisis threatens Poland under the non-agricultural use of grain. Ed. Wieś Jutra, Warszawa, pp. 66-78, **2007** [In Polish].
41. KUŚ J., FABER A., MADEJ A. Expected trends in crop production in regional perspective. W: Regional differences in agricultural production in Poland. Raporty PIB, IUNG Puławy, **3**, 195, **2006** [In Polish].
42. MICHAŁEK R., KUBOŃ M., GROTKIEWICZ K., PESZEK A. Scientific and technological progress in the modernization of Polish agriculture and rural development. PTIR Kraków, ISBN 978-83-935020-5-9, **2013** [In Polish].
43. LICKER R., JOHNSTON M., FOLEY J.A., BARFORD C., KUCHARIK C. J., MONFREDA C., RAMANKUTTY N. Mind the gap: how do climate and agricultural management explain the 'yield gap' of croplands around the world? Global Ecol. Biogeogr. **19**, 769, **2010**.
44. Report of the results. Agricultural Census 2010. Central Statistical Office, Statistical Publishing Establishment, Warsaw, Available on: http://www.stat.gov.pl/cps/rde/xbcr/gus/rl_psr_raport_z_wynikow_PSR_2010_260711.pdf, **2010** [In Polish].
45. GRZYBEK A.: Land area as a factor conditioning production of the biofuels. Problemy Inżynierii Rolniczej. **16**, (1), 63, **2008** [In Polish].
46. CONNOR D.J., MÍNGUEZ M.I. Evolution not revolution of farming systems will best feed and green the world. Global Food Security **1**, (2), 106, **2012**.
47. PHALAN B., BALMFORD A., GREEN R.E., SCHARLEMANN J.P.W. Minimising the harm to biodiversity of producing more food globally. Food Policy **36**, S62, **2011**.
48. BALMFORD A., GREEN R., PHALAN B. What conservationists need to know about farming. Proceedings of the Royal Society B. pp. 1-11, **2012**.
49. PERFECTO I., VANDERMEER J. The agroecological matrix as alternative to the land-sparing/agriculture intensification model. P. Natl. Acad. Sci. USA., **107**, 5786, **2010**.
50. LATAWIEC A.E., STRASSBURG B.N.S., RODRIGUEZ A.M., MATT E., NIJBROEK, R., SILOS M. Suriname: reconciling agricultural development and conservation of unique natural wealth. http://dx.doi.org/10.1016/j.landusepol.2014.01.007 Land Use Policy, **38**, 627, **2014**.
51. MICHAŁEK R., KUBOŃ M. Scientific and technological progress and its social and ecological effects. Inżynieria Rolnicza, **1**, (110), 207, **2009** [In Polish].
52. MICHAŁEK R., GROTKIEWICZ K. The scientific and technological progress and land and labor productivity in selected Polish Regions. Problemy Inżynierii Rolniczej, **2**, (64), 25, **2009** [In Polish].
53. MICHAŁEK R., GROTKIEWICZ K., PESZEK A. Land and labour productivity in selected European Union countries. Inżynieria Rolnicza, **1**, (110), 199, **2009** [In Polish].