Effectiveness of a shelterbelt in decreasing the level of inorganic elements in agricultural landscape

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Abstract. Concentrations of calcium, magnesium, and carbon in inorganic compounds were measured in the groundwater crossing a shelterbelt. The differences among the concentrations of Ca, Mg, and C in inorganic compounds were attributed solely to the width of the shelterbelt. This biogeochemical barrier efficiently decreased the concentrations of chemical substances: the fall in the dry mass was 30–75%, in Ca 20–54%, in Mg 46–72%, and in C in inorganic compounds 58–71%.

Key words: shelterbelt, biogeochemical barrier, calcium, magnesium, carbon in inorganic compounds, groundwater.

INTRODUCTION

Degradation of water quality by nonpoint source inputs is not a recent phenomenon, but the visibility of its effects has increased because of greater regulatory, public, and research awareness of this pollution source. More recently, the impacts of nitrogen, phosphorus, oxygen demand, microbial species, and other components of nonpoint source pollution have attracted attention. This attention coincides with success in reducing point source inputs to receiving waters, resulting in greater emphasis on evaluation and control of nonpoint sources. Thus, to control nonpoint sources information is required on the phenomena resulting from rainfall runoff and other diverse water movement processes responsible for transporting pollutants. Modelling nonpoint pollution serves as a guide for understanding and quantifying the various soil, vegetation, and climate elements that control water quality. That is, by conceptual structuring of the processes involved between land uses and the ultimate impact on receiving water quality, modelling clarifies data and research needs. The phenomena connected with chemical and biological material transported from rainfall runoff to receiving waters constitute two broad areas of research: (a) transformations in the form and amount of material present on the land surface, and (b) the transfer and transport of material from the land surface into water moving across or through the land and ultimately to receiving

waters (Khaleel et al., 1980; Overcash & Davidson, 1980; Enfield et al., 1981; Correll, 1997; Eggen & Majcherczyk, 2006).

The impact of agricultural activities on water quality results from a complex set of circumstances. Source control is an attempt to reduce edge-of-field pollution. Delivery control focuses on measures that prevent the movement of pollutants from the field to the streams of aquifers. Agricultural pollution can be considered as two major groups: land-based and management-related. Land-based pollution is associated with the soil and results from erosion and subsequent movement of soil particles to surface waters. Management-related pollution is due to measures applied to the crop or land to enhance productivity and reduce pests. Some of the pollutants may be soluble in water and move with the runoff. Others may adsorb to the soil and move as the soil moves when eroded (Loehr, 1984; Sharpley & Smith, 1992).

Long-term investigations carried out in the Wielkopolska region (Western Polish Lowland) by the Research Centre for Agricultural and Forest Environment of the Polish Academy of Sciences in Poznań revealed leaching of large amounts of chemical compounds, including Ca and Mg ions, with groundwater from adjoining cultivated fields (Szajdak, 2011). Due to their high mobility in the soil profile, they immediately washed away from soil into groundwater. Both ions migrate apparently in the form of mineral salts and also mineral–organic complexes (Boratyński, 1981). The decrease of their concentrations in the sorptive complex due to excessive leaching seems to be a negative effect. They are available and indispensable nutrients for plants and undoubtedly they significantly participate in biological, physical, chemical, and biochemical processes in soils (Szajdak, 2002; Szajdak & Maryganova, 2009; Maryganova et al., 2010; Szajdak & Gaca, 2010).

The overall objective of researches dealing with the problem of agricultural nonpoint source pollution is to reduce the hazard of sediment and agricultural losses. There are several key processes that have to be studied, such as infiltration, runoff, erosion, adsorption–desorption, and chemical transformations in the soil.

Our earlier investigations showed that biogeochemical barriers in the form of meadows and shelterbelts separating cultivated fields from watercourses as well as small ponds have a significant impact on the spread of chemical pollution in agricultural landscape (Ryszkowski, 1987; Ryszkowski & Życzyńska-Bałoniak, 1998; Ryszkowski et al., 2002). This paper is a continuation of these researches. It focuses on the effect of shelterbelts on the levels of Ca, Mg, and C in inorganic compounds in the groundwater of agricultural landscape. It attempts to clarify the degree of the migration of mineral compounds with groundwater through a bio-geochemical barrier. The study reported herein was conducted to establish the optimum width of a shelterbelt to function as a biogeochemical barrier. At present, insufficient data are available on the efficiency of shelterbelts as biogeochemical barriers to the spread of these compounds in agricultural landscape. Additionally, the results obtained from all the experiments should give a better insight into the changes that take place in the landscape furnished with functional elements such as biogeochemical barriers.

25

MATERIAL AND METHODS

The investigations were carried out in the Chlapowski Agroecological Landscape Park in Turew situated 40 km south-west of Poznań on the Western Polish Lowland (Fig. 1). This area is located on loamy soils. It contains 70% cultivated fields, 12% meadows and pastures, and approximately 14% forestland including a well-developed network of shelterbelts.

Groundwater samples from artificial wells under a cultivated field and a shelterbelt were taken once a month during five years (2005–2009) and investigated. The groundwater under the shelterbelt flows away from the adjoining cultivated field and passes through the shelterbelt. The first 104 m of this shelterbelt is located on mineral soils (division: autogenic soils, order: brown forest soils, type: hapludalfs, subtypes: glossudalfs and ochraqualfs) and the next 104–125 m on mineral–organic soils (division: hydrogenic soils, order: post-bog soils, type: mucky soils, subtype: muckous soils) (Table 1).

A detailed description of the experimental setup was given in (Szajdak & Życzyńska-Bałoniak, 2002). The main results concerning the properties of soil organic matter and chemical soil properties were reported recently in (Szajdak et al., 2002).

The direction of the water flow was estimated on the basis of the water level in the wells. The shelterbelt includes different species with maple, ash, beech, and hawthorn dominating. To determine the concentrations of chemical compounds and their changes, water samples were taken along a 125 m long transect passing through the shelterbelt. The concentrations of Ca^{+2}, Mg^{+2}, and C in inorganic compounds were studied by examining groundwater filtered through Whatman GT/C filter paper. The concentrations of Ca and Mg were investigated by the method of Hermanowicz et al. (1976). Carbon in inorganic compounds was
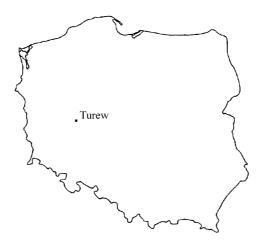

Fig. 1. Location of the study area in Poland.

Table 1. Soils of the groundwater sampling sites

Place of sampling	Kind of soil
	Mineral soils
I. Border between field and shelterbelt	D – autogenic soils,
II. 16.5 m from edge of shelterbelt	O – brown forest soils,
	T – hapludalfs,
	S – glossudalfs
III. 45.5 m from edge of shelterbelt	D – autogenic soils,
	O – brown forest soils,
	T – hapludalfs,
	S – ochraqualfs
	Mineral–organic soils
IV. 104.0 m from edge of shelterbelt	D – hydrogenic soils,
V. 125 m from edge of shelterbelt	O – post-bog soils,
	T – mucky soils,
	S – muckous

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D – division, O – order, T – type, S – subtype.

determined on TOC 5050A facilities (Shimadzu, Japan). Total dissolved solids were isolated by freeze-drying and drying to constant of weight at 105 °C.

The total amount of yearly rainfall was 700 mm in 2005, 800 mm in 2006, 750 mm in 2007, 810 mm in 2008, and 660 mm in 2009. The mean temperatures ranged from 7.9 to 10.0 °C. The highest temperature, +30 °C, was measured in July 2005, and the lowest, −16 °C, was registered in February 2006.

The precision based on replicate analyses was ±4% for Ca^{+2}, ±3% for Mg^{+2}, and ±4% for dry mass. All the determinations were run in triplicate, and the results were averaged.

RESULTS AND DISCUSSION

Nonpoint pollution from agricultural lands involves primarily three transport processes: runoff, leaching, and erosion–sedimentation. The primary transport medium for all three processes is water, which is also a significant carrier of nutrients and sediments. Hydrologic processes important relative to nonpoint pollution are: (i) infiltration, (ii) subsurface flow, (iii) overland flow, and (iv) evapo-transpiration (Overcash & Davidson, 1980).

The impact of agricultural activities on water quality results from a complex set of circumstances. Potential pollutants such as sediment and nutrients may leave a cropped field in runoff, or percolation water may be transported across or through the landscape to surface waters or groundwater, and depending on their effects in receiving waters, may produce water quality problems. The physical and chemical properties of nonpoint pollutants determine their path and mode of travel out of a field. Nonpoint source pollutants can be dissolved in water,

adsorbed to soil particles or into the solid phase. Soluble substances will be transported in the surface and subsurface runoff, and solid and adsorbed substances will be transformed in the surface runoff (Loehr, 1984).

Calcium and magnesium are extremely common in natural water systems, with calcium carbonate (limestone) and dolomite being two widespread natural sources. Solubility in water is influenced by the pH and CO_2 content of the water. Surface waters are always oversaturated with respect to calcite and aragonite and thus the carbonate skeletons should be entirely preserved in the photic zone. It then may be concluded that the biological production of $CaCO_3$, which is equal to the flux of particulate inorganic carbonate, would probably be close to 8.5×10^{15} g y^{-1} (Likens, 1981, pp. 136–139).

Chemically, Mg behaves similarly to Ca but is found in much lower concentrations in water. Both Ca and Mg prefer oxygen as a donor atom. It can therefore be expected (i) that both will bind the oxygen-containing carboxylic groups in humic substances and (ii) that the complexes formed will be of a predominantly electrostatic nature. Being the major cations in natural waters, Ca and Mg are of importance for the state of aquatic fulvic and humic acids.

Changes in the concentrations of mineral substances in the groundwater passing through a wide old leafy shelterbelt were investigated. As reported by Szajdak & Życzyńska-Bałoniak (2002) and Szajdak et al. (2003) and as observed in the present study, the concentrations of chemical compounds in the dry mass of groundwater flows from cultivated fields to the shelterbelt were very high, amounting to 4996.0 mg L^{-1} in 2005. However, the five-year mean concentration was 1839.0 mg L^{-1} (Table 2). Like the content of dry mass, the concentrations of Ca and Mg systematically decreased during the entire period of the investigations. The mean content of Ca was 349.7 mg L^{-1} in 2005 and it fell to 175.0 mg L^{-1} in 2009.

The highest mean concentration of Mg was registered in 2005, when it equalled 77.3 mg L^{-1} in the flow to the shelterbelt. In the following years the concentration fell, being 35.6 mg L^{-1} in 2009 (Table 3). Over the five years of the investigations the yearly mean contents of Ca and Mg decreased to 49.9% and 53.8%, respectively. Long-term investigations on leaching carried out in the Research Centre for Agricultural and Forest Environment of the Polish Academy of Sciences showed that due to this process the concentrations of Ca and Mg and also of many organic compounds released from soils increase in groundwater (Karlik & Życzyńska-Bałoniak, 1985; Karlik, 1993, 1997).

The reason of the high quantities of Ca and Mg in groundwater passing through the shelterbelt from the cultivated field was liming carried out in these years. The high amount of rainfall in June 2005 (105.3 mm) activated the migration of these ions, which caused their high concentrations in dry mass (Życzyńska-Bałoniak et al., 1998).

Dissolved organic matter leached from soil may carry nutrient cations such as Ca^{2+} and Mg^{2+}. This makes the study of dissolved organic matter even more important. Many of the functional groups of dissolved organic matter are acidic and deprotonated, resulting in anionic charged matter, which facilitates its solubility and ability to complex with metals.

Table 2. Yearly concentrations (mean±95% confidence level, mg L^{-1}) of total dissolved solids in groundwater under the shelterbelt at different distances from the edge of the shelterbelt

Soil and distance from shelterbelt edge	2005	2006	2007	2008	2009	2005–2009
Mineral soils						
Supply from the field	2544.4±89.5	1828.7±65.1	1925.7±70.3	1645.8±60.1	1251.0±45.3	1839.0±68.0
16.5 m	647.2±22.6	860.5±30.6	698.0±27.1	537.7±19.3	872.2±31.8	723.1±26.4
45.5 m	537.9±19.3	543.2±21.2	547.3±20.8	503.2±19.6	521.3±17.7	530.6±19.1
Mineral–organic soils						
104 m	871.1±30.5	803.2±28.9	919.0±32.3	940.6±33.8	1236.0±44.6	954.0±34.0
125 m	–	–	697.6±25.1	861.6±30.1	1118.8±39.8	892.7±34.5

– Means not determined.

29

Table 3. Yearly concentrations (mean±95% confidence level, mg L^{-1}) of Ca^{+2}, Mg^{+2}, and C in inorganic compounds in groundwater under the shelterbelt at different distances from the edge of the shelterbelt

Year of investi-gations	Flow to shelterbelt	Mineral soils		Mineral–organic soils	
		16.5 m	45.5 m	104 m	125 m
Ca^{+2}					
2005	349.7±12.2	162.5±5.8	131.5±4.9	234.0±7.5	–
2006	241.8±8.4	194.6±6.8	136.5±4.9	213.5±8.1	–
2007	278.9±10.5	176.5±6.2	147.7±5.3	254.9±9.1	201.6±7.0
2008	239.7±8.9	143.7±5.2	129.0±5.4	250.5±9.0	256.3±8.9
2009	175.0±6.2	129.0±4.8	142.0±5.1	340.0±11.9	327.2±12.5
Mg^{+2}					
2005	77.3±2.8	21.6±0.8	20.2±0.9	340.0±13.3	–
2006	49.8±1.8	27.0±1.2	22.7±0.8	256.7±9.2	–
2007	61.3±2.2	23.9±1.0	20.5±1.3	28.5±1.5	22.5±1.4
2008	47.9±1.9	18.4±0.9	19.6±0.9	22.6±1.0	37.3±1.3
2009	35.6±1.3	37.9±1.2	22.1±0.7	43.2±2.0	49.0±1.7
C-in					
2005	108.0±3.9	35.5±1.4	30.2±1.2	42.1±1.5	–
2006	107.5±3.7	39.6±1.4	33.2±1.1	41.3±1.6	–
2007	38.3±1.5	38.3±1.6	31.6±1.3	48.6±2.0	44.7±2.0
2008	121.9±4.4	35.6±1.3	28.6±1.3	47.7±1.7	52.2±1.9
2009	112.7±4.0	47.0±1.9	31.5±1.2	58.9±2.1	54.2±1.9

C-in – carbon in inorganic compounds; – means not determined.

Contrary to Ca and Mg, the concentrations of C in inorganic compounds increased over the investigation period. This phenomenon may result in high mineralization of organic matter in groundwater under the shelterbelt. The lowest yearly mean content of C in inorganic compounds was observed in 2005 and 2006: 108.0 and 107.5 mg L^{-1}, respectively. During the following years an average increase of 23% was estimated in the mineral cation concentrations (Table 3).

Earlier research shows a strong impact of rainfall on the changes in the concentrations of dissolved chemical compounds in groundwater passing through shelterbelts (Szajdak & Matuszewska, 2000). The effect of rainfall on the migration of these compounds from cultivated fields to shelterbelts could be observed five to eight months later. The heavy rainfall in August 2006 (203.7 mm) seems to have played an important role in the highest concentrations of chemical compounds in groundwater under the shelterbelt in January 2007. However, the heavy rainfall events in July and August 2007 caused the highest content of chemical compounds in groundwater flows to shelterbelts in April 2008, that is eight months later. It is obvious that the highest concentrations of chemical compounds in groundwater correspond to periods of rainfall.

A significant correlation was observed between rainfall and the concentration of chemical compounds in groundwater. In our earlier studies an impact of rainfall also on the concentration of nitrogen substances in groundwater was found (Szajdak & Matuszewska, 2000; Szajdak et al., 2003).

It was established that the concentrations of all investigated chemical compounds in the groundwater passing through the shelterbelt at a distance of 16.5 m from the edge were significantly lower than in the flow to the shelterbelt. The highest decrease of dry mass was observed in 2005. That year the decrease in the concentration of total dissolved solids in the groundwater that had passed through 16.5 m of the shelterbelt was 75%. Moreover, the concentrations of Ca in that period decreased by 20–54%, Mg by 46–72%, and C in inorganic compounds by 58–71% (Tables 2, 3).

In our earlier investigations (Życzyńska-Bałoniak et al., 1998; Szajdak et al., 2002; Meysner et al., 2006) the highest significant decrease of organic C and humic substances was also recorded after the flow of groundwater through 16.5 m width of the shelterbelt. The concentrations of organic C decreased by 55–63% and of humic substances by 69–79.5%. One of the reasons of unequal decrease of mineral substance passing through different distances of the shelterbelt is the different properties of mineral and mineral–organic soils. Mineral soils are acidic (pH 3.9–5.2), while mineral–organic soils are neutral (pH 6.9–7.4) (Szajdak et al., 2003). Higher acidity of mineral soils may cause a larger removal of Ca and Mg from their inorganic compounds and mineral–organic complexes. Applying various analytical techniques, Szajdak et al. (2003) proved significant differences between humic compounds isolated from these two different soils under a shelterbelt. The highest maturity and thermal stability of humic acids were characteristic of the edge of the shelterbelt and the adjoining cultivated field. The activity of urease and the concentrations of total nitrogen, nitrates, and ammonium were also the highest at the edge of the shelterbelt. With respect to the nature of humic acids these substances characterize a high potential of complexity of metals including Ca and Mg. Our results concerning the part of the shelterbelt located on mineral soils suggest that the highest decrease of these ions may be due to the complexity and maturity as well as stability of humic substances. These findings are in line with the results of Szajdak & Meysner (2002), Szajdak & Życzyńska-Bałoniak (2002), Szajdak et al. (2002), and Meysner et al. (2006).

Our earlier studies on the influence of meadow on the process of groundwater purification showed that a significant decrease in the concentrations of inorganic and organic compounds occurred only in dry years. Moreover, during wet years accumulation of chemical substances as a result of the flooding of the meadow was observed. This resulted in their increasing concentrations in groundwater (Ryszkowski et al., 1990; Szajdak, 2011). However, in the case of groundwater passing through the shelterbelt this phenomenon was not observed either during wet or dry years. These findings suggest that the efficiency of shelterbelts as biogeochemical barriers is independent from atmospheric conditions.

Comparison of the efficiency of groundwater purification over the whole width of the shelterbelt revealed a significantly higher decrease in the first 16.5 m than in the following 45.5 m. Over the distance of 16.5 m the concentrations of Ca, Mg, and C in inorganic compounds significantly declined: by 8–22%, 6–16%, and 15–17%, respectively (Table 3). A similar phenomenon was observed for the migration of organic compounds. This means that the greatest decrease in the concentrations of organic compounds in groundwater under the shelterbelt took place in the first 16.5 m. Moreover, our earlier findings about the efficiency of the limitation of nitrogen and phosphorus over the first 10 to 15 m by a biogeo-chemical barrier such as a shelterbelt (Ryszkowski & Życzyńska-Bałoniak, 1998; Szajdak et al., 2002) are in good agreement with the present results for Ca, Mg, and C in inorganic compounds. Further flow of groundwater up to 104 m under the shelterbelt resulted in the increasing concentrations of all compounds deter-mined in dry mass. The characteristic increase of the contents of Ca, Mg, and mineral C along with the increase of the width of the shelterbelt was up to 46.6%, 25.9%, and 33.5%, respectively. High concentrations of all investigated compounds in the groundwater at this distance are connected with the change of soil from mineral to mineral–organic (Table 3) (Szajdak et al., 2002).

CONCLUSIONS

Concerns over the environmental impacts of chemicals in agricultural landscapes have focused attention on the study of calcium, magnesium, and carbon in inorganic compounds in groundwater. These investigations have shown that large amounts of chemical compounds migrate into groundwater from cultivated fields. Our study revealed high concentrations of calcium in the groundwater under a cultivated field: its yearly mean concentration equalled 373.8 mg L^{-1}.

It was proved that a biogeochemical barrier such as a shelterbelt can efficiently decrease the content of chemical compounds in groundwater. The highest decrease in the concentration of determined compounds was observed over the first 16.5 m of the shelterbelt where it was 30–75% for dry mass, 20–54% for calcium, 46–72% for magnesium, and 58–71% for carbon in inorganic compounds. Father, up to 45.5 m width of the shelterbelt, the impact on the contents of dissolved chemical compounds was not so striking: the decrease in their concentration was 8–22%. All aspects of our findings indicate that the first 16.5 m of the shelterbelt was the most efficient for the purpose of functioning as a biogeo-chemical barrier.

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Kaitsevööndi efektiivsus anorgaaniliste elementide taseme vähendamisel põllumajandusmaastikus

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Aastatel 2005–2009 uuriti Turewi Agroökoloogilises Maastikupargis (Poola) haritava maaga piirneva kaitsevööndi (kaitseriba) tõhusust haritavalt maalt pärineva pinnasevee (põhjavee) mineraalainete sisalduse vähendamisel. Põllualade pinnasevee mineraalainete üleküllus võib osutuda koormavaks ümbritseva keskkonna tasakaalustunud seisundile. Eksperimentaalselt hinnati kaltsiumi, magneesiumi ja anorgaaniliste ühendite süsinikukoguseid ning nende kontsentratsiooni muutusi kaitsevööndit läbinud pinnasevees sõltuvalt kaitsevööndi laiusest ja mullastikust. Vee proovivõtukohad asusid mineraalmuldade puhul 16,5 ja 45,5 meetri ning mineraal-organogeensete muldade puhul 104 ja 125 meetri kaugusel proovivõtukohast haritaval maal.

Selgus, et biogeokeemilise barjäärina talitlev kaitsevöönd vähendab efektiivselt keemiliste ühendite sisaldust kaitsevööndist läbivalgunud pinnasevees. Suurim keemiliste ainete kontsentratsiooni vähenemine toimus esimese vööndiriba (laiusega 16,5 m) läbimisel, mil vees sisalduv sade vähenes 30–75%, kaltsiumisisaldus 20–54%, magneesiumisisaldus 46–72% ja anorgaanilistes ühendites oleva süsiniku sisaldus 58–71%. Edaspidisel pinnasevee läbivalgumisel kaitsevööndis (kuni 45,5 meetri kaugusele) kaasnesid samuti vees sisalduvate ainete kontsentratsiooni vähenemised, kuigi tunduvalt väiksemas ulatuses. Nii vähenes vees kaltsiumi, magneesiumi ja anorgaanilistes ühendites oleva süsiniku sisaldus vastavalt 8–22%, 6–16% ning 15–17%. Liikudes mineraalmuldadelt mineraal-organogeensete muldade suunas (104. ja 125. meetrile), suurenes üha enam mullaomadustest tingitud pinnasevee kaltsiumi, magneesiumi ning anorgaanilistesse ühenditesse talletatud süsiniku sisaldus.