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Environmental impact assessment of chemical plant protection in intensive crop production

Ocena oddziaływania chemicznej ochrony roślin na środowisko w intensywnej produkcji roślinnej

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Abstract

The study aimed to assess the environmental impact of chemical plant protection on the environment in an intensive crop production. This was conducted in a large-scale farm, located in the Wielkopolska voivodeship (Poland), in the years 2010-2013. The greatest number of chemical plant protection treatments were carried out for root crops and the lowest number for annual fodder crops (approximately 4 and 2 treatments, respectively). On average, there were carried out 3 chemical protection treatments for one plant species. The largest quantities of active substances were used in protection of root crops (5.72 $kg \cdot ha^{-1}$), followed by annual fodder crops (2.97 $kg \cdot ha^{-1}$), and smaller ones in oilseed crops (2.63 $kg \cdot ha^{-1}$) and cereals (2.44 $kg \cdot ha^{-1}$). The average consumption of active substances was 2.68 $kg \cdot ha^{-1}$. The most consumed were herbicides and fungicides. The average value of the multi-criteria index of the impact of plant protection on the environment amounted to -63.9 points. The lowest value of the index, indicating the most negative impact, was found for protection of root crops (-135.3 points), followed by annual fodder crops (-100 points). While the highest index value, resulting from smaller use of toxic substances, had oilseed crops (-54 points) and cereals (-62.4 points). The environmental impact of chemical plant protection was mainly related to a high risk of volatilisation into the atmosphere, followed by leakage into groundwater and a risk of surface water contamination. The threat of bioaccumulation of substances in living organisms was smaller.

Keywords: environmental impact, intensive crop production, plant protection products, potential toxicity index

Abstrakt

Badania miały na celu ocenę oddziaływania chemicznej ochrony roślin na środowisko w intensywnej produkcji roślinnej. Przeprowadzono je w wielkotowarowym gospodarstwie rolnym, położonym w województwie wielkopolskim (Polska), w latach 2010-2013. Największą liczbę zabiegów chemicznej ochrony roślin wykonano dla roślin okopowych, a najmniejszą dla roślin pastewnych jednorocznych (odpowiednio około 4 i 2 zabiegi). Średnio dla jednego gatunku rośliny przeprowadzono 3 zabiegi chemicznej ochrony. Największe ilości substancji aktywnych zastosowano w ochronie roślin okopowych (5,72 $kg \cdot ha^{-1}$), następnie pastewnych jednorocznych (2,97 $kg \cdot ha^{-1}$), a mniejsze w roślinach oleistych (2,63 $kg \cdot ha^{-1}$) i zbożowych (2,44 $kg \cdot ha^{-1}$). Zużycie substancji aktywnej wyniosło średnio 2,68 $kg \cdot ha^{-1}$. Najwięcej zastosowano herbicydów i fungicydów. Średnia wartość wielokryterialnego indeksu oddziaływania środków ochrony roślin na środowisko wynosiła -63,9 punkty. Najniższą wartość indeksu, wskazującą na najbardziej negatywny wpływ, uzyskano w ochronie roślin okopowych (-135,3 punkty), a następnie roślin pastewnych jednorocznych (-100 punkty). Natomiast największą wartością indeksu, wynikającą z mniejszego wykorzystania toksycznych substancji, charakteryzowały się rośliny oleiste (-54 punkty) i zboża (-62,4 punkty). Wpływ chemicznej ochrony roślin na środowisko był głównie związany z dużym ryzykiem ulatniania się substancji aktywnych do atmosfery, a także ich wymywania do wód gruntowych i zanieczyszczania wód powierzchniowych. Mniejsze było zagrożenie bioakumulacją substancji w organizmach żywych.

Słowa kluczowe: indeks potencjalnej toksyczności, intensywna produkcja roślinna, oddziaływanie na środowisko, środki ochrony roślin

Introduction

Plant protection products used in crops can move with the wind, migrate into the soil and water (Bobrecka-Jamro and Janowska-Miąsik, 2014). The accumulation of active substances (a.s.) in human and animal tissues is the cause of many diseases (Chaturvedi et al., 2013; Parrón et al., 2014). Residues of plant protection products may be present in crops after harvest (Malinowska et al., 2015a). In order to protect the health of humans, animals and the environment the European Union seeks in agricultural and environmental policy to reduce the use of plant protection products. Poland‘s rules for placing plant protection products on the market and their use are set out in the Act of 8 March 2013 on plant protection products (Act 2013). This provides the legal basis to implement obligations of the Directive on the establishing a framework for Community action to achieve the sustainable use of pesticides (Directive 2009). Pursuant to the provisions of the Act, the national action plan to reduce the risk associated with the use of plant protection products was developed and adopted (Announcement 2013). Since 2014 the principles of the integrated pest management (IPM) are implemented in Poland (Regulation 2009; Act 2013). In accordance with IPM, non-chemical over chemical methods are recommended. In recent years, the use of active substances in Poland per hectare of arable land increased to over 2 kg (Malinowska et al., 2015b). Chemical preparations available on the market are characterized by a high efficiency at low dose levels. Therefore, the environmental impact assessment of chemical plant protection by a measure of the quantity of plant protection products used is insufficient (Matyjaszczyk, 2011). This also depends on chemical composition, toxicity and application techniques of plant protection products (Padovani et al., 2004; De Smet et al., 2005). Recognizing the negative impact of plant protection products is important in the development of management programs for plant protection and strategies to protect the environment in a crop production.

The aim of the research was to analyze a potential impact of chemical plant protection on the environment in an intensive crop production system.

Materials and methods

The study was conducted on the basis of the detailed data on chemical plant protection treatments in the years 2010-2013 from Trzebiny Agricultural Farm, located in Wielkopolska voivodeship (Poland). The farm belongs to the Długie Stare Agricultural Company Ltd. which is one of the strategic subsidiaries of the State Treasury, held by the Agricultural Property Agency. The studied farm has a total area of 492 hectares of agricultural land, which is used for intensive crop production (Table 1). Climatic conditions for crop production in Wielkopolska region are typical for the temperate zone, with predominance of oceanic influences, great weather variability, temperature and precipitation range below average in the country (Zastawny, 2006). The farm is characterised by the dominance of weak soils. Soil quality index of arable soils is 0.67. The level of NPK fertilization was high (246 $kg \cdot ha^{-1}$), as compared to the average of 129 $kg \cdot ha^{-1}$ for the country reported by Central Statistical Office of Poland (2014b). The share of cereals amounted on average to 61.1% of sown area of the farm. Other important plant group with large share of sown area (20.8%) were industrial crops, including root crops (sugar beet) and oilseed crops (winter rape). The high intensity of crop production has been partly influenced by the animal production on the farm. In order to ensure properly balanced animal feeding, the bulky feed was produced, thus the annual fodder crops (maize for silage) and perennial fodder crops (alfalfa) accounted in total for 18.1% of the total sown area. The farm achieved high results of crop production. The average crop yields were higher than those for the analyzed period in Poland (Central Statistical Office of Poland, 2012a; 2013; 2014a). The yield of basic cereals amounted to 4.4 $Mg \cdot ha^{-1}$ (was by 24.1% higher than the national average), and the yields of grain maize and sugar beet were 11.1 and 65.1 $Mg \cdot ha^{-1}$ (by 58.7 and 12.4% higher), respectively.

Analysis of chemical plant protection impact on the environment was performed using the potential toxicity index, which results from the quantities and physico-chemical properties of active substances of plant protection products. The following variables have been taken into account: octanol-water partition coefficient (denoted as K_{ow}), solubility in water, Henry's constant and ground-water ubiquity score index (GUS) (Lewis and Tzilivakis, 1998). K_{ow} coefficient is a measure of the lipophilicity and indicates potential of a substance to bioaccumulation. Solubility in water determines the risk of surface water pollution. Henry's constant is calculated based on the solubility in water and vapor pressure parameters, indicating the ability of a substance to volatilize. GUS reflects the susceptibility of a substance to leaching and potential to contaminate groundwater. This index is computed as follows (Gustafson, 1989):

$$GUS = \log DT_{50} \cdot (4 - \log K_{OC}),$$

where:

DT_{50}- half-life of the active substance degradation in the soil [days],

K_{OC} - coefficient of adsorption by organic carbon compound.

On the basis of the average values of properties of active substances derived from available pesticide databases (EU Pesticides Database, 2014; Pesticides Properties Database, 2014), and criteria for point assessment of active substances (Table 2), as well as plant protection products consumption data, the index of the potential impact of plant protection on the environment (EMA) was calculated:

$$EMA = \sum_{i=1}^{n} (E_i \cdot Q_i) \text{ [points]},$$

where:

E_i - sum of points obtained by the i-th active substance on the basis of its physical and chemical properties [points],

Q_i - the amount of the i-th active substance used [$kg \cdot ha^{-1}$],

n - the number of active substances.

Table 1. General information about studied farm (averages for the years 2010-2013)

Tabela 1. Ogólne informacje o badanym gospodarstwie (średnie z lat 2010-2013)

Specification	Mean	Standard deviation
Agricultural land [ha]	492.29	-
Arable land [ha]	439.15	-
Soil quality index [points]	0.67	-
Livestock density [$LU \cdot ha^{-1}$]	0.66	0.01
NPK fertilization [$kg \cdot ha^{-1}$]	245.94	43.61
Structure of sown area [%]		-
Cereals	61.1	8.2
Root crops	7.9	1.2
Oilseeds crops	12.9	10.7
Fodder crops	13.4	4.6

Table 2. Point assessment of environmental risk of active substances

Tabela 2. Ocena punktowa zagrożenia środowiskowego substancji aktywnych

Parameter	Value range	Points
Octanol-water partition coefficient	<2.8	0
	≤2.8 – <3	-5
	≥3	-10
Water solubility [$mg \cdot l^{-1}$]	$\leq 1 \cdot 10^{-2}$	0
	$\leq 1 \cdot 10^{1}$	-2
	$\leq 1 \cdot 10^{2}$	-4
	$\leq 1 \cdot 10^{3}$	-6
	$\leq 1 \cdot 10^{4}$	-8
	$\geq 1 \cdot 10^{4}$	-10
Henry's constant	$\leq 2.5 \cdot 10^{-10}$	0
	$\leq 2.5 \cdot 10^{-9}$	-2
	$\leq 2.5 \cdot 10^{-8}$	-4
	$\leq 2.5 \cdot 10^{-7}$	-6
	$\leq 2.5 \cdot 10^{-6}$	-8
	$\leq 2.5 \cdot 10^{-5}$	-10
	$\leq 2.5 \cdot 10^{-4}$	-12
	$\leq 2.5 \cdot 10^{-3}$	-14
	$\leq 2.5 \cdot 10^{-2}$	-16
	$\geq 2.5 \cdot 10^{-2}$	-18
GUS index	≤1.8	-2
	<1.8 – ≤2.8	-7
	>2.8	-15

Source: Lewis et al. (1997); Lewis (1999)

Results

Figure 1 shows the differences in the number of plant protection treatments between plant groups and the average for the farm. The most treatments were carried out in root crops, followed by oilseed crops, cereals and annual fodder crops. On average, one plant species had 3 treatments. It was found that 62% of the overall amount of plant protection products used was represented by herbicides, 20.7% by fungicides, 9.2% by growth regulators and 8.1% by insecticides.

The largest consumption of active substances was found in protection of root crops (5.72 $kg \cdot ha^{-1}$) (Figure 2). Next were annual fodder crops (2.97 $kg \cdot ha^{-1}$) and oilseed crops (2.63 $kg \cdot ha^{-1}$). The lowest quantities of active substances were used in cereals (2.44 $kg \cdot ha^{-1}$). The average consumption of plant protection products was 2.68 kg of a.s. per hectare of sown area. The most consumed were herbicides (75.8%) and fungicides (14.5%). In addition to this, protection of oilseed crops was characterized by greater use of insecticides (6%) and of cereals - by greater use of growth regulators (13.7%) than any other plant.

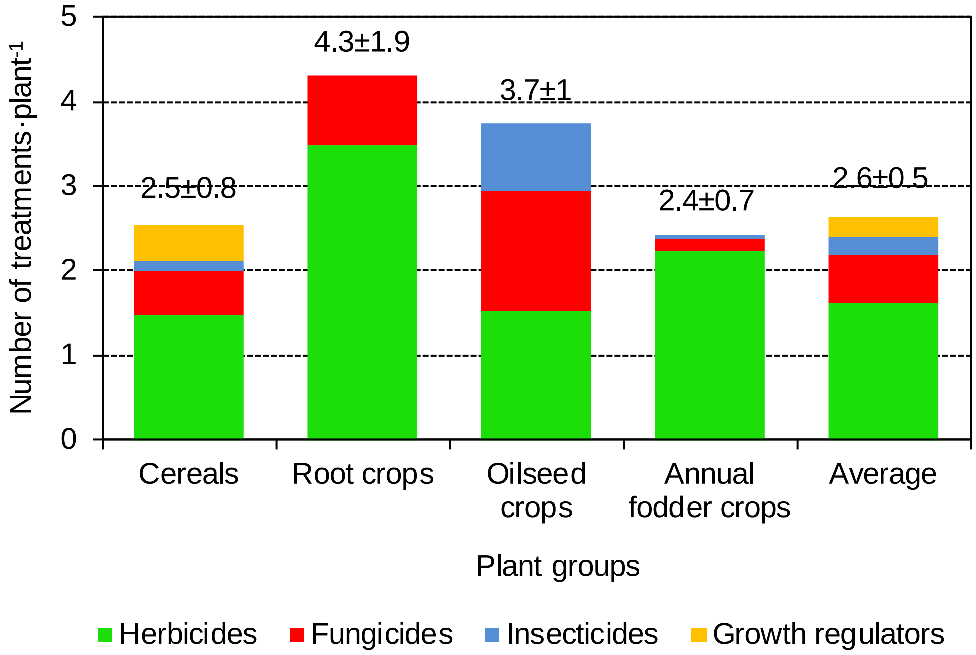

Figure 1. Number of treatments by the type of plant protection products used according to plant groups and the average for the farm (averages for the years 2010-2013 ± standard deviation)

Rysunek 1. Liczba zabiegów ochrony roślin według ich rodzajów w grupach użytkowych roślin uprawnych i średnia w gospodarstwie (średnie z lat 2010–2013 ± odchylenie standardowe)

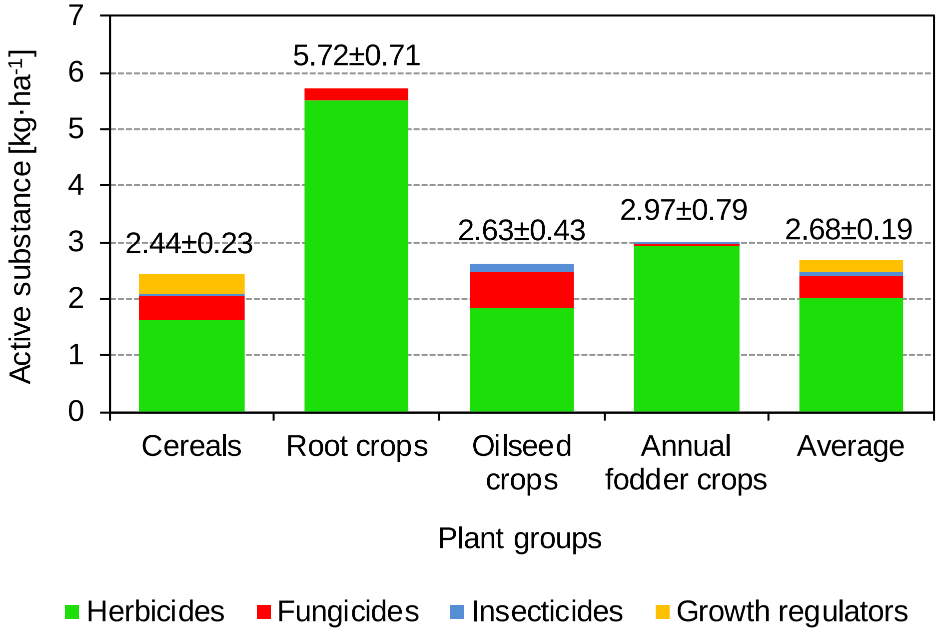

Figure 2. Consumption of active substances by the type of plant protection products used according to plant groups and the average for the farm (averages for the years 2010–2013 ± standard deviation)

Rysunek 2. Zużycie substancji aktywnej według rodzajów stosowanych środkach ochrony roślin w grupach użytkowych roślin uprawnych i średnia w gospodarstwie (średnie z lat 2010–2013 ± odchylenie standardowe)

The most negative value of the potential toxicity index, indicating the largest use of plant protection products with high toxicity to living organisms and the environment, had root crops (-135.3 points), followed by annual fodder crops (-100 points) (Figure 3). While less negative points had cereals (-62.4 points) and oilseed crops (-54 points). The average value of the index amounted to -63.9 points for the whole farm.

The values of individual components of multi-criteria index of the impact of plant protection on the environment for the farm are shown in Figure 4. The greatest threat to the environment was volatilisation (-20 points), followed by leaching potential (-17.4 points) and surface water contamination (-15.4 points). There was a lower risk of accumulation of the substances in living organisms (-11.1 points).

The values of the index components varied between plant groups (Figure 5). Chemical protection of root crops was associated with the greatest risks of leaching into groundwater (-56.6 points) and surface water contamination (-44.2 points), while there was the lowest risk of bioaccumulation (-7.4 points). Bioaccumulation was a major risk to the environment in protection of annual fodder crops (-19.2 points). The greatest risk of volatilization was observed in protection of annual fodder crops and root crops (-30.1 and -27.2 points, respectively), and the lowest in protection of oilseed crops (-16.7 points).

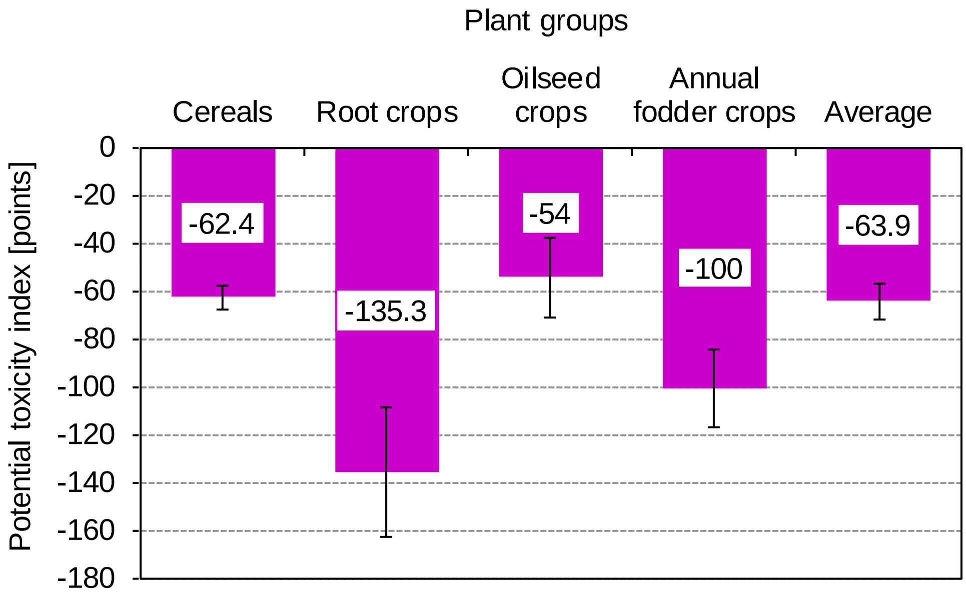

Figure 3. Values of multi-criteria index of the impact of plant protection products on the environment according to crop groups and the average for studied farm (averages for the years 2010–2013 ± standard deviation)

Rysunek 3. Wartości wielokryterialnego indeksu oddziaływania środków ochrony roślin na środowisko dla grup użytkowych roślin i ogółem w badanym gospodarstwie (średnie z lat 2010–2013 ± odchylenie standardowe)

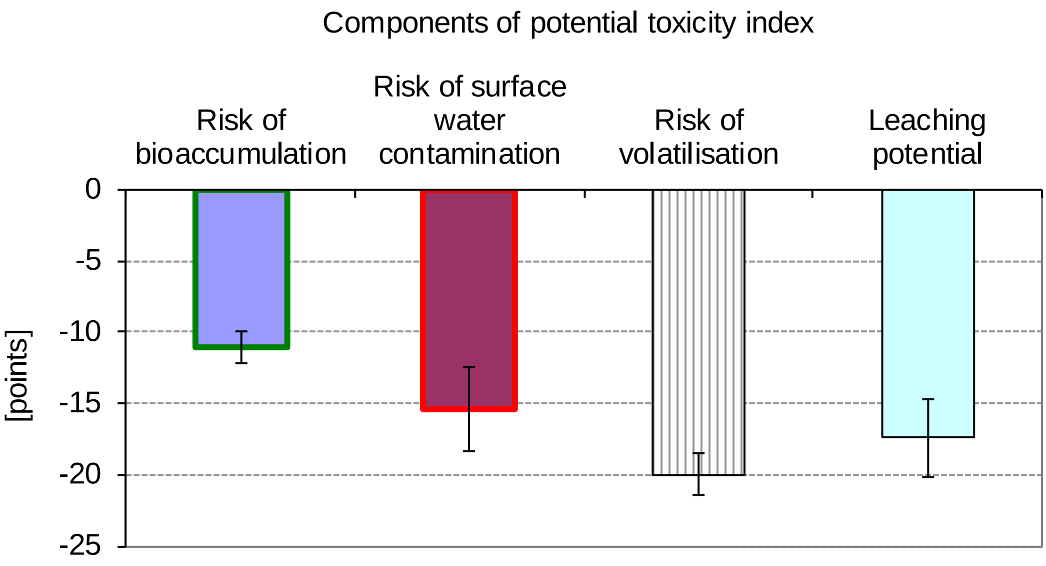

Figure 4. Values of components of multi-criteria index of the impact of plant protection on the environment on studied farm (averages for the years 2010–2013 ± standard deviation)

Rysunek 4. Ocena składowych wielokryterialnego indeksu oddziaływania ochrony roślin na środowisko w badanym gospodarstwie (średnie z lat 2010–2013 ± odchylenie standardowe)

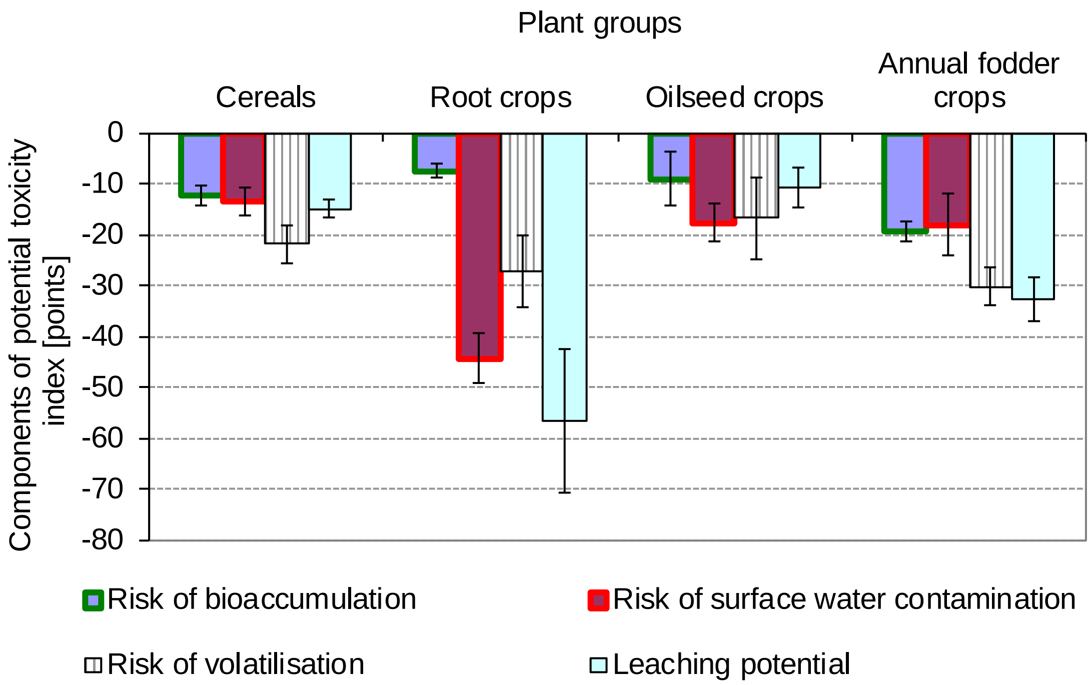

Figure 5. Values of components of multi-criteria index of the impact of plant protection on the environment according to plant groups on studied farm (averages for the years 2010–2013 ± standard deviation)

Rysunek 5. Ocena składowych wielokryterialnego indeksu oddziaływania ochrony roślin na środowisko dla grup użytkowych roślin w badanym gospodarstwie (średnie z lat 2010–2013 ± odchylenie standardowe)

Discussion

The intensive use of plant protection products increases the risk of their release to air, surface water and groundwater environment (Żak, 2016). There is also the likelihood of the presence of plant protection products residues in food products (Nikolopoulou-Stamati et al., 2016). Increased plant protection products usage is considered as an important factor of biodiversity loss (Kędziora and Karg, 2010; Sieminiak, 2014).

On the examined farm, the average number of spray treatments was smaller and the consumption of plant protection products was higher than in the country with the average of 7 treatments carried out during the 2012/2013 growing season, and of 2.02 kg of active substances used per 1 hectare of arable land and orchards (Urban, 2014). Most types of preparations used were herbicides and fungicides, as it was already noted in other studies (Jankowiak et al., 2012).The average consumption of active substances in chemical protection of cereals was 2.44 $kg \cdot ha^{-1}$. Syp et al. (2012) for winter wheat grown in Poland showed 1.9 $kg \cdot ha^{-1}$, and in Europe 2.3 $kg \cdot ha^{-1}$ a.s. The consumption of active substances in root crops (sugar beet) and oilseed crops (winter rape) amounted to 5.72 $kg \cdot ha^{-1}$ and 2.63 $kg \cdot ha^{-1}$, while the average in the country was 2.76 $kg \cdot ha^{-1}$ and 1.97 $kg \cdot ha^{-1}$, respectively (Central Statistical Office of Poland, 2012b; 2014b). Łozowicka and Konecki (2011) also observed intensive protection of winter rape. They noted from 5 to 6 spray treatments and the consumption of 2.57 $kg \cdot ha^{-1}$ a.s.

Bieńkowski (2011) obtained a higher average value of the multi-criteria index of the impact of plant protection on the environment from farms with different types of agricultural production and thereby indicated a smaller environmental impact than what was shown on the studied farm. The lowest index value had a group of farms with dominant cash crop production (-39.4 points), while the higher values were on dairy farms (-35 points) and farms specializing in pig production (-23.6 points). According to the mentioned author, the value of the index is related to the structure of sown area. Compared with farms specializing in pig production, farms with milk production had, despite less consumption of active substances, the index value indicating greater risk of environmental hazards. That depended mainly on chemical protection of annual fodder crops with being characterized by a use of active substances responsible for a high negative effect on the environment. The index for this plant group on studied farm amounted to -100 points. Lower value of the index had root crops (-135.3 points). Both plant groups occupied a large area on the farm. Therefore, it can be assumed that their chemical protection took part in the formation of the index value for the whole farm. The value of the index was also affected by the changes in the chemical plant protection as a result of adverse weather conditions during the winter 2011/2012. Winter crops were frost damaged that caused the necessity of spring resowing. It resulted in the fact that there was observed an increase in the number of spray treatments by 39.9% and consumption of plant protection products by 51.9% (Jankowiak et al., 2013).

Conclusions

1. The intensity of chemical plant protection varried among plant groups. The largest number of treatments and the largest consumption of active substances were required by root crops. On average, 3 chemical protection treatments were performed for one plant species, and the use of the active substance per 1 ha was 2.68 kg.
2. The multi-criteria index of the impact of plant protection on the environment was determined by the structure of production, and especially the structure of sown area and the selection of plant protection products applied in different plant groups. The average value of the index amounted to -63.9 points.
3. Among analyzed plant groups, the highly negative values of the potential toxicity indexes had root crops and annual fodder crops (-135.3 and -100 points, respectively) which resulted from larger consumption of active substances with properties associated with higher environmental threats. Chemical protection of oilseed crops and cereals was potentially less harmful to the environment which was indicated by less negative values of their indexes, equal to -54 and -62.4 points, respectively.
4. Complex index which takes into account both the consumption of plant protection products and physico-chemical properties of active substances can be a useful, research tool for the assessment of potential toxicity of chemical plant protection.

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